A roadmap for the Digital Transformation of labour-intensive organisations

by

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Declaration

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Abstract

Labour-intensive firms, or those that rely heavily on labour value creation to deliver their goods or services, find it challenging to adopt Digital Transformation initiatives. This is especially true in developing nations such as South Africa, where the industry has a high unemployment rate and extensive labour usage. These organisations struggle with implementing Digital Transformation due to the high labour variance in their value-creation. Additionally, some firms are hesitant to start the process of Digital Transformation due to them having other priorities or not seeing the need to implement digital transformation. As the world's industries progress in Digital transformation, in what is known as the Fourth Industrial Revolution, the demand for it grows. Eventually, businesses must decide whether to implement some levels of digital transformation. A practical strategy is desired to ensure that these labour-intensive environments can adapt and achieve digital transformation.

The study approaches the problem by creating a roadmap for the digital transformation of labour-intensive organisations explicitly intended to change some aspects of these environments' value creation practically. The research approach starts by researching Digital Transformation and supporting concepts such as Industry 4.0 and Industry 5.0. The inclusion of this literature serves two purposes: first, it explores various digital or technological tools that might be used in the transformation endeavour; second, it investigates diverse approaches to Digital Transformation. Additionally, the roadmap approach draws on enterprise engineering theory, where reference architectures are considered and ultimately used in the development.

To further investigate various types of labour-intensive environment, observational case studies, supported by literature, is used to understand these types of environment and investigate the common cause-and-effect relationships found in them. This investigation's findings and the literature on reference architectures are then used to develop a reference architecture for these firms to map their current and aspiring digital progression. Additionally, a technology mind mapping methodology is developed for these firms to use with the architecture to identify various digital or technological tools in their Digital Transformation effort.

The next step combines the reference architecture and the technology mind mapping methodology with other tools used in operations management in the form of an incremental roadmap. The roadmap is developed to be continuously used by these firms and focuses on identifying and implementing practical solutions in their Digital Transformation effort.

This research aimed to find a practical approach to Digital Transformation, where these labour-intensive organisations can use the roadmap and the accompanying architecture and mind mapping methodology to find and implement digital or technological solutions practically. After evaluating the approach in expert verification and practical validation, minor changes produced a working roadmap that medium-sized labour-intensive environments can use in their Digital transformation effort. Alternatively, digital consulting agencies can use the roadmap in the Digital Transformation of smaller labour-intensive environments.

Opsomming

Arbeidsintensiewe firmas vind dit uitdagend om Digitale Transformasie-inisiatiewe aan te neem. Dit is veral waar in ontwikkelende lande soos Suid-Afrika, met 'n hoë werkloosheidsyfer en 'n hoë afhanklikheid van arbeid. Hierdie organisasies sukkel met die implementering van Digitale Transformasie as gevolg van die variasie van arbeid in hul waardeskepping. Daarbenewens is sommige firmas huiwerig om die proses van Digitale Transformasie te begin weens ander prioriteite. Soos die wêreld se nywerhede vorder in Digitale Transformasie, in wat bekend staan as die Vierde Industriële Revolusie, groei die vraag daarna. Uiteindelik moet ondernemings besluit of hulle sekere vlakke van Digitale Transformasie moet implementeer of nie. 'n Praktiese strategie word verlang om seker te maak dat hierdie arbeidsintensiewe besighede kan aanpas en 'n tipe Digitale Transformasie kan bereik.

Die studie benader die probleem deur 'n padkaart vir die Digitale Transformasie van arbeidsintensiewe organisasies te skep, wat uitdruklik bedoel is om sommige aspekte van hierdie besighede se waardeskepping prakties te verander. Die navorsingsbenadering begin deur Digitale Transformasie na te vors en konsepte soos Industrie 4.0 en Industrie 5.0 te benader. Die insluiting van hierdie literatuur dien twee doeleindes: eerstens ondersoek dit verskeie digitale of tegnologiese hulpmiddels wat in die transformasiepoging gebruik word; tweedens, ondersoek dit uiteenlopende benaderings tot Digitale Transformasie. Verder maak die padkaart gebruik van ondernemingsingenieursteorie, waar die idee van 'n verwysingsargitektuur gebruik word.

Om verskeie tipes arbeidsintensiewe besighede verder te ondersoek, word waarnemingsgevallestudies, ondersteun deur literatuur, gebruik om hierdie tipe besighede te verstaan, en die algemene oorsaak-en-gevolg-verwantskappe wat daarin gevind word, te ondersoek. Bevindinge in hierdie ondersoek, tesame met die literatuur oor verwysingsargitekture, word dan gebruik om 'n verwysingsargitektuur te ontwikkel vir hierdie firmas om hul huidige en aspireerde digitale vordering op te karteer. Daarbenewens word 'n tegnologiese breinkaart-metodologie ontwikkel vir hierdie firmas om saam met die argitektuur te gebruik om verskeie digitale of tegnologiese ondersteuningsmetodes in hul Digitale Transformasiepoging te identifiseer.

Die volgende stap kombineer die gebruik van die verwysingsargitektuur en die tegnologiese breinkaartmetodologie met ander instrumente wat in operasionele bestuur gebruik kan word in die vorm van 'n inkrementele padkaart. Die padkaart is ontwikkel om deurlopend deur hierdie firmas gebruik te word, en fokus op die identifisering en implementering van praktiese oplossings in hul Digitale Transformasiepoging.

Die navorsing se doel was om 'n praktiese benadering tot Digitale Transformasie te vind, waar hierdie organisasies die padkaart kan gebruik om digitale of tegnologiese oplossings prakties te vind. Nadat die benadering deur beide deskundige verifikasie en praktiese validering geëvalueer is, is daar vernaderinge gemaak en 'n werkende model is opgelewer wat mediumgrootte arbeidsintensiewe besighede kan gebruik in hul Digitale Transformasiepoging, of wat konsultasieagentskappe kan gebruik in die Digitale Transformasie van kleiner arbeidsintensiewe besighede.

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List of Acronyms

AER: Adaptive enterprise reference model

AI: Artificial intelligence

AR: Augmented reality

CAD: Computer-aided design

CAM: Computer-aided manufacturing

CPS: Cyber-physical systems

DT: Digital Transformation

EA: Enterprise architecture

ERA: Enterprise reference architecture

ERP: Enterprise resource planning

F1: Formula 1

HMLV: High-mix low-volume

ICT: Information and communications technology

IIoT: Industrial Internet of Things

IoE: Internet of Everything

IoS: Internet of Services

IoT: Internet of Things

I4.0: Indsutrie 4.0/Industry 4.0/The Fourth Industrial Revolution

I5.0: Indsutrie 5.0/Industry 5.0/The Fifth Industrial Revolution

MCU: Microcontroller

M2M: Machine-2-machine

NIST: National Institute of Standards and Technology (USA)

OEE: Overall equipment effectiveness

OMS: Online maintenance/management system

PLC: Product life cycle

PV: Practical validation questions

P2P: Peer-2-peer

QR: Quick Response

RAV: Roadmap approach validation questions

RV: Rationale validation questions

RFID: Radio frequency identification

ROI: Research objective

RTC: Resistance to change

RTOS: Real-time operating system

SGV: Self guided vehicle

SLF: The Stellenbosch Learning Factory

SOP: Standard operating procedure

SMEs: Small and medium sized enterprises

TBL: Triple bottom line

UHF RFID: Ultra high-frequency RFID

UPS: Uninterruptible power supply

USDA: United States Department of Agriculture

VR: Virtual reality

Wi-Fi: Wireless fidelity

WIP: Work-in-progress

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CHAPTER 1

Introduction

"The man who moves a mountain begins by carrying away small stones"- Confucius

With the 4th Industrial Revolution's rise, more and more traditional business models are becoming obsolete. Some might feel that the term "Digital Transformation" is becoming somewhat overused in modern technology and business magazines. Digital Transformation (DT) is, however, of increasing importance in the modern competitive market, and such a transformation should be a top priority [118][108].

In theory, Digital Transformation is crucial for growth in a modern market. A recent Harvard Business School study found that firms which embrace Digital Transformation experience an average growth of up to 55% compared to an average of 37% for those who do not embrace the transformation (in the same period) [118]. Digital Transformation is not always an easy endeavour to undertake, and firms may be hesitant to start such a transformation and often require guidance before making such a jump [108]. This is especially true in a labour-intensive context, where low-tech industries demand high levels of labour [90]. Firms that rely heavily on labour often lag behind the globe compared to other firms. Given the variable nature of labour, where one production cycle might differ from the next, the fear of potential obsolescence, where DT might replace the worker and the financial requirement of Digital Transformation, labour-intensive firms often struggle with their approach to Digital Transformation [41][105].

Additionally, given the challenges in labour standardisation, it can be beneficial for firms first to understand their environment, attempt to optimise it and identify areas for value-adding DT before moving to major forms of Digital Transformation [97][108]. The goal of such an incremental strategy is to minimise disruption, encourage digital acceptability among all stakeholder levels in the organisation, and assure value-adding Digital Transformation rather than transforming for the sake of Digital Transformation.

1.1 Background

Ever since the turn of the 19th century, society has undergone a rapid and continuous evolution. During the last 200 years, our lives have dramatically changed in almost every aspect. Society went from waging war with frigates, muskets and swords to tanks, nuclear missiles and, eventually, cyber-attacks. Two hundred years ago, it would take us months to travel distances which can be reached within hours today. Our population grew from 1 billion in 1800 to more than 7 billion in less than 250 years, and the global extreme poverty rate has dropped from 90% to less than 10% [106]. Today we have incredibly high literacy rates, and low child mortality rates and more than half the world lives in full democracies [106]. These statistics show the impact of how the industrial revolutions of the past 200 years have directly and indirectly impacted our societal growth and development.

To understand what happened in the past 200 years, one has to go back to the advent of the first industrial revolution, which started with the birth of the steam engine and the mechanisation of industry [47]. This period marked a time of immense development that transformed Europe and North America from farming communities to fully industrial powerhouses. The steam engine's disruption capabilities, which emerged in Britain, fuelled the first revolution. This technology dramatically revolutionised society by allowing for speedier transportation and expanded industrial capacity, allowing formerly hand-crafted things to be manufactured much more quickly and without the need for skill. The impact of this revolution had an immense disruption on society and brought in a new age of living [47][108].

The first revolution led to a subsequent revolution. What is now known as the 2nd Industrial revolution is also seen as one of the world's most significant periods of technological change in the late 19th and early 20th centuries. During this time, more and more humans moved to developed urban areas and switched from using the sun as a timekeeper to using clocks. During these times, rapid advancements were made in steel, electricity and chemical development that led to the introduction of the mass production of consumer goods and weapons. Everyday items were now being mass-produced in factories, and the livelihoods of humans were changed dramatically. The world was starting to become a more connected place, with railroads connecting countries and continents from North to South and East to West [84][108][44].

The third industrial revolution began in the 1960s, with the advancement of nuclear energy and the beginning of the atomic era. This sparked the rise of electronics, telecommunications, and increased computer use. As a result of advancements in space technology, research, and plant automation, new frontiers have formed. This period also brought forth the development and implementation of robotics and programmable logic controllers that gave rise to a new era of production[108][44].

The fourth industrial revolution, colloquially known as Industry 4.0 (i4.0), is already underway. The increasing presence and utility of the internet brought with it new manners of operation and production [84][108]. i4.0 uses the concept of Digital Transformation or digitalisation in short, where more and more opportunities are available for firms to switch to a digital, interconnected manner of operation, which will be discussed further in detail in the subsequent chapter. Concepts such as smart systems, cloud servers and the Internet of Things (IoT) are busy revolutionising the industry at this very moment [44][89].

As more sectors of the modern economy adopt Industry 4.0, new challenges and problems have emerged. How ready are different industries for quick changes in how they operate, and how feasible and affordable is a quick Digital Transformation? The divide between organisations that embrace the change and those that choose to put off its implementation is gradually widening as it proceeds [97][63]. With the advent of Industry 4.0, computers can now be connected and communicate with each other, bringing many new opportunities and threats.

It is therefore important to establish what impact this revolution has on businesses that have delayed the implementation of Digital Transformation in their environment and whether or not it is necessary for all organisations to embrace the change or to continue as they see fit.

As with all significant shifts or paradigms, one should not transform overnight or start without assessing the environment [41]. It is, therefore, vital for organisations to understand where their practises and organisation fits in within the ongoing revolution before undergoing the process of transforming their business towards an innovative modern solution.

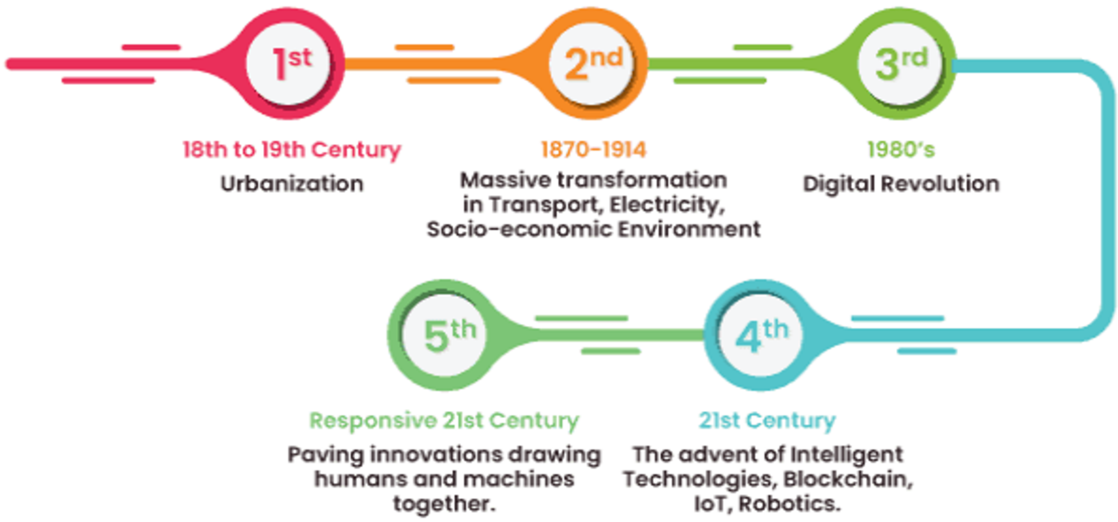


FIGURE 1.1: *The 5 Industrial revolutions [78]*

The concept of Industry 5.0, a novel and somewhat vague idea, has recently started a conversation in the academic and industrial worlds. Industry 5.0 refers to the impending 5th Industrial revolution shift, which revolves around the collaboration of humans, robots and traditional Industry 4.0 components and serves as an answer to the ethical and practical considerations by suggesting a human-centric approach to modern manufacturing [78]. Figure 1.1 shows the five paradigm shifts of the industrial revolution.

In modern times the need to transform digitally is frequently raised. Digital Transformation is becoming increasingly widespread, and organisations must modernise if they want to stay competitive [64][78]. It is vital to keep in mind, nevertheless, that organisations cannot immediately reap the rewards of Digital Transformation; instead, significant choices must be taken prior to starting a project of this sort[108][44]. This is particularly true in circumstances requiring a large amount of labour, where factors like fluctuating labour requirements, difficulties with data collecting and data-driven decision-making, and transformation hesitation must all be considered before a project can begin [41].

These workplaces also demand a practical approach to Digital Transformation (see section 6.7.1) where all the factors are considered, and practical outcomes can be objectively quantified.

1.2 Problem statement

Labour-intensive companies, where the labour-delivery of goods or services is the primary value-contribution, have difficulty implementing value-adding Digital Transformation in their environments [41]. The high process variance of labour and transformation hesitation impede the deployment of digital or technological aid in their environments. Some factors also prevent these organisations from being directed to where to begin their transformation process, thereby delaying implementation. A practical approach that considers all crucial elements of these environments and yields observable results is also desired.

Based on the problem statement, the following research questions were formulated:

1. **Primary Research Question:** How can organisations using labour-intensive environments undergo the process of Digital Transformation?

2. **Secondary Research Questions:**

   - What areas (processes, technologies, scope etc.) within the nature of these environments should be considered?
   - What are the cause-and-effect relationships between the identified areas?
   - How can these identified areas be reflected on a reference architecture?
   - How can these environments find practical digital solutions in these area?
   - How can a roadmap be developed based on the defined cause-and-effect relationships and architecture?
   - What is required from organisations to implement a roadmap for Digital Transformation successfully?

1.3 Research focus and objectives

It is apparent from the information presented thus far that, despite these companies' desire to embrace the power of some Digital Transformation, several obstacles prevent major digital implementations. Given the variability of labour in these environments, gathering valuable data and making data-driven decisions are complex. Additionally, a labour force's resistance to change is another factor that hinders the push for transformation. Even if the company aspires to a possible DT endeavour, they frequently lack the knowledge to begin and manage such a project (see feedback from expert D in section 6.1.5). They often find existing solutions too theoretical to have real-world applications or yield high-quality outcomes for their environments.

This study focuses on supporting these types of organisations to start a practical DT endeavour. The study's goal is to create a plan for gradually implementing different types of Digital Transformation through digital or technological support methods (DT support methods). A reference architecture is utilised in the roadmap to illustrate to these environments where they are and where they aspire to be. The roadmap also uses technology mind maps as a methodology with the reference architecture to identify various forms of digital or technological support. The roadmap is then presented to industry professionals in the field of Digital Transformation and labour-intensive environments, to verify the usability and output thereof.

Finally, the roadmap is practically tested in a learning-factory setting with the valuable input of the middle management of one of these environments. This is done to reduce the disruption of this environment and practically show these middle managers the power of Digital Transformation and get their practical and expert opinions on validating the roadmap.

Based on the problem statement and research questions outlined in 1.2 above, the following research objectives were developed:

ROI 1: Development of a DT roadmap and supporting techniques to achieve the desired level of Digital Transformation within labour-intensive environments:

1. Determine the areas in these settings where prospective digital or technological support can be beneficial.

2. Explore the cause-and-effect relationships of the identified areas.

3. Create a reference architecture using the information above to visualise an environment in its current and desired state.
4. Develop a technology mind mapping methodology to identify various low-level and high-level DT support methods from the architecture.
5. Choose, decide, and then create the different components of the roadmap.
6. Develop a roadmap for progressing from the current situation to an ideal future one.

ROI 2: Validate the feasibility of the developed roadmap.

1. Present the roadmap, reference architecture and mind mapping methodology to industry experts to verify the research.
2. Test various methods of digital support by replicating a labour-intensive environment in the Stellenbosch Learning Factory (SLF).
3. Present the findings to the management of a labour-reliant firm for opinions and interpretation for validation in the form of a survey and critical discussion.
4. Continuously improve the research approach and investigate new research avenues.

1.4 Research gap

Although there are many frameworks, roadmaps and methods of Digital Transformation, a gap in the literature exists regarding labour-reliant value-creation. Firms that use labour-intensive environments lack an easy and practical method to implement Digital Transformation. The research will aid such organisations in their approach to Digital Transformation by creating a set of steps in the form of a continuous roadmap for these firms to implement incremental Digital Transformation. Specifically, the roadmap would address obstacles such as waste management, workforce support and data collection to enable more advanced Digital Transformation in the value-creation of these environments.

1.5 Expected contributions

Firms that use labour-intensive environments, where the labour-delivery of goods or services is the primary value contribution, will be able to use the research to implement incremental Digital Transformation by first implementing lower levels of digital or technological support before moving on to more advanced methods of Digital Transformation. The research will enable such firms to envision different methods of digital support within their operational processes by outlying these areas on a reference architecture.

1.6 Limitations of the research

The research is limited to a developing country context as observational data, middle management and industry professionals from South Africa are primarily used to develop the solution approach (reference architecture) and solution and to validate and verify.

Additionally, these DT support methods are not implemented at the partner institution to not disrupt the environment and due to the time limitations of the study. In this way, only one possible implementation method is done in the thesis, where the input of middle management is used for opinion validation and expert input for verification.

The research is aimed at the value-creation of these environments - where the actual labour takes place, and the focus of the research is to find a form of Digital Transformation in this operational area. For this reason the research does not cover the business, organizational and supply chain aspects of these environments in detail.

1.7 Research methodology

The procedures or techniques used to find, select, process, and analyse data on a subject are referred to as research methodology [19].

Chapter 1 expresses the need for Digital Transformation or Industry 4.0 implementation in a labour-intensive environment. This section briefly describes the methodology and approach to the research by exploring the philosophies, approaches, strategies and data collection methods used in this thesis.

The thesis methodology roadmap is reviewed, showing the study's logical flow to the reader. The chapter concludes with a description of the research technique, including the methods for conducting surveys, observational case studies, and literature reviews.

1.7.1 Research design: Methodology onion

Saunders and Tosey [109] devised the research onion, a research design tool used in research to design and implement the outcomes of a research project. The research onion is designed using different layers to the research that are used to fulfil the requirements and objectives of the research eventually.

An onion-type figure is used to portray the various elements and layers of the research design. Each layer builds on the previous to provide context surrounding the collection and analysis of data to be adapted to a functional model.[109]

The outer layer refers to the research philosophy or how the researcher views the world or research environment. The philosophy selected for the research in this thesis is a pragmatic approach, where the practical consequences are the most important in the end. A pragmatic approach considers no single view, given that a singular viewpoint cannot cover an entire picture of a labour-intensive environment[109].

The next layer represents the methodical choice taken and refers to if quantitative, qualitative or mixed-method methods are used within the research design [109]. This layer is adapted to represent the research approach taken in the methodology onion used in this thesis. The research used in this thesis is deductive, where literature is reviewed deductively, and inductive, with observational studies. These two methods are used together to develop the roadmap in this thesis.

The third layer in Saunders and Tosey's [109] onion and the penultimate layer in the adapted onion represent the strategies taken to answer the research questions and problem. The outcomes of the roadmap developed in this thesis are used practically in the Stellenbosch Learning Factory, where practical implementation and process optimisation will be used in a case study of a

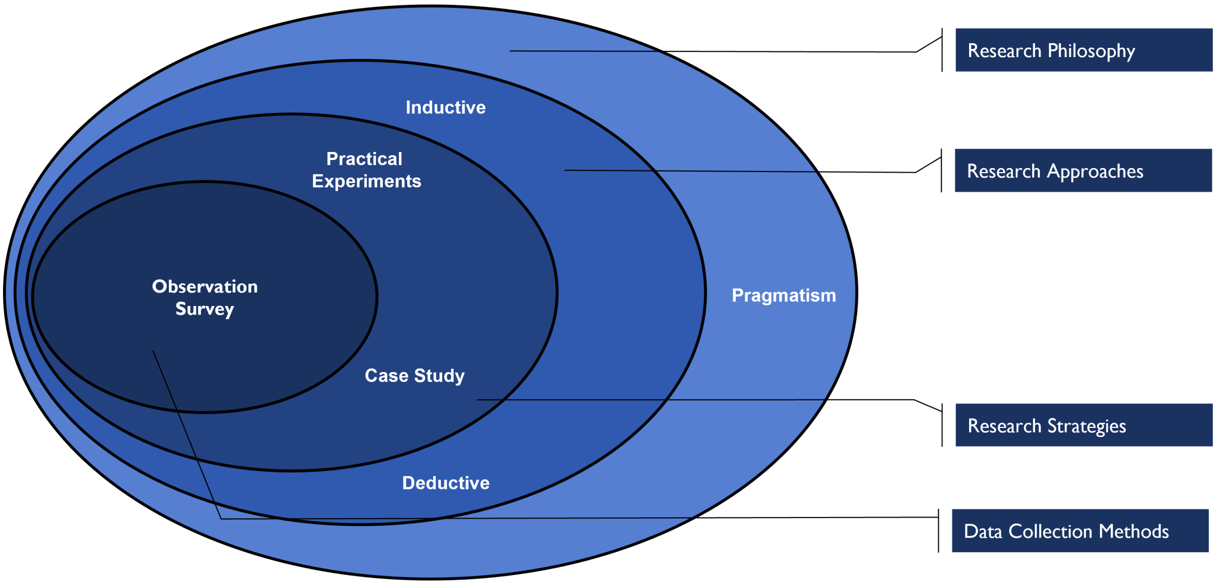


FIGURE 1.2: *Thesis methodology onion - adapted from Saunders and Tosey [109]*

replicated labour-intensive environment. Saunders and Tosey's [109] time horizon is omitted from the adapted research onion to simplify the approach, as a Gantt chart is used to define the time requirements for the research

Finally, the innermost layer represents the data collection methods used in the research [109]. The collection methods in this thesis are observational studies with informal discussions and surveys for qualitative data collection.

1.7.2 Thesis approach and methodology roadmap

The research approach consists of four stages, where various concepts and methods address the problem statement and objectives.

1. Literature study: In this stage, research on Digital Transformation is conducted. This includes terms and concepts similar to Digital Transformation, such as Industry 4.0 and Industry 5.0s. The research on these concepts is two-fold, firstly to investigate various approaches to Digital Transformation, such as the human-centric, sustainable and reliant approach of Industry 5.0. Secondly, to explore the various digital or technological support methods associated with these concepts. Enterprise engineering is also investigated, as it involves an enterprise's design and redesign (transformation) and includes concepts such as Enterprise Reference Architectures and change management, which are used in both the solution approach and roadmap development. Finally, challenges in the Digital Transformation of labour-intensive environments are briefly touched on.

2. Solution approach: In this phase, observational studies and theoretical research are used to understand these labour-intensive environments better. This stage identifies areas where digital or technological support can be used, investigates the cause-and-effect and other relationships in these areas, and maps these areas on a reference architecture that can be used as both an as-is and to-be reference point for the roadmap in the following phase. In addition a technology mind mapping methodology is developed to be used to potentially find these DT support methods.

3. Roadmap development: The roadmap is developed by creating steps to implement the DT support methods on the reference architecture. The roadmap addresses the three questions of a roadmap by using the architecture as both an as-is and a to-be digital state for labour-intensive organisations in their DT journey. In addition use of the roadmap allows users to choose DT support methods in their DT project physically (see section 2.14.1).

4. Research verification and validation: Verification in the form of an industry experts' discussion is used to verify the research and output of the roadmap. The roadmap and architecture are finally validated by testing various DT support methods on the SLF in the incremental approach, with input from the middle management of a labour-intensive partner institution.

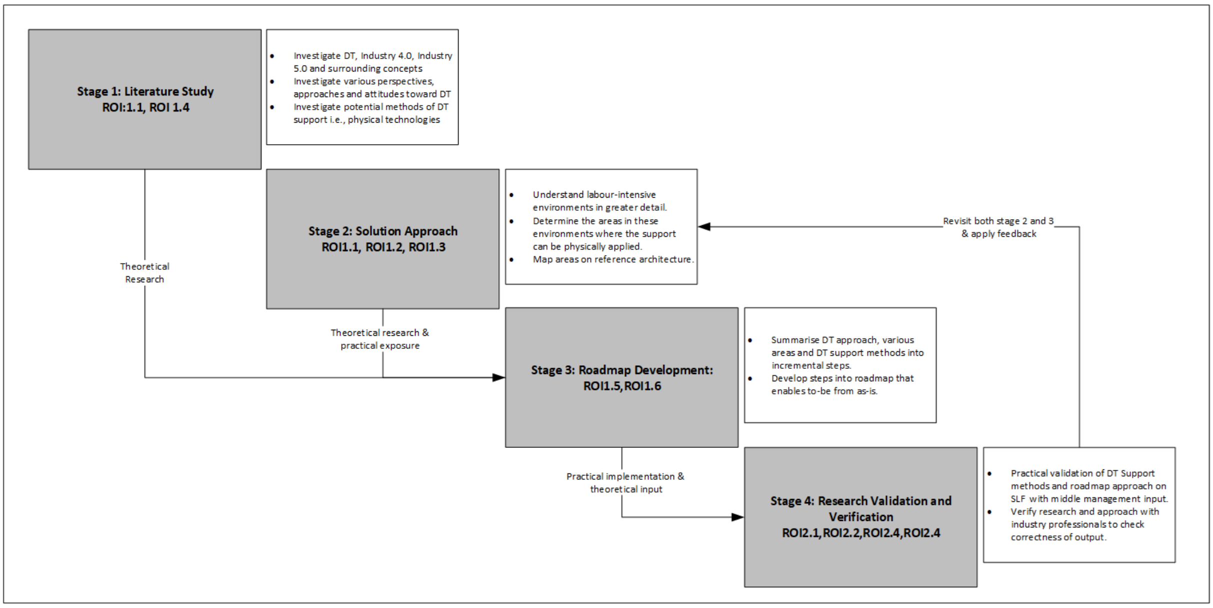


FIGURE 1.3: *Thesis methodology roadmap*

1.7.3 Literature study

A mixed-literature review on Digital Transformation, Industry 4.0 and Industry 5.0, as well as enterprise engineering and problems in labour-intensive environments, is undertaken to look into various forms of digital support in these settings. The research is conducted in several domains of engineering, information technology, computer science, and management. The sources used for this research are journals, conference papers, prior theses or dissertations, textbooks, and websites from both educational and occupational organisations. In order to bolster the other sources, commercial opinion articles are also utilised.

In order to apply operational digital support in a labour-intensive setting, research is conducted on each of these topics. Any digital or technological support within an organisation, including but not limited to hardware, software, or other resources, is considered digital support for this study (DT support methods). The various themes shown in figure 1.4 are used to study different Digital Transformation strategies, such as human-centric or triple-bottom line approaches, as well as to find different practical digital or technological support methods.

The literature review followed a narrative review, which is the traditional way of conducting a literature review [92]. In order to provide a qualitative interpretation, the literature review summarises the prior research that has been published on each subject.

Paré and Kitsou's [92] three-step process for conducting a literature review is followed :

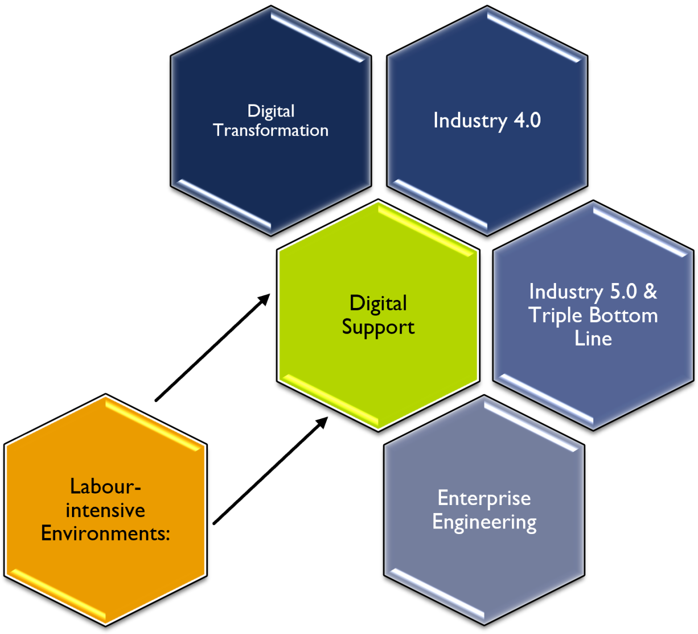


FIGURE 1.4: *Thesis literature*

1. **literature search and screening:** literature on each subject is searched, primarily using google scholar, sun scholar or Scopus platform, and briefly screened to ensure that the research piece is relevant.

2. **Information extraction and analysis:** This step involves gathering and extracting relevant information from the research piece. All information about the literature piece is captured for correct referencing, access to the literature and the date accessed.

3. **Writing the literature review:** The information is then summarised and written in the logical order of the literature review, as seen in Chapter 2, where it is ensured that all sources are cited correctly.

1.7.4 Observational research

Observation is a data collection methodology where the researcher immerses in the environment with the respondents and includes watching, listening, reading, touching, recording behaviour and taking notes. Observational case studies use overt observation, where subjects and the environment are aware that they are being observed in an unobstructed manner [129]. In this thesis, two case studies are done using observation as a data collection method.

The notes of the observational study are stored and compared to each other and relevant research in the domain of labour-intensive manufacturing and Industry 4.0 or Digital Transformation. Findings are used to develop the reference architecture and roadmap by mapping the general areas of labour-intensive value-creation found in the studies.

1.7.5 Survey research

Survey research is a way of doing research that involves researchers sending surveys to participants [129]. This kind of study permits numerous techniques for participant recruitment and data collection. Survey research can employ quantitative research techniques (such as rating the respondents' degree of concordance between two (or more) sets of measurements), qualitative research techniques (such as open-ended questions), or mixed methods [96].

The application of the roadmap is validated by a mixed-method survey that includes open-ended questions and a discussion with the middle management of a partner institution. Respondents' degree of concordance with statements from the researcher on the rationale, model and outcomes of the research are used alongside open-ended questions to validate the use of the roadmap.

1.8 Research ethics

This study's ethical implications are deemed to be low-risk. Data from the public domain and observational data from partner institutions were gathered to complete the study. Additionally, middle management and industry specialists in the relevant domains provided their opinions in survey form. To ensure acceptable ethical conduct, the Social, Behavioural, and Education Research Ethics Committee (REC: SBE) evaluated and approved the research's data collection under project number ING-2022-25070.

1.9 Thesis organisation

The thesis is used to present the research and model development of the proposed roadmap. There are seven chapters in total, with this one serving as the introduction and methodology of the study.

A mixed literature review of concepts enabling Digital Transformation is completed in chapter 2. In chapter 3, observational case studies and further research are used to comprehend the typical labour-intensive workplace and explore the numerous relationships and cause-and-effect structures in these environments.

The research is used in Chapter 4 to design a reference architecture for visualising these kinds of environments in both their intended and present states, together with a methodology used to develop technology mind maps based on the reference architecture.

Chapter 5 develops the DT roadmap, where the reference architecture and technology mind maps are used in the transformation effort. The roadmap's validation and verification are carried out in Chapter 6. To confirm the model's output, experienced industry experts are first consulted. The roadmap is then validated using a learning-factory scenario with input from the middle management of a research partner that uses a labour-intensive environment.

The thesis is finally concluded in chapter 7 with suggestions for additional research, reflections on the research, and closing remarks.

1.10 Research project plan

The thesis is planned to be completed over two years. The project plan can be seen in Appendix A. The first year is used to build knowledge on Digital Transformation and labour-intensive value-creation. This is done by research on both topics and a part-time internship at a partner institution.

After completing the internship, the researcher spent a semester abroad in Reutlingen, Germany, as a part of a double-degree programme, attending courses and participating in workshops that cover issues related to digital industrial management and engineering (DIME).

During the second year, observational case studies are conducted to create and support the solution approach. After that, the roadmap is developed and tested in the Stellenbosch Learning Factory (SLF), where middle management and industry experts' feedback is used for validation and verification. The research is written in the latter half of the final year.

CHAPTER 2

Literature review

This chapter's goal is to review the literature pertinent to creating a roadmap for Digital Transformation, emphasising sectors that use labour-intensive work environments. Concepts derived from Digital Transformation, such as Industry 4.0 and Industry 5.0, are used to investigate different approaches to Digital Transformation and the different digital or technological support methods aligned with them. The typical challenges of Digital Transformation in a labour-intensive environment are then briefly covered. Enterprise engineering theory is also explored, focusing on a business's design, redesign, and transformation. The literature includes the use of reference architectures that map the many layers of an enterprise. Finally, a range of Digital Transformation strategies is researched to choose the best implementation methodology for the study.

2.1 Digital Transformation

One of the primary drivers of the shift in industry in recent years is the advancement of technology and the digital realm. Digital Transformation refers to the process of an organisation's transition to a digital business model [13]. This section discusses the concept of Digital Transformation, how it differs from digitisation and digitalisation, different perspectives of Digital Transformation and its drivers.

2.1.1 The differences between digitization, digitalization and Digital Transformation

There is a common misunderstanding that digitisation, digitalisation, and Digital Transformation are synonyms. All three terms are crucial concepts in the process of Digital Transformation; however, it is essential for the research that all three terms are defined precisely to prevent misunderstandings when they are used as references. In order to grasp each term properly and to emphasise their similarities and distinctions, this subsection defines each term.

Digitization

Digitisation refers to converting analogue information into a digital format to allow computers to store, analyse and transmit or transfer such information [13][48]. Within an organisational context, digitisation is important when dealing with both digital and analogue information and specifically deals with the information rather than the processes within the organisation, which is more the focus of digitalisation [13][48]. An example of digitisation is converting a handwritten journal into a digital format such as a text or MS document file.

Digitalization

Digitalisation is the process by which organisations change their business model by utilising technology, concepts, and IT-based solutions to transform their business operations, as opposed to digitisation, which is focused on the capture, processing, and digital communication of information [13][107].

Digitalisation has also defined the process of using digitised products or systems to develop new organisational procedures - answering the relevance of technology used within a specific process or organisation [107]. In contrast to digitisation, digitalisation revolves around using products, systems and digital information rather than simply converting analogue information.

The general definition of digitalization is the process of using digital technologies to transform the business operations of an enterprise [107].

Digital Transformation

Vial [126] defines, based on 23 unique definitions from 28 sources, Digital Transformation as *"a process that aims to improve an entity by triggering significant changes to its properties through combinations of information, computing, communication and connectivity technologies."*

In their derived definition, Vial [126] refers to an entity rather than an organisation or firm specifically. The phenomenon that is Digital Transformation has been widely explored and encountered from various perspectives, both academic and organisational perspectives, resulting in a crude and wide understanding of the term. [50][13][48].

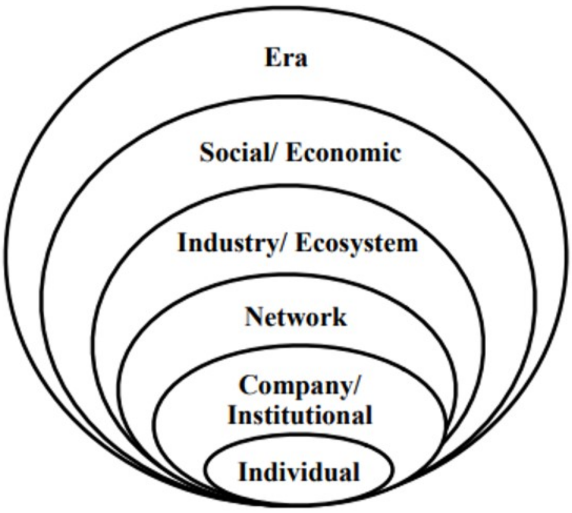


FIGURE 2.1: *Digital Transformation perspectives in literature [50]*

To fully understand, Ismail, Khater & Zaki [50] look at different Digital Transformation perspectives in their study, *Digital Business Transformation and Strategy: What Do We Know So Far?*, depicted in figure 2.1, where Digital Transformation perspectives are explained as follows:

1. **Era:** Digital technology's impact on how we live our daily lives. These modern technologies— such as smartphones, wireless technology, and mobile internet access —were not utilised by those who lived in the past.

2. **Economy:** Rapid change has accelerated the creation of ideas and technology more than ever. The emergence of a new global economy characterised by competitiveness, digital innovation, flexibility, customisation, and a gradual move to a circular flow of goods has facilitated this digital era and the world's industrialisation since the Industrial Revolution.

3. **Industry or ecosystem:** This perspective focuses on how the disruptive nature of these technologies has fundamentally changed how many industries function and how the once-clear borders between them are constantly shifting.

4. **Network:** The decentralising characteristics of these technologies have produced a shift in dynamics away from the core of businesses and toward the edge, where customers, consumers, communities, and organisations collaborate to create value within a digital ecosystem.

5. **Company or institutional perspective:** The effect that the perspectives above have on the requirement for businesses or enterprises undergoing Digital Transformation.

6. **Individual:** How these developments and trends have affected people through contemporary interaction.

In comparison to digitisation and digitalisation, Digital Transformation is the process of adapting firms to new organisational forms and acquiring new abilities to remain relevant and viable within a new digital landscape [107]. It involves redesigning entire firms from a managerial, operational and product or service delivery perspective to a digitally viable form.

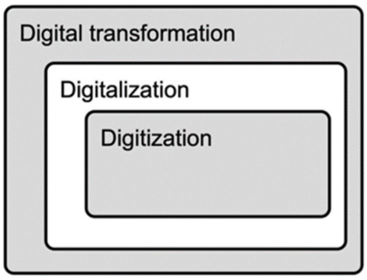


FIGURE 2.2: *Digital domains[107]*

Figure 2.2 shows the relation of the three domains towards each other. Digital Transformation is the overarching process that involves digitalisation, which in turn involves digitisation.

There are numerous definitions of Digital Transformation and angles from which to view this transformation. It is clear that Digital Transformation is disrupting certain industries, and ultimately it is up to each business or sector to establish its individual Digital Transformation approach.

2.1.2 Drivers of Digital Transformation

Primarily, companies are driven and motivated by the goal of process improvement and customer demands [65]. To truly understand Digital Transformation and its relevance to organisations, it is crucial to understand what drives the phenomenon that is Digital Transformation.

There are both internal and external drivers towards Digital Transformation. Some internal changes are brought on by diminishing sales, financial strain, social and economic considerations, and practical concerns like higher productivity, more flexible manufacturing, and enhanced efficiency [50]. Emerging technology, the increasingly disruptive and dynamic competitive environment, customer expectations, connectivity, and other factors influence organisations externally [50]. There are several drivers identified in the literature on Digital Transformation. As the world changes, more drivers will impact the direction of this change and the demand for organisations to adapt.

To simplify and list a few drivers, Liere-Netheler, Packmohr and Vogelsang [65] have used a qualitative approach by interviewing 16 participants from 6 different industries to define a few drivers of Digital Transformation. Based on their 16 cases the following drivers have been identified as substantially drive Digital Transformation [65]:

- **Process improvement**: The need for self-adapting systems to improve the processes within a firm, such as systems that aid in process optimisation and predictive maintenance, are primary drivers to implement digital solutions and therefore stimulate the need for Digital Transformation.
- **Workplace improvement**: The constant need to improve safety, ergonomics and resource management drives organisations toward digital solutions that aid workplace improvement and management.
- **Vertical integration**: Field technology directly collects information at the operational level, which is processed for management-level integration and delivered back via the hierarchy as instructional data. Information sharing allows for producing a wider range of items in lower quantities while enhancing the precision of production-level planning.
- **Management support**: The need for Digital Transformation, modern technology and up-to-date systems is often driven by the management of a firm, as digital solutions can aid in managing firms and building modern business strategies
- **Horizontal integration**: The integration of the different levels of an organisation, from production to sales and management is increasingly important to firms as they add a holistic point of view to organisations. Digital Transformation opens up the possibility for new business models and sustainable business growth.
- **Cost reduction**: Digital Transformation aids firms by improving processes, reducing setup time, reducing waste and stimulating cost reductions.
- **Customer demands**: The traceability and transparency of products are becoming increasingly important for customers. This, together with the desire for exceptional quality assurance and competition, drives organisations to implement digital innovations.
- **Supply chain**: Digital Transformation affects the supply chain as other stakeholders on the supply chain drive the need for technological innovation through implementation and desire.
- **Innovation push**: The potential of these new disruptive technologies drives organisations to find areas where value can be added to their environments.
- **Market pressure**: As with many trends, competition drives transformation as other firms continuously use new technologies - ensuring organisations do not fall behind.

- **Laws/Government**: Legal frameworks have driven the use of digital technologies for environmental and sustainability standards in certain circumstances.
- **Employee support**: Digital systems prove to aid employees in performing their tasks and training, allowing for simpler, safer and often more stimulating work - thus ensuring the support of employees.

2.2 Industry 4.0

Industry 4.0 (In German: Industrie 4.0, or I4.0, colloquially known as the 4th Industrial revolution), as described in section 1.1 is the continuation of the ongoing industrial revolution, currently well into the fourth stage of its development[64] [59].

The concept of Industry 4.0 was first coined by a group of German representatives from different fields, including industry, politics, academics and businesses, at the Hannover Messe (fair) in 2011 [64][91]. The term was developed to enhance the competitiveness of the manufacturing industry in Germany. I4.0 involves the digitalisation and cross-linking of all actors, including the hardware, software and use of a human workforce in an integrated form that has never existed before [59][48]. A growing number of industries are embracing the power of the internet and intelligent technologies to transform into a more computerised and automated operational system digitally.

The core of Industry 4.0 is the adoption of multiple technologies that combine the digital and physical worlds to reinvent how businesses operate and focus on their customers. Technologies include the use of sensors, data analytics, additive manufacturing, intelligent automation and many more [59].

Industry 4.0 includes the use of these technologies under the intelligent digitalisation of all processes and products. I4.0 leads to a company-specific product, service, technical process and organisational innovation.

2.2.1 Industry 4.0 vision

There is no single agreed-upon vision or concept of Industry 4.0, as there is no one generic approach for all organisations to implement Industry 4.0. However, most experts and literature agree on specific concepts and visions within the broader scale of Industry 4.0, which can lead to a broad and general vision for Industry 4.0 and adapted for an industry-specific perspective [14][59].

A primary vision for Industry 4.0 includes the notion that products, systems and services become intelligent through identification technologies - such as bar-codes, RFID and QR-codes (Quick-Response codes), and therefore able to exchange information with both humans and machines. The concept of intelligent or smart components creates the vision that actors in industry are enabled to autonomously exchange information utilising embedded systems aided by micro computers[14][59].

It is also widely accepted that an ideal I4.0 vision is the dynamic and decentralised control and management of industry - rather than that of a central management system.

This vision ideally includes the components summarised in the paragraphs above with the concept of connecting all involved actors throughout the entire supply chain by using information and communications technology.

Other visions of Industry 4.0 entail the personalising and customisation of products, the shift from central industrial control to a manner of control where the intelligent products can define the production steps and more widespread automation than that of Industry 3.0.

Finally, as the term was created to empower the competitiveness of the German manufacturing market, a widely agreed upon vision is to increase the competitiveness of organisations to ensure substantial industry development and therefore empower a customer-orientated approach to industry [64][14].

In summary, a broad vision of Industry 4.0 is using a system with high levels of automation that uses decentralised control and autonomous decision-making that uses intelligent products, services and systems along the entire supply chain to enable a customer-orientated and value-adding industry.

2.2.2 Challenges and uncertainties of Industry 4.0

As with all revolutions or disruptive trends, certain challenges must be addressed before simply designing or implementing an Industry 4.0 framework. Some challenges are relatively straightforward, such as the apparent necessity to access the internet and associated hardware and software. Other challenges, which are not always as upfront, include the ethical implications associated with the replacement of humans with machines, and Industry 4.0 often neglects the human aspect[14][59][128]. The following are significant challenges which arise with Industry 4.0:

1. **Reliance on internet and technology:** Industry 4.0 involves the use of the internet and technology, thus without the internet and without access to these technologies I4.0 implementation is not possible [72][108].

2. **Lack of skills:** Often noted as the biggest hurdle in Industry 4.0 implementations, the lack of the required skills is widespread. This includes the difficulty in educating about user interfaces, data science, software implementations and use. Furthermore, the novelty of some of the technologies leads to the gap in the skills and often calls for the need of external parties to aid in[72][108].

3. **IT security:** The rapid rise in I4.0-associated technologies has led to increasing concerns surrounding IP privacy, online identity, data breaches and cyber breaches. The heavy reliance on the internet, data and IT services coincides with the rise of their associated risks[72][108].

4. **Cost risk:** Depending on the organisation's vision, the implementation of Industry 4.0 can be expensive. High upfront costs are often required as the associated technologies of I4.0 involve hardware and software costs which can be substantial[72][108].

5. **Industry 4.0 culture hesitancy:** This challenge is two-fold. Firstly, organisations are often convinced that they do not need to digitally transform due to financial reasons or comfort in their current position [108] - leading to managerial or corporate hesitancy that impedes Industry 4.0 implementation. Secondly, internal culture change can be problematic if not addressed correctly. It is vitally important that organisations ensure that employees are ready for the changes, as, without the buy-in of the workforce, further issues can arise. Articles such as *More Robots, Fewer Jobs* from Bloomberg [105] are examples of concerns of how employees can be very hesitant towards Industry 4.0.

6. **Ethical uncertainties:** Coinciding with the abovementioned point, hesitancy can be prevalent in an organisation wishing to implement Industry 4.0 as often employees fear that they may be replaced by machines or technology. As mentioned earlier, Industry 4.0 often overlooks the human aspect. Although exaggerated in the opinion that humans are being replaced, there are undoubtedly ethical challenges, especially in countries such as South Africa with high levels of unemployment where jobs can be changed drastically by I4.0 [128] [31].

The challenges listed above are a few significant challenges generally found in the literature. Other challenges, small and big, and often depending on an industry, such as education issues in i4.0, financial feasibility and implementation time constraints, also exist [108].

2.3 Primary components of Industry 4.0

To define Industry 4.0 and its components two literature analyses' were used comparatively. The first performed by Hermann et al. [44] was performed in 2015, 4 years after the coining of the term Industry 4.0 and was performed to define Industry 4.0 at the time. The second literature analysis, performed by Oztemal and Gurzev [89], was performed in 2018 and again published in the Journal of Intelligent Manufacturing in 2020. Both literature analyses were covered comparatively to effectively define Industry 4.0 and how the definitions and components changed and remained the same over the Industry 4.0 period.

Herman et al. [44] firstly identified key concepts associated with Industrie 4.0 (German) and Industry 4.0 (English) on six different databases (ACM, AISeL, EBSCOhost, CiteSeerX, Emerald Insight and Google Scholar) with which they emerged with eight distinct keywords associated with Industrie 4.0/Industry 4.0. These keywords, identified by using both English and German translations, were Cyber-Physical systems (CPS), Internet of Things (IoT), Internet of Services (IoS), Smart Factory, Smart Products, Big Data, Cloud and Machine-to-machine(M2M) (including the translations identified in German). Using the keywords, 51 publications were found that addressed Industry 4.0. A backwards and forward search followed, and eventually, the list of primary components was narrowed to 4. The four primary components defined by Hermann et al. [44] are the Internet of Things, Cyber-Physical systems, Internet of services and smart factories. M2M, Smart Products, Big Data and the Cloud were considered not to be independent i4.0 components.

Similarly, Oztemal and Gurzev [89] conducted their extensive review using the eight databases (CiteSeerX, ACM, AISeL, EBSCOhost, Emerald Insight, Taylor Francis, Science Direct) and Google Scholar to perform their analysis. The results of their keywords and publications, done similarly to Herman et al. [44], resulted in 620 publications, with the keyword frequency indicated in table 2.1.

The results of Oztemal and Gurzev [89] with a review of 620 publications performed in 2018 suggests including the components left out by Herman et al. [44] along with the addition of other components of Industry 4.0. Due to this being the later publication and the number of publications reviewed by Ostemel and Gurzev [89] compared to Herman et al. [44], the inclusion of all these components was decided on for the literature review in this thesis. The components defined by Ostemel and Gurzev [89] are: CPS, Cloud Systems, M2M, smart factories, Augmented reality (AR) and Simulation, data mining, IoT, Enterprise resource planning (ERP) and business intelligence, Virtual Manufacturing and Intelligent Robotics.

TABLE 2.1: *Key words list and publication results used in literature analysis by Oztemal and Gurzev [89]*

Key words	Number of publications reviewed
Industry 4.0 in general	132
Cyber-physical systems (CPS)	81
Cloud, cloud systems	53
Internet of things	110
M2M, machine to machine	45
Smart factory	38
Data mining, big data	55
ERP and business intelligence	21
Augmented reality, simulation	23
Virtual manufacturing	30
Intelligent robotics	20
Others (projects and national initiatives)	60
Total # of publications	**620**

2.3.1 Cyber-physical systems

The primary idea of Industry 4.0 revolves around the combination of the cyber and physical worlds within a system. The fourth industrial revolution is often referred to as the revolution based on cyber-physical systems (CPS) [53]. The most basic and frequent definition of Industry 4.0 is that it is the revolution based on the combination of these two worlds, and CPS is one of the most recurring words found in the literature [89][64] [59]. A cyber-physical system is an automated system that connects the physical reality's operations with computing and communication infrastructures [53][89]. Jazdi [53] further details that CPS use embedded systems, such as smartphones, watches, cars etc., to network. The inevitable networked world of the modern CPS goes along with the trend of having information and services everywhere at hand. Oztemel and Gurzev [89] mention CPS as one of the essential i4.0 components and is 2nd in their keyword literature analysis' frequency. In their analysis, Oztemel and Gurzev [89] describe that CPS are generally capable of the following function in manufacturing:

- Process Monitoring
- Applicable in different domains to contribute to generating large-scale systems.
- Integrating different disciplines in different domains.
- Handling effective dependability.
- Substantial user interaction
- Alive performance monitoring.
- Real-time configuration, deployment and decommissioning
- Self-behaving and decision making.
- Distributed an interconnected communication.

Both Hermann et al. [44] and Oztemel and Gurzev [89] describe 3 phases that characterise the development of CPS. First-generation CPS include identification capability and technology such as RFID tags (see section 2.3.2), where storage and analysis are provided as central services. Second-generation CPS include embedded systems that are provided with several functions. Finally in the 3rd generation of CPS in addition to the capabilities of the 1st two phases systems are now able to store, analyse and be designed to be network compatible. Functionalities of CPS in 3rd Generation systems include easier information access, preventative maintenance, decision-making capabilities and optimisation methods.

CPS is regarded as the backbone of Industry 4.0, leading the way in transforming the manufacturing industry to the next generation [62]. To aid in developing and deploying a cyber-physical system in manufacturing, Lee et al. [62] created the 5C CPS architecture. The 5C architecture defines how to construct a CPS from data acquisition to value-creation. The 5C levels - configuration, cognition, cyber, conversion and connection, are described in the 5C architecture as seen in figure 2.3. Table 2.2 summarises the five levels defined by Lee et al. [62].

TABLE 2.2: *5C architecture levels, descriptions and implementations examples*

Architecture Level	Description
I - Smart Connection Level	Data is acquired from machines and components either directly from sensors or from manufacturing systems. The level includes connecting physical devices and recording data. [62]
II - Data-to-information Conversion Level	Converting the data recorded from the physical devices to usable data [62]. Various tools are available and stimulates component self-awareness [62]
III - Cyber Level	Central information hub, receives data from every connected device [62]. Analytic measurement that allow for machine comparison, behaviour analysis [62].
IV - Cognition Level	This level involves the presentation of the outputs of the previous steps to the user to aid in decision making [62]. Analysis is presented to provide visual support to users and organisation [62]
V - Configuration Level	Feedback loop of architecture, where physical space received feedback from cyberspace [62]. Links previous level decisions to configure and adapt physical system [62].

CPS is often seen as the primary component of Industry 4.0, as a CPS environment is the description of an I4.0 environment, and includes the other components which are covered in this chapter.

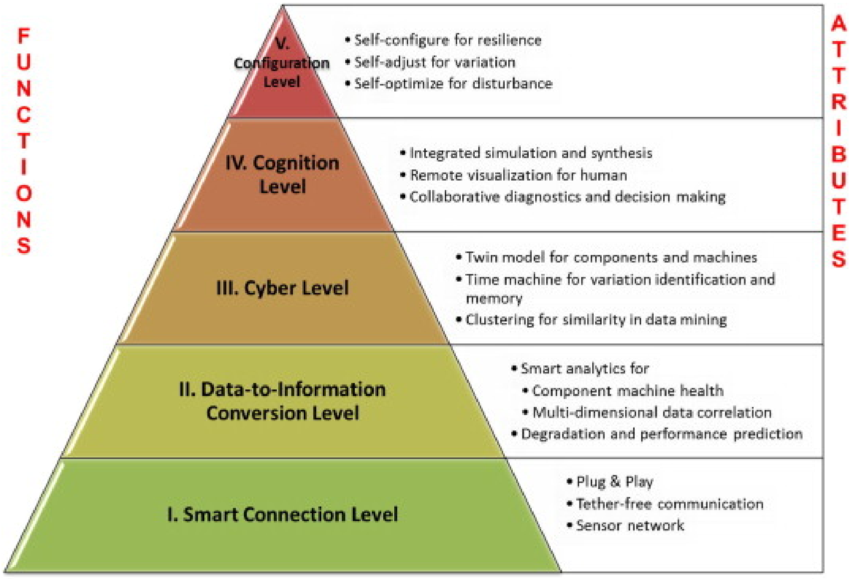


FIGURE 2.3: *5C cyber-physical system architecture [62]*

Embedded and intelligent objects

A major enabler of IoT, cyber-physical systems and I4.0 overall is the development of embedded items that can communicate with each other. Embedded objects are embedded with electronics such as sensors, actuators, RFID tags etc. [55] They connect the virtual and physical world and are enablers for CPS systems and systems that make use of the Internet of Things. Intelligent, or smart, objects are objects capable of different levels of communication with each other or a system [48][108]. Similar to the generations of CPS described in Oztemel, and Gurzev [89], intelligent objects in class 1 are capable of identification, class 2 are further capable of storage, with class 3 having intelligent data processing included. Finally, class 4 has all qualities mentioned above and is capable of communication and interaction with each other [48].

2.3.2 Internet of Things

The Internet of Things, or IoT, is a technological concept envisioned as a global network of devices, machines and other actors, such as sensors, that are connected and communicate. An IoT system makes use of hardware such as sensors, micro-computers and real-time operating systems (RTOS) and the relevant software to facilitate communication[108][44]. IoT is a primary subset of CPS. Oztemel and Gurzev [89] identified IoT as the key term that corresponds the most with the idea of i4.0. IoT is the primary enabler of the connection between the real and virtual world in i4.0 within manufacturing, and other sectors [44][89][108]

Radio frequency identification

One of the building blocks of the fourth industrial revolution is the advent of radio-frequency identification or RFID. RFID makes use of electromagnetic fields to identify and track various objects. Items are attached with an RFID-enabled tag with such a system further involving a radio transponder, receiver and transmitter [82][86]. The most basic IoT and CPS system uses RFID for tracking, data collection and application.

Workings of IoT

Devices in an IoT-enabled environment contain sensors and microcontrollers (MCUs). Data is gathered via the devices' sensors, where the MCUs act on the collected data via Machine Learning (ML) methods [61]. IoT-enabled devices are connected to what is known as a real-time operating system, which is an operating system for the real-time processing of data and events within critically defined constraints [108]. Together the RTOS and MCU form a gateway. This wireless portal gives IoT-enabled devices access to the web and cloud and enables the interconnection of these devices along with sensors and smart devices to the cloud [67][131]. This way, all IoT-enabled actors are connected, and communication and intelligent systems can operate.

IoT architecture

Various methodologies or architectures are used to define the physical, analytical and functional configuration of The Internet of Things. Similar to the concept of I4.0, there is no single agreed-upon architecture or methodology to implement an IoT system. Sources suggest that three layers within existing architectures are widely accepted and formatted into the majority of IoT architectures. These three layers, as seen in figure 2.4, are the **perception** layer, which contains the use of devices and sensors to collect information. The **network** layer, the layer that transfers the data, and the **application** layer, which is responsible for the distribution of the learning content [6][138]. Figure 2.4 also includes a fourth layer which is widely used. Various architectures include a **data management** or **business** layer, which includes the application of the data, i.e. how the data is used.

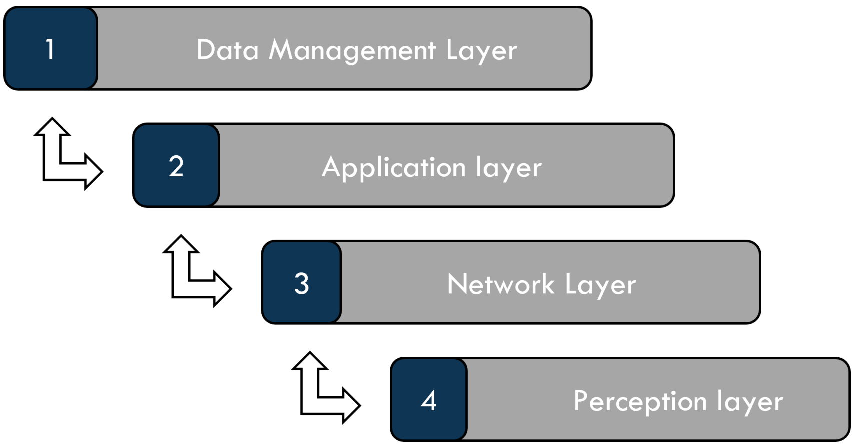


FIGURE 2.4: *Simplified example of IoT simplified four-layer architecture based on Antoa [6], Wu [138]* and Mahmoud [67]

Industrial Internet of Things

The industrial use of IoT has a branch: The Industrial Internet of Things (IIoT). IIoT is a scaled-up version of IoT that has been designed and developed around Industry [108]. It is used to increase the safety and speed of manufacturing whilst reducing the cost of manufacturing or other industry forms. IIoT is focused more on aiding the efficiency and safety of the industrial sector whereas IoT is focused more on aiding in the convenience of the consumer[108]. Figure 2.5 further illustrates the difference between IoT and IIoT.

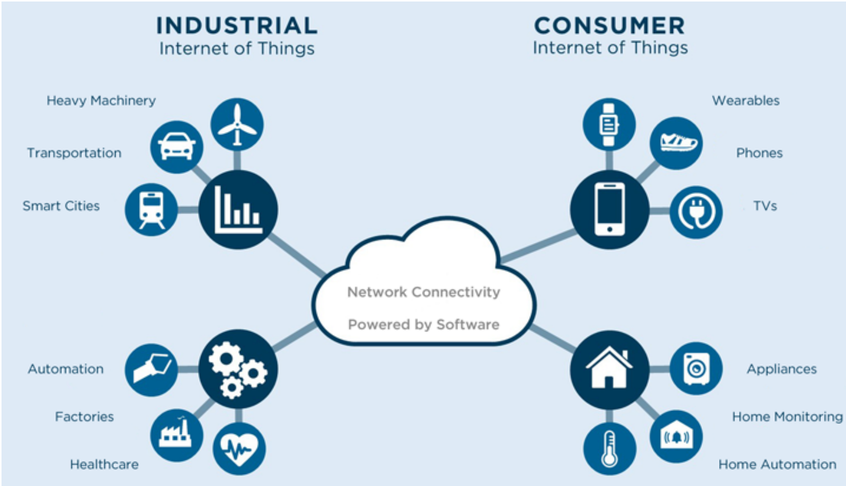


FIGURE 2.5: *IoT vs IIoT[133]*

2.3.3 Internet of Services

Although not mentioned in Ozetemal and Gurzev's I4.0 literature analysis [89], the Internet of Services, or IoS, is widely considered to be a major component of Industry 4.0 a[44] [104].

Reis and Conçalves's [104] conclude that IoS was developed from the convergence of Web 2.0 and Service-oriented architecture (SOA).

2.3.4 Big data analytics and data mining

Zakir et al. [140] describes big data as data sets that do not conform to the typical structure of a traditional database. Rather than simply capture, store, control and analyse data, big data includes technologies that work together to extract value from what was previously identified as dead or unusable data. Only an estimated 5 % of available data from organisations are effectively used due to the high cost of dealing with it [140]. Big data aims to solve this issue using traditional data analysis methods and other paradigms of unstructured data, such as machine-derived data and social media-enabled human-derived data, to name a few [140]. An increase in sensor capability increases the smart capacity of products, services and systems and the access to industrial, transactional, business processes and fraud detection data sources, which further warrant the need for increased data analytics [48][8].

There are various applications for big data analytics, and with the constant development of technologies and data-capturing capabilities, more trends and applications arise in big data development. In Kambatla et al.'s [54] *Trends in big data analytics*, the following applications of big data are summarised:

- **Wealth and human welfare:** The capture, analytics and synthesis of healthcare-, pharmaceutical- and physical healthcare data to empower an increased human welfare capability.
- **Nature and natural processes:** Big data that concerns our environment, including changes, conversational empowerment and resource management-related processes.
- **Government and public sector:** The usage of big data within the governmental sector

is seen as a primary motivator for the big data analytics initiative, with increasing use to build a "21st Century Government."

- **Social networking and the internet:** With increasing access and usage of the internet and social media, there is an increase in the opportunities for the usage of big data to analyse trends in customisation and the speed of information flow.
- **Computational and experimental processes:** The usage of big data on emerging technological and computational trends, platforms etc., to enable in-line analysis with simulation and data acquisition. Essentially the usage of data sets generated to generate and validate scientific insights.

The applications above are summarised as fractions of the usage capability of big data analytics. The volume of data is growing at a tremendous rate, thus leading to the increasing need for concepts such as big data. The advent of big data compliments the other components summarised in this chapter, as various methods of intelligent data capturing, storing and usage are explored.

2.3.5 Machine-to-machine communication

Machine-to-machine (M2M) communications are direct communication between devices. M2M includes industrial implementation where an embedded device or microelectronic device can communicate recorded data to application software that can apply it [89] [23]. Figure 2.6, from Cheng et al.'s [23] *Machine-to-machine communications: Technologies and challenges* portrays a network architecture for a cloud-based M2M communication system, where a cloud, infrastructure and machine swarm is portrayed. High-speed wired or optical networking mechanisms network by connecting data centres, servers and gateways to and from the cloud [23]. The infrastructure, which can be wired or wireless, interconnects the cloud and machines in the machine swarm.

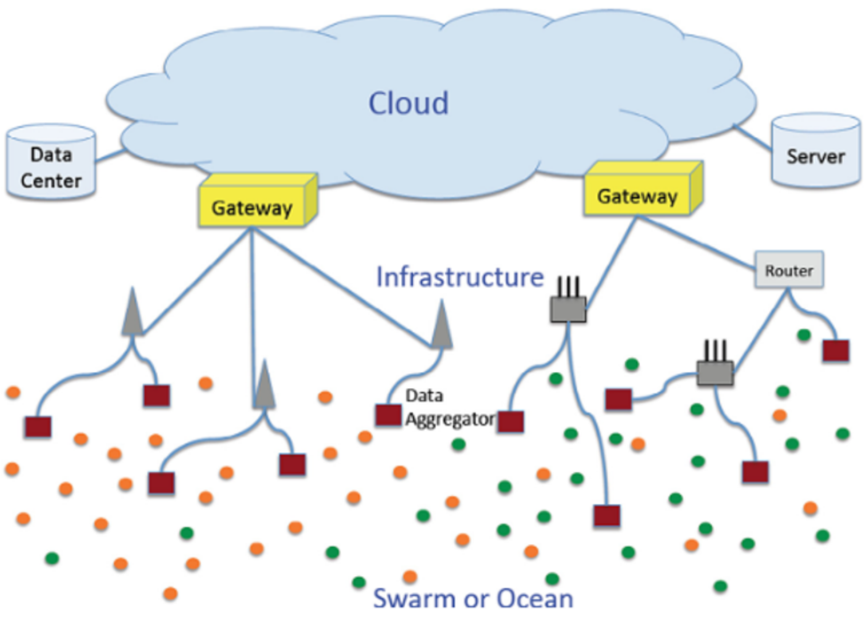


FIGURE 2.6: *Cloud-based M2M communications [23]*

2.3.6 Digital and smart factory concept

Smart or intelligent manufacturing aims to optimise concept generation, production etc., from traditional approaches to digitised and autonomous systems [89][55]. Smart manufacturing is a subset of conventional manufacturing (creating a product out of raw materials) that uses computer control and adaptability to achieve manufacturing [89]. Intelligent manufacturing also uses new technology, information and all the components above of I4.0 to enable flexible and dynamic processes. A smart factory refers to a factory where CPS communicate over the IoT and assists human resources and machines in executing their tasks. Depending on interpretation and definition, certain papers also refer to smart factories as "dark" or "unmanned factories" [89]. In this case, they refer to factories in which a system is built in such a manner that constitutes minor or no human interaction. In such factories, everything is produced and executed solely by robotic systems [89]. As in the description of this definition, various problems arise with using smart factories, bringing in ethical and moral questions.

2.3.7 Virtual reality and augmented reality

Zheng et al. [142] summarised virtual reality as the application of computer technology to create an interactive world, allowing virtual user control in real time. In virtual reality, humans enter a 3-dimensional computer-generated environment, where they are cut off from the real world. Augmented reality (AR) is the merging of the real and virtual world where an environment exists/is created where virtual and actual objects interact with each other [21]. Augmented reality is aimed to simplify the user's life by combining virtual information with their immediate surrounding. AR allows virtual assistance within a setting and can educate and assist the user in accomplishing specific tasks [21].

2.3.8 Simulation

Increased availability of digital services and software allowed for the development of simulation tools that organisations can use to simulate environments and test different scenarios, alternatives and the feasibility of their processes [52]. These technologies allow for the optimisation of processes, reduced error costs and lead times and better utilisation of resources. Simulation models are a primary part of the digital factory concept.

2.3.9 Advanced robotics and artificial intelligence

Another major element of the fourth industrial revolution is the increased use of robotics. As technology develops, the field of robotics continues to develop with it. Artificial intelligence (AI) refers to systems with a human-like rational and thinking ability, including disciplines such as natural language processing, automated reasoning, and machine learning [142]. Essentially artificial intelligence is the developing concept where non-biological and human-created intelligence can increasingly make autonomous decisions and act like humans. AI is a vital contributor to the development of the robotics field. Modern advanced robots are increasingly becoming more autonomous as they can learn from their environments and work without breaks [35]. These robots are known as autonomous robots and use sensors, infrared and ultrasound technologies etc., to work, learn and adapt to their environment and subsequently increase their precision [35]. These robots can also work for extended periods without human intervention [35][48]. Examples of these robots include autonomous helicopters, robots vacuum cleaners, and self-guided vehicles (SGV) [35][48] .

2.3.10 Cloud computing

Mell and Grance [71] describe cloud computing as a model that enables ubiquitous, convenient and on-demand network access to a shared pool of networks, servers, storage applications and other configurable computing resources that can be provisioned and released rapidly with minimal effort or service provider interaction. Oztemel and Gurzev [89] consider cloud systems a primary component of Industry 4.0.

Cloud technologies are simple online storage services that provide users operational convenience with web-based applications without the need for installation [89]. Cloud systems are adequate solutions to handle big data since the capacity to handle big data for cloud systems is much more efficient than a traditional computer [89]. More often than not, cloud systems are the backbone of Industry 4.0 systems. The use of a cloud system in CPS, M2M and IoT systems is ubiquitous, as cloud systems or computing were a recurring subject in all three systems above. Cloud systems are very versatile and can be used in manufacturing, supply chain and other business processes to increase speed and quality [89]. There are four primary types of cloud systems[89][71]:

- **Private cloud:** Exclusive use of a single organisation with multiple consumers (departments, business units etc.). These servers can be managed or subcontracted both on or off-premises.
- **Public cloud:** Open to the general public. It could be business, academic, governmental or combined servers. Exists on the site of the provider.
- **Community cloud:** The co-operation of any cloud service with a few companies. These servers can be managed or subcontracted both on or off-premises.
- **Hybrid cloud:** Combination of the aforementioned cloud servers.

From the content mentioned above and the prevalence of cloud systems or cloud computing in the other sections of this chapter, it is evident that cloud computing is a vital part of I4.0, especially with a focus on data management and analysis.

Mell and Grance's [71] NIST publication of computer security also defines the following essential characteristics:

- **On-demand self-service :** User provided with computing capabilities automatically without human interaction
- **Broad network access:** All capabilities are available over a network and can be accessed through standard devices (phones, tablets, laptops).
- **Resource pooling:** Providers' resources are pooled to enable multiple consumer services.
- **Rapid elasticity:** Elastic provision and releases of capabilities (automatically, in some cases) to enable rapid outward and inward scaling.
- **Measured service:** Cloud systems automatically manage and optimise all resources by leveraging a metering capability (typically pay-per-use or charge-per-use) at some level on some level of service (storage, analysis etc.). Usage can then be monitored, controlled, and reported to provide transparency for all parties.

2.4 Sub-components and concepts or technology that aid in the technological advancement of Industry 4.0 systems

This section covers technologies, concepts and components that aid in the advancement of Industry 4.0 and are often found in the literature to be independent of Industry 4.0 and not necessarily a "primary" component of Industry 4.0. Many of these technologies and components were developed independently from i4.0 or are natural precursors to i4.0. However, these technologies aid in the technological advancement towards I4.0 and the development of the fourth industrial revolution.

2.4.1 Cyber security

In 1988, Gasser [39] first mentioned the term cyber security and described it as protecting information systems from theft or damage. As organisations adopt Industry 4.0 technologies, their environments, information, and industries are increasingly appealing to cyber attackers [55]. The interconnected nature of Industry 4.0 and cyber-physical systems, accompanied by the speed of Digital Transformation, has heightened the risk for CPS-enabled environments to be the victims of cyberattacks [135][55]. Due to their nature, cyberattacks can be vast and affect the whole environment, leading to changes in the manufacturing process, the destruction of data and even the leaking of company intelligence [55][9]. As I4.0 continues to be developed and implemented, the security issues surrounding it become more critical and the need for security continues to grow. It becomes ever more important for organisations to be secure, vigilant, and resilient and invests in cyber security technology, i.e. technology that is made to combat the increasing threats from the usage of internet-enabled and cyber-physical systems [55][135][9].

2.4.2 Blockchain technology

Blockchain is distributed ledger technology used for secure processing and verifying data and transactions based on a peer-to-peer network [85]. Zheng et al. [142] summarised that blockchain is a database that creates a distributed and secures digital, including timestamps of blocks maintained by every node. Compared to central networks, peer-to-peer (P2P) networks are used in blockchain [85]. P2P networks have transparency and security advantages compared to central networks. Blockchain uses cryptographic algorithms that 'hash' data to connect blocks to a block sequence on the network (where the term blockchain is derived from) [85]. Every block in the chain is linked to the previous one, ensuring the blockchain's immutability. Blockchain is commonly used in cryptocurrency, cyber security, and digital supply records in digital supply chain management solutions [85].

2.4.3 Additive manufacturing

The desire for customised and individualised products has brought fought the rise of additive manufacturing, also known as 3D printing [116]. Where traditional machining, including milling, drilling, cutting and sanding - referred to as subtracting manufacturing is focused on the removal of material, 3D printing is additive, where final products are made up of successive layers of the printing material - removing the need for a part, or component assembly [55]. 3D printed products are designed using computer-aided design (CAD) software to create a digital model that can be printed in a 3-dimensional object using liquid-, solid- or powder-based material [137]. The material is then fed through a 3D printer, where thin layers are deposited microscopically onto the printer's base. The final product is a formation of successive layers of the material that are deposited onto each other to form the finished product [55][137]. Additive manufacturing enables small batch production with a broad customisation and flexibility range. With the advent of 3D printing, organisations can produce highly customised customer-driven products that enable sustainable management of a wide inventory variety and a wide variety of customised orders [116]. As the technological capability of the industry continues to grow, more methods of additive manufacturing are evolving, enabling the use of diverse and resistant materials for new uses [137]:

2.4.4 Information and communication technology

The rapid change in what is known as information and communication technology (ICT) has substantially contributed to the development of various Industry 4.0 components, such as big data, cloud computing, CPS, IoT and smart factory development [91]. ICT is the technology used to handle communications processes such as telecommunications, broadcast media, smart maintenance systems, audiovisual processing, transmission systems and network-based control and monitoring functions [130]. It also describes the convergence of several technologies and uses common transmission lines to carry diverse data and communication [130].

5G

5G, or the 5th generation of mobile, cellular and network technologies, is an ICT technology that is rapidly changing mobile and network communication in the world of today [101] [66]. 4G, the previous generation, saw growth of over tenfold of its previous generation, 3G. 4G is the extension of 3G (with higher bandwidth and services) and allows data transfer speeds of up to 100 Mbits/s [101].

5G brings significant changes in mobility and is a major growth driver in IoT technology, enabling more sophisticated and innovative technology. Where previous generations, such as 4G and 3G, had limitations in reliability, energy consumption, transfer speeds and the lack of support for dense and complex IoT systems, 5G promises to solve these issues. 5G accomplishes this by proving to be a fast and reliable access for IoT technologies, enabling even more widespread use of IoT, not simply limited to the connectivity constraints of the 4G/3G wireless markets [101]. 5G offers reliability figures of up to 99.999 % with a low power requirement and promises and currently does satisfy the shortcomings of other ICT technologies, offering alongside the benefits mentioned previously also the capacity for flexibility and standardisation systems through 5G [101].

2.5 Industrie 4.0 design principles

Ozetemal and Gurzev [89] refer to six fundamental design principles that Hermann et al. [44] defined. These six design principles were developed from their original four components to aid organisations in developing sample projects to investigate potential I4.0 transformation and technology implementation. The 6 principles are shown in figure 2.7 , and are summarised as follows:

1. **Interoperability:** All components of Industrie 4.0 are connected over the IoT and IoS. Interoperability refers to the ability of the manufacturing environment to have all entities

communicate with each other [44][49]. All of these components must have the built-in ability to communicate, process and act on information [44][49]

2. **Virtualization:** Ability to monitor physical processes within the manufacturing environment through means of linking sensor data with simulation software, including in real-time [44][49]. This principle represents the need for a virtual copy of the physical world, aiding in process monitoring, M2M, failure identification, and safety provision advancement [55][49].

3. **Real-time capability:** The ability to monitor, collect and analyse data in real-time through a CPS and connected IoT or IoS system [44][49]. This changes the manner of decision-making within the manufacturing environment.

4. **Service orientation:** The integration of the components allows for access to services provided in the CPS, manufacturing environment over the IoS, not limited to internal borders [44][55]. This service orientation facilitates the creation of a flexible product-service system that can rapidly respond to market changes and allow for value-creation on both an intra- and inter-organisational level [55].

5. **Modularity:** The ability to adapt to changing requirements by the replacement and expansion of individual modules [44]. This principle allows for easy adjustments, such as seasonal fluctuations and customer requirements. Facilitates simulation of different interconnecting processes to enable interchangeability [55][49].

6. **Decentralization:** One of the primary drivers of I4.0 is the rising demand for individual and custom products, which makes it increasingly more complex to control systems centrally [44]. This principle refers to the ability of all components to make decisions without the need for a centralised decision-making computing system [55]. Embedded items allow for these decisions, with only failed tasks delegated to higher decision-making systems [54][49].

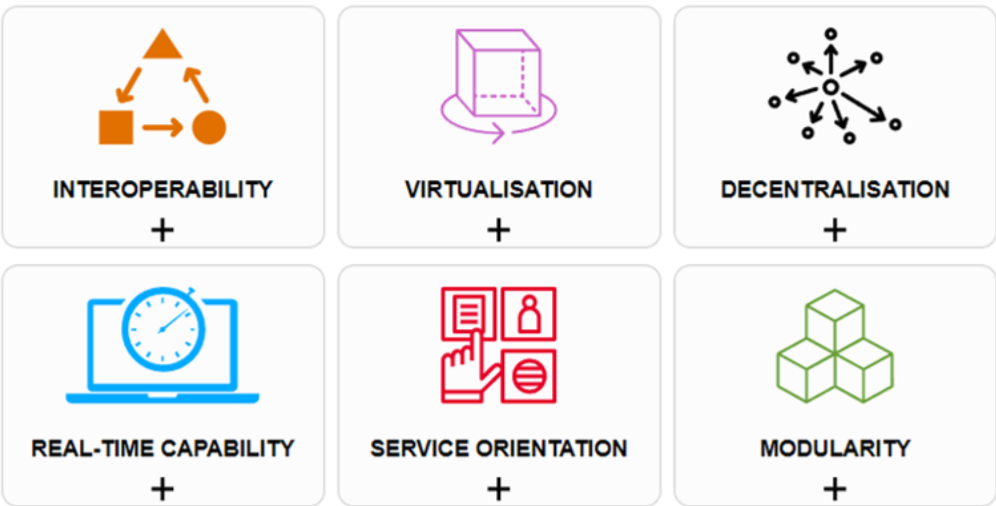


FIGURE 2.7: *Six design principles of Industry 4.0 [49]*

2.6 Benefits of Industrie 4.0

The impact of Industrie 4.0, as seen in the previous sections of this thesis, is widespread. With the disruptive nature of Industry 4.0 and the changing manufacturing landscape, the potential of Industry 4.0 is clear. The benefits of Industry 4.0, from the increased transparency, productivity and flexibility within production to the reduction in cost and lead times, are becoming more noticeable to firms worldwide. Notably, development organisations, such as the Business Development Bank of Canada [10], and management consulting firms, such as Accenture [1], McKinsey & Company [70], and the MPI Group [122] all have articles, case studies or analysis of the potential benefits of Industry 4.0.

Accenture [1], a technology consulting firm, already argued in 2020 that based on their work and research of the previous ten years, the time for Industry 4.0 experimenting is over. Their study, involving more than 600 industrial firms in North America, Europe and Asia, found that more than merely experimenting with Industry 4.0 implementations may be required.

Based on the research by these three organisations, alongside other articles and reports in the literature, the following benefits of Industry 4.0 implementation have been summarised. There are many benefits beyond the few listed here.

Increase in productivity

All three organisations highlight the potential increase in productivity of Industry 4.0 implementation. The capabilities of I4.0 components and technologies such as CPS, smart factories and IoT allow organisations to enable an increased capacity to manage downtime, optimise equipment and technology management, can operate transparently and increase worker productivity and asset utilisation [1][10]. The use capture and use of data also allow organisations to increase their operational capabilities and subsequently increase their productivity [70]. The BDC [10] report in their survey research that out of 1000 entrepreneurs they consulted with, 60% of adopters agree that digital technologies aid in an increase in productivity. Regarding labour specifically, in their 2021 report, Bettiol et al. [11] investigate how Industry 4.0 boosts labour productivity (specifically within Italy) and found as much as a 7% increase in labour productivity after adoption, although with a decreasing effect after the peak. They also find that firms should keep investing in Industry 4.0 adoption to counteract a dip after a peak.

The US-based consulting firm The MPI Group conducted an analysis of productivity and profitability on the effects of Industry 4.0 from 2016 to 2020. Their study, *Industry 4.0 Drives Productivity and Profitability for Manufacturers* [122], finds that as much as 83% of manufacturing leaders globally list Industry 4.0 as extremely important to their firms. Figure 2.8 shows the impact of Industry 4.0 based on a survey from 679 manufacturers globally in 2020. Based on their findings, it is evident that Industry 4.0 adoption has benefits both towards productivity and profitability of a firm, with overall 88% of manufacturers showing improved productivity thanks to Industry 4.0 adoption.

Additionally, MPI Group [122] also predicts the impact of Industry 4.0 adoption on the productivity and profitability of firms for the next five years. Figure 2.9 shows the potential impact of Industry 4.0 over the next five years; they found that up to 92% of investigated firms are mobilising their plants for bigger scale Industry 4.0 adoption, with the promise that Industry 4.0 can and will change the nature of their business and therefore substantially increase their operational gains and figures. The group also predicted the impact of Industry 4.0 adoption on the productivity and profitability of firms for the next five years. Figure 2.9 shows the potential

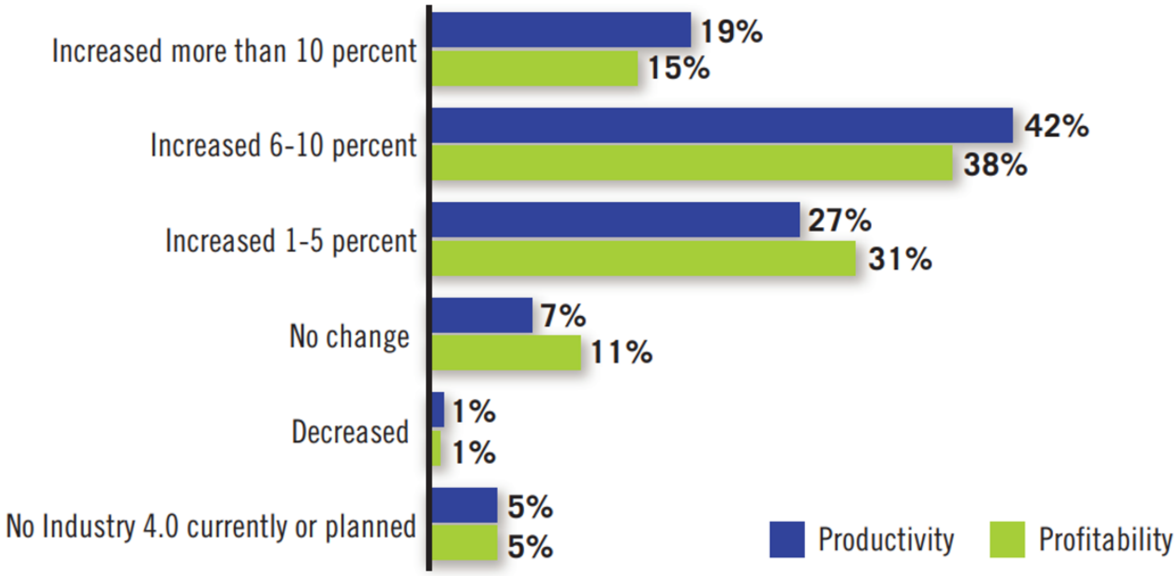


FIGURE 2.8: *Impact of Industry 4.0 to plants and processes on productivity and profitability in the past year (percentage of manufacturers - 2020) [122]*

impact of Industry 4.0 over the next five years. They found that up to 92% of investigated firms are mobilising their plants for bigger scale Industry 4.0 adoption, with the promise that Industry 4.0 can and will change the nature of their business and substantially increase their operational gains and figures.

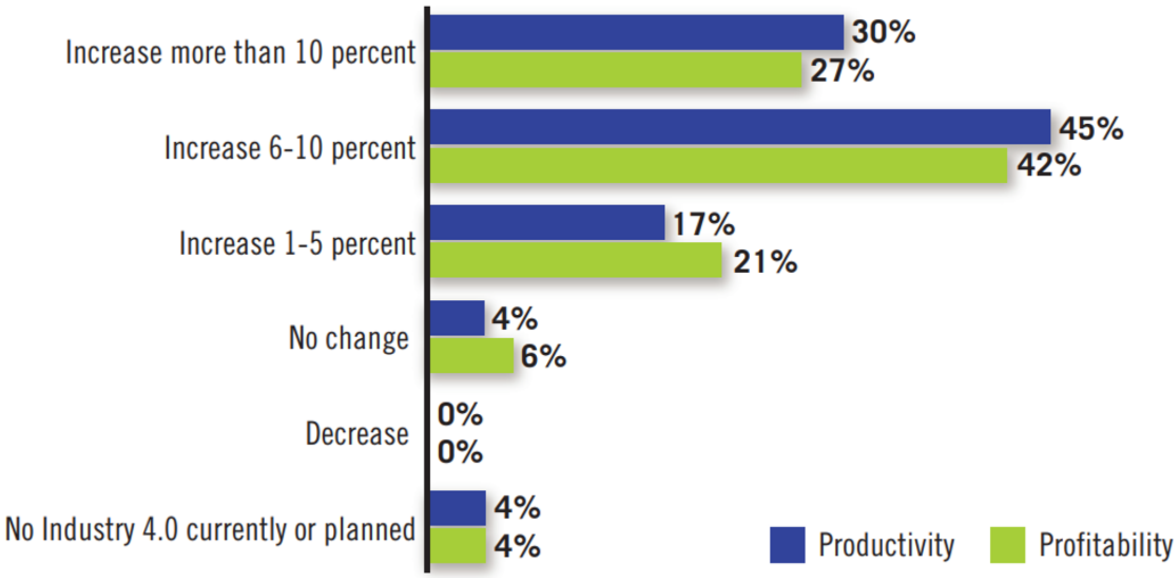


FIGURE 2.9: *Impact of Industry 4.0 to plants and processes on productivity and profitability over the next five years (percentage of manufacturers - 2020) [122]*

Financial benefits

Accenture [1] found that the financial reward of digital investment should be a major incentive for organisations. They found that with ample investment, firms within their research gained an increase of 2.1 - 3.1% in short-term sales and a 3.4 - 4.3% increase in medium-term sales. Furthermore, they noted substantial increases in connected services sales across their research.

Accenture [1] also found that the overall benefits of Industry 4.0 and Digital Transformation in their research accumulated to a significant improvement in ROCE and EBIT, with a reduced need for capital, employed. The BDC [10] survey found that 50% of digital adopters note that it helped them with a reduction in operating costs. The implementation of Industry 4.0 and Digital Transformation technologies, such as M2M, IoT and other CPS, all point to a more cost-effective manner of production [70].

The MPI group's [122] findings also make it clear that adopting Industry 4.0 has advantages for a company's profitability, with 84 % of manufacturing indicating increased profitability as a result of adopting Industry 4.0 and that an increasing number of businesses are mobilising towards Industry 4.0 to do the same.

Competitive advantage

BDC's [10] survey research points out that 13% of Industry 4.0 adopters point out that modern technology has enabled them to increase their innovation capability, with new research and technology promising to increase this statistic significantly in the years to come. Furthermore, they found that digital adopters are twice as likely as others to reach annual revenue growths in the years following their survey. There is a clear link between the use of technology and the competitiveness of firms in the market [80][10][70]. McKinsey & Company [70] predicted in 2015 that in the next ten years the competitive landscape of organisations would be more complex and uncertain. The research and examples used by the BDC [10] support this idea five years later, as more firms now have online ordering platforms, where the majority of business processes in select firms are automated. Overall, with the increased complexity in demand and the flexible desire of customers, the adoption of digital and Industry 4.0 technology has the potential to enable firms to compete and stay digitally relevant.

Quality improvement

The increased traceability, transparency and production management capability of Industry 4.0 components and associated technologies enable firms to manage their products' quality better. The literature surrounding Industry 4.0 in the previous sections already outlines this. Furthermore, a BDC [10] survey found that 42% of adopters recorded an improved overall quality after implementation, as real-time control and data capture have aided with quality management in these firms. McKinsey & Company [70] also found that an increase in quality is expected with Industry 4.0 adoption.

2.7 Labour-intensive environments

Labour has always been an important part of industry. People have been part of the production process since the dawn of time. In its simplest definition, labour is any work done (mostly physical manual work) for remuneration by a human being [114]. Labour can come in various forms, both mental and physical, in a skilled or unskilled environment that requires income for work.

More specifically, this research looks at labour-intensive environments. Given the open definition of labour, a labour-intensive environment's definition can also often have an ambiguous interpretation. Monash university [76] defines labour-intensive environments as industries that require a large amount of labour for their production or service delivery, where a more significant portion of the total costs of industry is due to labour compared to other portions. These environments still use machines and special tools but predominately use human effort, and creativity within industry [58]. Examples of labour-intensive environments are repair shops, construction sites, the mining industry and agriculture.

Advantages of these environments include greater flexibility, customised production and reduced equipment and machinery cost. In principle, these environments use human-centric processes that enable human initiative and adaptive problem-solving [58]. Given the human-centric approach to industry, human error and the labourer's experience directly influence the environment's production or service delivery [58].

One of the trends of industry today, which is also one of the consequences of Industry 4.0, is that with increased digitisation and automation, the role of the human worker is increasingly at risk, due to the technological advances of industry today and the drawbacks listed above [17][88][78].

This research considers labour-intensive environments within the manufacturing or repair industry. A labour-intensive environment is defined as a production environment that makes use of manual work for manufacturing or repair. The remainder of this section briefly investigates the common challenges in labour-intensive industries before moving on to DT approaches in these environments.

2.7.1 Challenges of Digital Transformation in labour-intensive industries

Given the human-dependent nature of these environments, challenges such as human error, change management and union agreements are evident.

Upon further investigation, more challenges become apparent. Three of these issues are the unpredictable attendance of an organisation's employees, the high turnover and skills management [41][127].

A major challenge is the unpredictable attendance of an organisation's employees. Given their human dependency, these organisations can never be sure of the attendance of their employees on a day-to-day basis. This leads to further challenges such as production schedules, human resource management and profitability. Often these issues are due to external influences such as unreliable transportation and family care [41].

The "cluster effect" of these environments, where often firms with these environments are situated together, can also be problematic for these environments [41]. These firms face the uncertainty of how long employees can reliably stay at their firm.

Employees' training and skill management are also significant issues within these environments. Hiring the right employees with the right skills is important and often challenging [41][97]. Given the emerging state of South Africa's market, where a higher percentage of employees do not have tertiary education, the training and management of skills can be understandably hard for organisations to undertake [97].

Furthermore, it was found that these environments find it challenging to enact value-adding transformation, with practical and visible results due to the variations of a labour process (the employee's actions are not always the same in each value-creation process) and that often a hesitancy exists from the labour workforce due to the disruptive nature of DT to both the process and potentially the employee. For example, the idea exists that more robots and more forms of Digital Transformation can reduce job opportunities by replacing a human workforce [105].

Finally, the issue of data collection. Currently, data collection is often built into production machinery [41][60]. This is not the case everywhere, as some industries, especially in developing nations still use old and outdated machinery that predates Industry 4,0 and even Industry 3.0. As productivity improvement and optimisation can be dramatically improved through data analytics, a major challenge facing these firms are their means of data collection to stimulate productivity and other measures within their environments.

2.7.2 Approaches to labour-intensive settings and Industry 4.0 taken in literature

The labour dilemma in Industry 4.0 has been raised ever since the inception of I4.0. Various firms and academics have attempted to find methods and approaches to face the dilemma sustainably. To support the idea and implementation of digital support within a South African setting, approaches from around the world should be considered to look at previous examples of implementations and tools that could aid in developing this research. This subsection looks at both practical solutions and conceptual solutions to tackle the issue of Digital Transformation.

McKinsey & Company

Management consulting company, McKinsey and Company, developed an analytics tool in 2021 to aid manufacturers in using labour-intensive environments to boost productivity and potentially boost earnings by "double-digit" percentages [41]. Their approach cites analytics as a solution. Although the manufacturing sector produces a lot of data, only a few organisations have successfully used their data to aid their decision-making.

As highlighted in the challenges above, the issue of data collection is prominent in these industries, thus leading to the need for efficient data collection. As part of their analytics tool, McKinsey & Company [41] outlines various tools and software which have the potential to collect data that can aid in productivity and earnings:

- **Machine-utilization measurement:** Photo-electronic sensors can continuously track the material flow, running time and idling to subsequently calculate overall equipment effectiveness.
- **Route track:** Sensors can be used to analyse the distance and movement within the setting to calculate the output.
- **Motion measurement:** Sensors, algorithms and software can be used to measure the non-value-adding times of the operator.
- **Cycle-time measurement:** RFID can be used to record cycle times to find push-back incidents and calculate variance.
- **Digital performance management:** Real-time data analyzing and problem-solving.

McKinsey & Company's studies concluded that the use of motion-measurement systems in North America and Asia could stimulate so much as a 25% to 35% increase in production by calculating non-value added activities and simply optimising tasks, often even so simply by eliminating unequal workloads between a worker's left and right-hand [41]. Based on these findings, it may be concluded that even the simplest inefficiencies, which are not always identified by firm management, can be identified and optimised by digital support methods.

Another potential of McKinsey & Company's approach is dynamic scheduling. They find that firms spend time and money on production planners and schedulers to work out optimal production plans [41]. Dynamic scheduling uses analytical algorithms that optimise scheduling and planning with minimal supervisor guidance by guiding employee management and maximising productivity and service levels.

In their article, McKinsey Company [41] uses an example of a dynamic scheduling system by a firm investigated by McKinsey Company, where an algorithm assigned the station of a worker upon their clock in is used by taking their skill, experience and requirements for the task into consideration, leading to the elimination, of a minimum of 12%, productivity loss and even higher percentages in other productivity measures. This scheduling system can be deployed in real-time and gives managers the flexibility to address other more specific issues [41].

Finally, McKinsey & Company addresses the issue of skill management. Analytics enable firms to train employees faster by using digital tools, such as digital screens, advanced IoT guidance systems and dynamic scheduling to stimulate skill management, narrowing skill requirements, lowering teaching and training times and stimulate worker concentration through interactive systems [41].

In summary, McKinsey and Company show the potential of digital support technologies, in their case specifically towards analytics, to increase productivity within labour-intensive industries. Their approach shows a suitable approach to Digital Transformation within the context of Industry 4.0, without threatening the employee and by even encouraging workers, leading to productivity and subsequent turnover increases.

The International Labour Organization

The International Labour Office contains several resources on the digital revolution and labour. The International Labour Office is a United Nations organisation that aims to improve social and economic fairness through international labour standards. In their 2016 research paper, Walwei [127] already raised the issue in the German labour market, where they list skill adjustment and development, social dialogue and regulations as major topics. Due to limited research, they only gave a few recommendations. Using workshop training, higher levels of formal education and ICT skill development could help guarantee the worker's relevance.

In general, Walwei [127] suggests a proactive approach in which policy, social dialogue, and upskilling are employed to guarantee the worker's ongoing employability and modern culture shift.

The European Commission

Industry 5.0 is discussed in this thesis's section 2.9 and was briefly referenced in the introduction. It is clear from the difficulties in section 1 that a more human-centric strategy for Digital Transformation is needed. The COVID-19 pandemic, rising automation, and the growing concern about the value of humans in industry, among other factors, have come together to give rise to Industry 5.0, a new way of thinking about Digital Transformation that was named by the European Commission [17].

2.8 Triple bottom line

The problem statement, background and the subsequent sections of Chapter 1 mention that there is a lack of a human-centric approach to Industry 4.0. The human-centric approach is of great importance, especially in South Africa, where there are high levels of unemployment - 34,9 % in Q3 of 2021 [117]. Furthermore, there is growing global concern about the earth's state and the approach humans need to take for a sustainable future.

The triple bottom line (TBL) is an accounting framework that incorporates three parts colloquially known as the three p's: people - the social equality bottom line; planet - the environmental bottom line and profit - the economic bottom line. The TBL approach aims to achieve a sustainable value-adding approach in all three parts [33] [115].

Although it is an accounting framework, the basis of the triple bottom approach is relevant to the underlying issues of labour in industry. It finds an equal compromise between three critical aspects in modern business and, therefore, in modern industry and manufacturing. The researcher believes that the literature surrounding the triple bottom line could aid in adding value to the new approach. Figure 2.10 shows the triple bottom line.

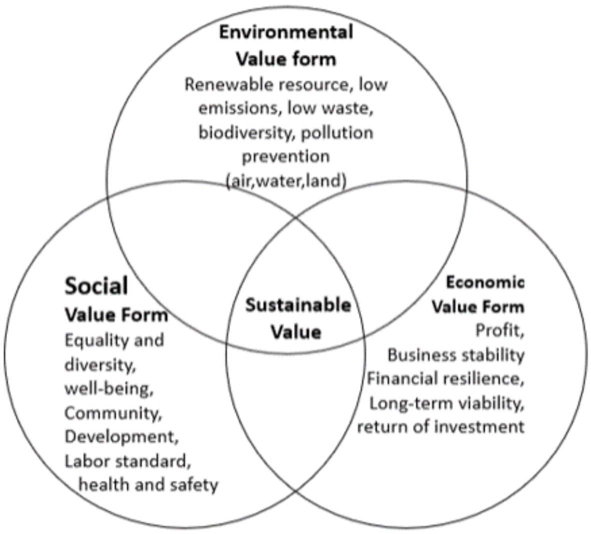


FIGURE 2.10: *Triple bottom line[16]*

2.8.1 TBL: People

The first bottom line surrounds the role of people. It seeks to ensure social equity within a TBL environment. The importance of people is noted in such an environment, and rather than exploiting human resources, labour and stakeholders, the well-being of humans is incorporated as a core principle of their accounting [12] [115]. The first bottom line in TBL measures the well-being of employees, communities and all other stakeholders are in place to ensure empowerment. Measures attaining equality, diversity, mental and physical well being and a community approach are included in these empowerment's [12] [115].

Besides the well-being mentioned above, a human-centric approach also adds value through motivation and morale, as with such an approach, employees have a sense of pride and responsibility towards the organisation that they work for - ultimately empowering both the people and profit aspect of the TBL approach [112].

2.8.2 TBL: Planet

The second P, the planet, revolves around a sustainable environmental approach where the organisation endeavours to benefit the natural order of things as far as possible. Environmental measures such as resource consumption limitation, waste management, pollution prevention and more are incorporated into the cornerstone operation of a TBL-enabled organisation [12] [115].

Alhaddi [5] and Elkington [33] highlight that within a sustainable environment three conditions are to be met. Firstly the consumption of resources should not exceed the regeneration of resources, non-renewable consumption should not exceed novel renewable development, and pollution rates should not exceed the environment's assimilative capacity.

The "green" approach empowers the responsible use of resources, the development and innovative use of green products, and the minimisation of an ecological and carbon footprint [5].

2.8.3 TBL: Profit

The final bottom line, profit, is the economic aspect of the TBL. It looks at the economic value created after all deductions. The inclusion of the third bottom line is also vital in the development of a TBL system, as economically it should still make sense for an organisation to introduce the TBL.

The profit aspect of TBL includes all variables and measures within the organisation. It ensures the financial and economic continuation of the organisation, as, without the third bottom line, an organisation would cease to exist. The economic bottom line includes the economic capital, accountability towards financial stakeholders, and the actual accounting [33]

2.9 Industry 5.0

One of the significant drawbacks of Industry 4.0, and possibly also an impediment to radical technological advancements in organisations that rely significantly on a labour workforce, is the ethical consideration surrounding Industry 4.0 implementation [78][88]. Industry 4.0 often ignores the human cost of its cyber-physical optimisation process, consequently facing resistance from both labour unions, politicians and employees fearing for their positions [105] [78].

Section 1.1 briefly mentions the concept of Industry 5.0 (I5.0), the proposed successor of Industry 4.0, a human-centric solution to industry. In their January 2021 publication, *Industry 5.0: Towards a sustainable, human-centric and resilient European industry* [17], the European Commission describes Industry 5.0 as an open concept that is continuously evolving, which is primarily focused on a human-centric, sustainable and resilient approach to industry's continuous service to humanity within planetary boundaries.

The European Commission also stresses that Industry 5.0 is not necessarily a chronological continuation or an alternative approach to Industry 4.0. It is instead the result of a sustainable, future-orientated and human-centric movement, which is focused on how the European industry and emerging societal and technological trends co-exist by taking economic, technological, environmental and social dimensions into consideration [17].

Industry 5.0 is still in its infancy, so the need for more research is noticeable. Early academic writing reveals that Industry 5.0 is focused on integrating the technological components and beneficial aspects of Industry 4.0 and cyber-physical systems with an emphasis on human interaction [88]. Besides the renewed human-centric and environmental focus of Industry 5.0, the mass personalisation of production is another proposed focus of Industry 5.0 [88]. A major introductory component of Industry 5.0 is the cobot, or collaborative robot, seen as the next generation of robots [88]. They are not only programmable machines but can also transform into the ideal human companion, having the ability to be aware of the human presence and learn from human interaction. Cobots also increase safety and reduce technical issues [78][48]. In their 2022 survey publication on enabling technologies and potential applications of Industry 5.0, Maddikunta et al. [66] mention seven possible definitions of Industry 5.0. These definitions are supplied by industry practitioners and researchers, six of which raise the importance of the human workforce and the bringing back of the human aspect to enable human-centric manufacturing.

2.9.1 Defining Industry 5.0

The European Commission strives to define Industry 5.0 in its publication. Their analysis of early academic writing points out that generally, uncertainty remains on how exactly Industry 5.0 will disrupt business and its potential to bridge the virtual and real-world [17]. Generally, their findings single out three core elements: human centricity, sustainability and resilience.

The emphasis of a **human-centric** approach puts the interests and needs of humans at the centre of production. Industry 5.0 aims to manage technology so that it aids humans rather than focusing on what can be done with new technology. Essentially Industry 5.0 does not impinge on a worker's fundamental rights, such as privacy, autonomy and dignity [17]. Given our planetary boundaries, the next step in the industry evolution needs to be **sustainable**, in such a manner that circular processes are developed where the re-using, re-purposing and recycling of resources contribute to waste reduction and minimal environmental impact [17]. It includes reducing energy consumption, greenhouse gas production, and other environmental considerations to ensure that the needs of the current generation do not jeopardise the needs of the future generation. Finally, it needs to be **resilient** i.e. industrial production has to be highly robust and armed against disruption by ensuring its capability to provide during times of crisis[17]. The outbreak of the Covid-19 pandemic has highlighted to industry exactly how vulnerable global supply chains and production are, thus emphasising the need for a more resilient industry.

The definition of Industry 5.0, as defined by the European Commission [17] is: "Industry 5.0 recognises the power of industry to achieve societal goals beyond jobs and growth to become a resilient provider of prosperity, by making production respect the boundaries of our planet and placing the well-being of the industry worker at the centre of the production process."

2.9.2 Benefits of Industry 5.0

Benefits for the worker: Human-centric approach

Industry 5.0 shifts to a human-centric approach. The new approach aims not to leave anyone behind and about a safe and beneficial working environment. Benefits include the changing role of workers from a previous "cost" perspective to the narrative of "investment" for employers. Employers invest in the skill, capabilities and well-being of their employees. The narrative of technology serving people, rather than people serving technology, is also leading to the shift in the fundamental work role of the employee to a more supportive role within industry [17].

Furthermore, new technologies and Industry 5.0 create the potential to make workplaces more

FIGURE 2.11: *Industry 5.0 [17]*

inclusive and safe for employees. Essentially, a shift is occurring in simplifying tasks, leading to a reduction in dangerous tasks and a subsequent increase in safety as technologies take over such tasks. Furthermore, the human-centric approach gives more focus on the employees, thus leading to an increase in job satisfaction and inclusively [17]

Finally, given the "investment" perspective of employees, the up-skilling and re-skilling, especially digital skills are of increasing importance to employees, leading to knowledge building and skill development of employees [17].

Benefits for industry

Benefits of Industry 5.0 are wide-ranging for industries, including talent management, resource efficiency and increased resilience [17]. Increased talent in the work pool and competition has stimulated workplace environments, leading to more attracting and retaining talent management opportunities [17]. Increased environmental and social pressure leads to the expanding importance of resource efficiency; thus, firms focus more on getting more out of their resources and spending less on them.

Finally, the ever-changing environment leads to the need for the ability to react quickly to change, i.e. resilience. Changes in global supply chains, natural emergencies (such as Covid-19) and cultural and societal changes are gradually compelling firms to become more resilient, thus creating opportunities for firms to react better to the environment around them[17]

2.9.3 Key supporting or enabling technologies of Industry 5.0

As Industry 5.0 is a novel term and describes recent developments or even the upcoming iteration of the industrial revolution, various opinions exist on what components would form part of industry 5.0. Maddikunta et al. [66] also used their survey research to construct key enabling technologies of Industry 5.0, which can be seen in Figure 2.12.

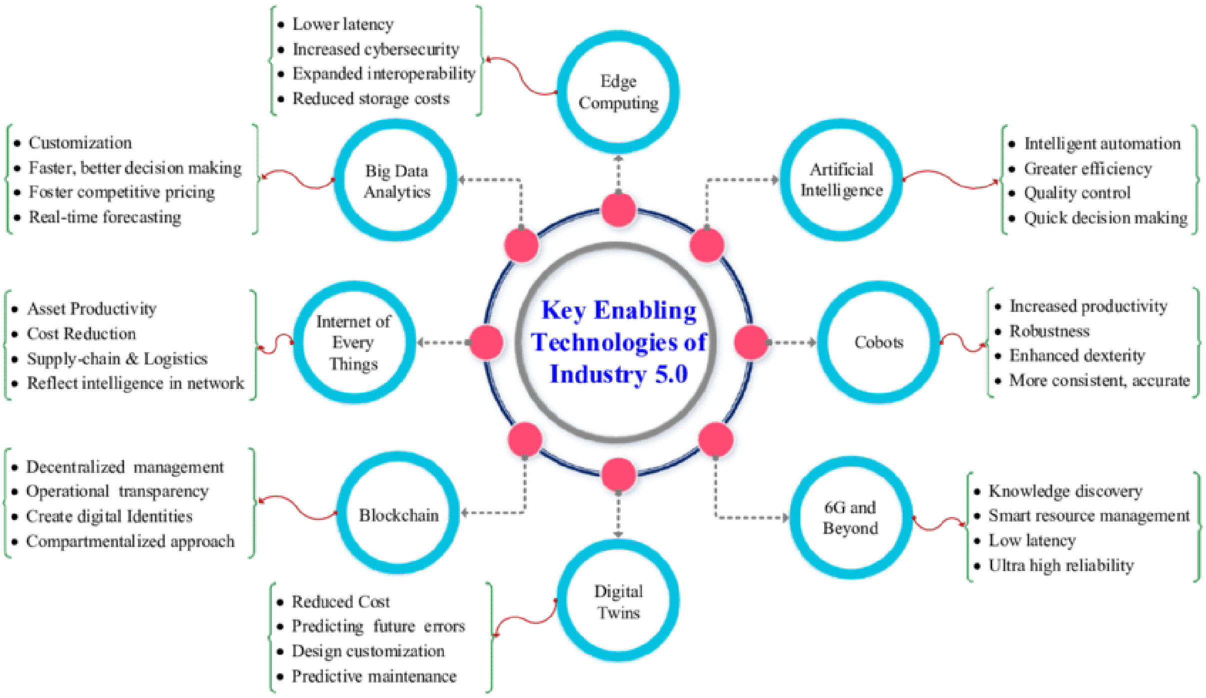


FIGURE 2.12: *Key enabling technologies of Industry 5.0 [66]*

Edge computing

The rapid growth and implementation of the IoT and the success of cloud systems have introduced a new conceptualisation of computing, Edge Computing [66][111]. Edge computing is the processing of data at the network's edge - the point at which the enterprise-owned network is connected to third-party networks [111]. Edge computing's rationale is that computing should happen as close as possible to the data sources, and the computing is focused more on the 'things' side within a CPS system [111]. Figure 2.13 conceptualises the edge of the network and how edge computing is centred around the data sources in a CPS or cloud system.

On the network, edge computing can request content/services from the cloud and perform computing tasks from the cloud. Edge computing promises to efficiently reach reliability, security, privacy, cost-effective and energy-saving issues associated with conventional cloud computing systems [111]. Edge computing promises to not only aid in Industrie 4.0 transition, but also the future of Industrie 5.0 [66]

Digital twins

A digital twin is a digital replication of a physical system or object [66][48]. The concept of a digital twin has widespread use in Industry 4.0. A digital factory, as described in section 2.3.6, is an example of a digital twin, and through CPS, IoT, IoS, AI, and big data systems have recently started to become more widespread due to the cost reduction ability of IoT systems [66]. IoT enabled the digital capturing of a factory environment, enabling the mapping of a digital twin. These digital twins enable environments to analyse, monitor and prevent errors [66].

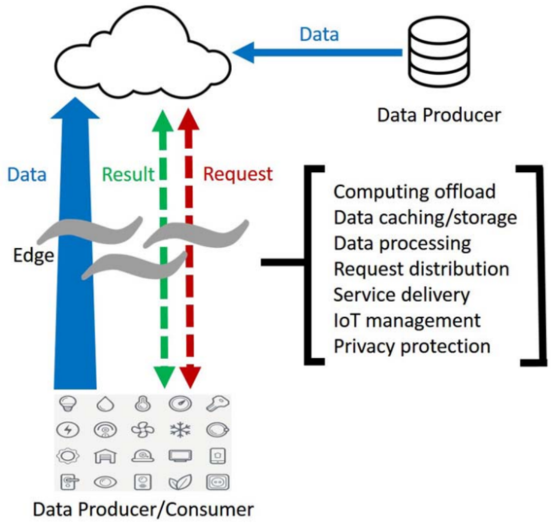


FIGURE 2.13: *Edge computing paradigm [111]*

Digital twins add value in Industry 5.0 by offering value to enhance customised product enabling, enhancing business functions, reducing defects and more. [66].

Digital twins also enable virtual training, a key component of Industry 5.0 according to Nahavandi [78]. Virtual training enables the ability to flexibly train a skilled workforce without compromising the organisation's production at a reduced cost within a safe, simulated environment [78]. Digital twins in the form of simulated environments or objects are used to train employees to enable improved production, advanced skill training, haptics training and safety, to name a few [78]. The Formula 1 (F1) simulator is an example of a digital twin and virtual training. In a team's F1 simulator the capabilities of their race car are coded into the digital twin vehicle. This digital twin vehicle is then placed in digital twin environments of each circuit on the calendar, enabling the F1 driver to train to get comfortable with the capabilities of the car and to get familiar with the various circuits, completing a virtual training session within a digital twin environment [123]. Figure 2.14 shows the Red Bull Racing team's F1 simulator in action.

Human and robot collaboration

A collaborative robot, or cobot, is seen as the next generation of robots in industry [78][88][68]. Due to recent trends in automation, robotics, AL, and smart technology, the need for more intelligent and adaptive robots has risen [66]. Cobots are designed to work together with humans with capabilities from their human counterparts, making data-driven and historical base decisions, being aware of their human counterparts and producing customised products on a mass scale [66][78][88].

As robots lack the critical thinking ability of humans but are preferable when it comes to the manufacturing process, the management of the ability of humans and robots to collaborate is critical [66]. Due to their interactive ability and the ever-growing cost of labour, the value that cobots add to Industry 5.0 and organisations is prominent as they enable the improvement of business performance [66]. Furthermore, the current market for robotics increasingly asks for a reduction in lead times and mass customisation, and collaborative robotics enables the flexible and multi-purpose assembly system ability needed to serve this need [69].

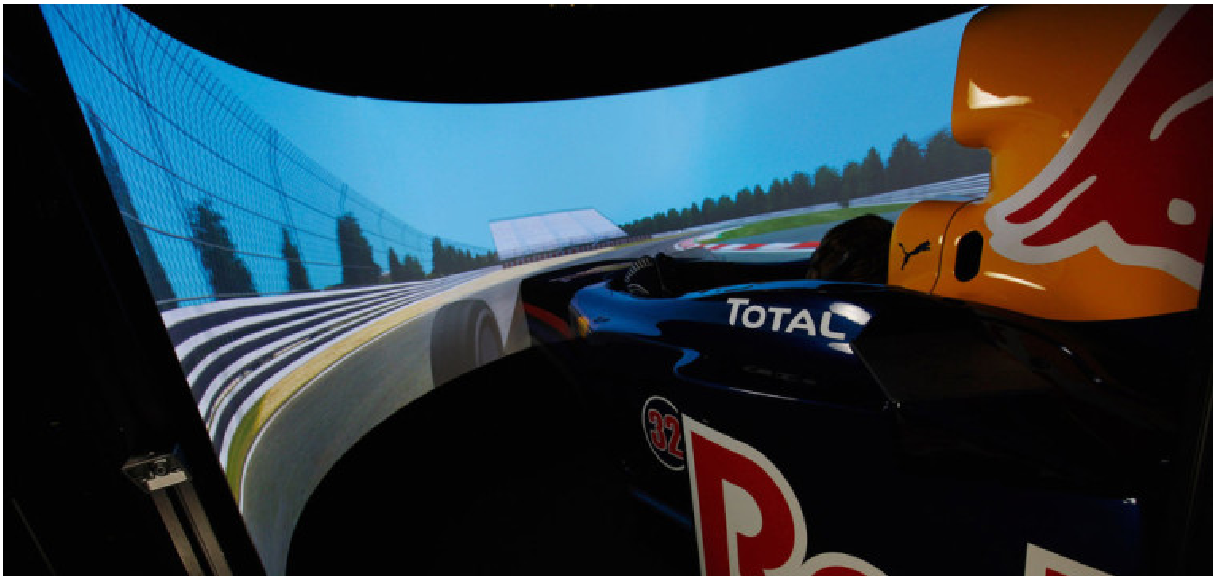


FIGURE 2.14: *Digital twin: Red Bull Racing F1 simulator in action [123]*

There are different types of cobots, different measures of collaboration and different learning abilities for different cobots. These cobots operate and learn by being programmed using three general programming approaches: online programming - using a teaching pendant, where the robot is unavailable to work; offline programming - on a pc where the robot is not physically needed and coordinate systems programming - positions in x,y, and z pane [48].

There are four types of uses for collaborative robots which can be seen in Figure '2.15 as described by Matheson [69]:

- Coexistence: Humans and cobots are present in the same environment but generally have no degree of interaction.
- Synchronised: Human and cobot use the same workspace but at different times.
- Cooperation: Both work in the same workspace at the same time focusing on separate tasks.
- Collaboration: Task is executed together, where the action of the cobot has immediate consequences on the human task, and vice versa, due to sensors and the ability of the cobot to adequately collaborate with the human

Cell manufacturing is where there is no degree of interaction between the human and the robot, such as in traditional automation.

ISO 10218-1 and ISO 10218-2 introduced guidelines on how operators proceed within a collaborative workspace. An important aspect covered in these guidelines is the necessity to result in a safety stop if any failure is detected [68]. Furthermore the following operating modes are describes [68][48]:

- Safety-rated monitored stop: The robot stops when a human enters the workspace and continues after the human leaves the work area.
- Hand guidance: Robot exclusively moves following manual input by operators.

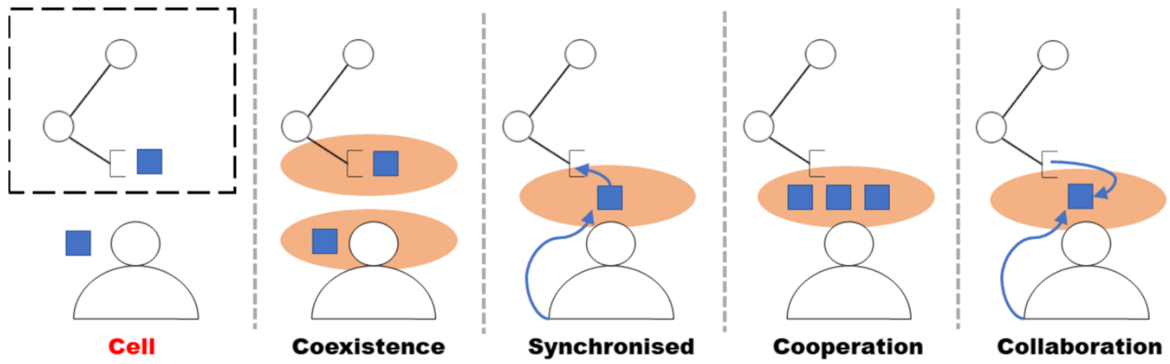


FIGURE 2.15: *Types of use of a collaborative robot [69]*

- Speed and distance monitoring: The robot senses the distance between humans and reduces speed as the distance is reduced, eventually resulting in a full stop when a human is too close.
- Force and power limitation: Robots' emitted forces are limited to ensure no physical harm is possible when colliding with humans.

Various methods such as light fences, contact floor mats, robot kinematics, laser scanners, capacities sensor skins for robots and force torque sensors can enable safety as introduced in the guidelines [48]

Big data analytics and blockchain technology

Both of these technologies/components have already been discussed in sections 2.3.4 and 2.4.2, respectively. Both technologies continue to grow exponentially. Given the recent developments and significant growth in concepts surrounding blockchains, such as cryptocurrencies and improved data security, and the continuous growth of big data analytics, Maddikunta et al. [66] notes the importance of these technologies towards the concept of Industry 5.0.

Blockchain's decentralised design enables the transparent and distributed management of vast numbers of connected devices in I5.0 [66][85]. Blockchain's immutable ledger and smart contract ability also aid with the security and protection of data and devices within an organisations environment [85]

Internet of Everything

The Internet of Everything, or IoE, is the link between people, processes, information, and things [66]. Essentially IoE is the inter-connectivity of all processes and entities within an intra- or inter-organisational context and creates new functionalities that build on IoT, IIoT, I4.0 technologies, and I5.0 envisioned technologies [66]. An example of an IoE environment is any collaborative environment between a human, cobot or sensory CPS that enables effective communication and collaboration through the use of IoT sensors [66]. A use case example is where sensors are connected to a patient, which detects abnormalities, alerting and advising the relevant hospital staff to proceed based on the data obtained.

6G and beyond

Section 2.4.4 covers the different generations of mobile, cellular and network technologies, where the concept of 5G is discussed. In recent years the roll-out of 5G has been widespread around the globe, and the speed, reliability and abilities of 5G can be seen within industry, and within the eyes of the consumer, [132].

In their survey paper, Maddikunta et al. [66] mention 6G, where they describe their vision for the next generation. Similar to 5G, 6G is envisioned as even faster, more reliable and with higher mobility than the previous generations. Also, 6G would be able to use quantum and free-space optical communication to provide high data rates for different applications [66].

Given the relatively recent roll-out of 5G in 2019 and still ongoing [132], and the infancy of Industry 5.0, it is safe to assume that 5G would still have a massive impact on Industry 5.0.

2.10 Enterprise engineering theory

Most of this literature review revolved around the transformation of firms towards modern and digitally relevant organisations through modern technology outlined in the components and sub-components of Industry 4.0 and Industry 5.0. Given that the research aims at the transformation of an organisation, the use of enterprise engineering or enterprise design could aid in accomplishing the objectives. In the Stellenbosch University's *Enterprise Design Textbook*, Du Preez et al. [29] define enterprise engineering as the discipline that concerns the design and redesign of enterprises - both business models and the organisation of the firm. Enterprises are very complex systems that contain processes that require comprehensive design/redesign to ensure realistic results in their design or transformation [29]. The concluding section of the literature review will briefly cover the theory surrounding the design and redesign of enterprises to aid in developing a transformation model that considers an enterprise and its systems to achieve a comprehensive and realistic outcome.

2.10.1 Explaining the need for change

Enterprises continuously experience transformation cycles. These cycles can be seen with the change in organisations and human life during the various phases of the Industrial revolution as outlined in section 1.1. The constant need for new products, target markets and organisational structures are examples of these cycles that organisations go through to maintain a competitive advantage and add value to customers and stakeholders [29].

As with all change, some factors and variables drive the need for change. These drivers can be internal drivers, such as the increased complexity of a firm's organisation, and external drivers, such as changing regulations and emerging technologies [29][50]. Table 2.3 briefly summarise a few drivers of change that Du Preez et al. [29] cover. Internal drivers for organisational change include rising financial pressure, shifting product requirements, and growing company complexity, similar to those driving Digital Transformation. Additional factors driving change outside include the availability of new technology, the evolving customer market, and rising competition and regulation. When comparing these drivers to the Digital Transformation drivers in section 2.1.2, it is clear that Digital Transformation can be seen as a type of organisational change.

TABLE 2.3: *Internal and external drivers for organisational change, adapted from Du Preez et al. [29]*

Internal Drivers	External Drivers
Complexity: Increased complexities on various levels in a firm, such as product, process or company policy, force enterprise to adapt to maintain relevancy	**Customer Expectations:** The needs of customers are constantly changing, thus firms are required to adapt to ensure that they meet the needs of their customers.
Financial: Financial pressure on all scales often cause the need for certain organisational changes on different company levels.	**Competition:** Action from, or the emergence of competition often force enterprises to change to keep their competitive advantage.
Product changes: Adapting to new external factors organisations have to develop new products or services.	**Regulation:** Government regulation often drive the need to change on various levels of an organisation
	Technology: The emergence of new technology drive change by ensuring that firms stay digitally relevant.

2.10.2 Core commitments of an enterprise

The mission statement, vision and values of an organisation, often referred to as the core commitments or the principles of management of an organisation, set out the foundation for its strategic [29][74].

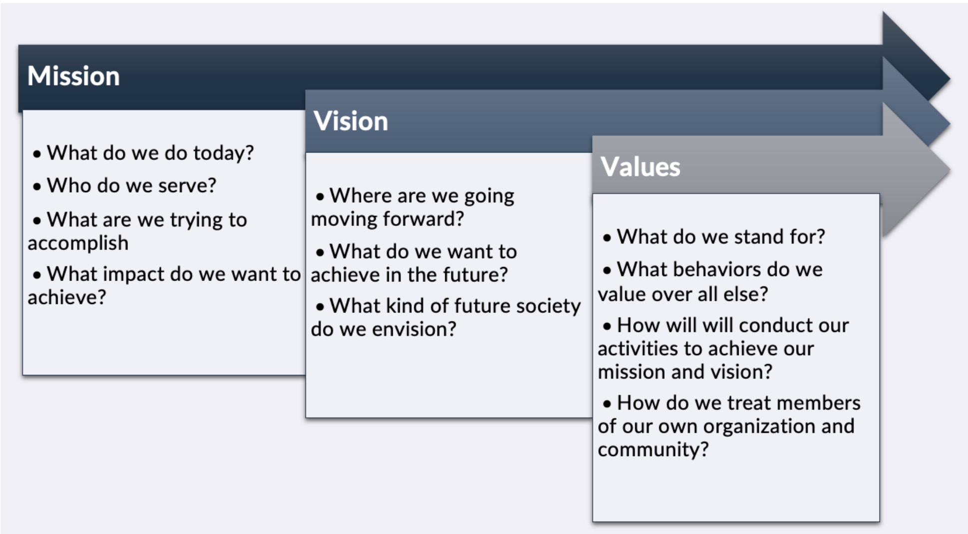


FIGURE 2.16: *Core commitments of an enterprise[74]*

The **mission** or **mission statement** of a firm defines the firm's purpose and should address its customers, products, competitiveness and target markets [74][29].

The **vision** of an organisation describes what the firm desires to become, i.e. the future of the firm [29]. It reveals the firm's aspirations, inspirations and motivation to achieve its future goals [74].

Finally, the **values** of a firm are the behavioural traits of that firm, it defines what the organisation stands for, how it interacts internally and externally and defines how they conduct its activities to achieve its mission and vision [74]. Figure 2.16 shows the relationship as described by bâton global [74], and which questions a firm should ask itself when designing its core commitments.

2.10.3 Enterprise engineering solution space

There are various life cycles which organisations can take into consideration when designing or redesigning a firm. The enterprise engineering solution space, from Stellenbosch University's Enterprise Engineering textbook [29], is the integration of three important life cycles that firms should consider when planning and administrating any changes. All changes take place in this space, depicted in figure 2.17, and all three life cycles impact and are impacted by these changes. Any enterprise design or redesign directly impacts the product design within a firm and the technological needs for the products and processes. Thus, any such design can be viewed from each life cycle perspective [29]. Naturally, as the design/redesign progresses, the perspective progresses, showing the interrelation between the product, enterprise and technology life cycle. Finally, the three resource architectures represent the **information technology** infrastructure, **human resource** usage and utilisation and the **physical assets** and all their dependencies.

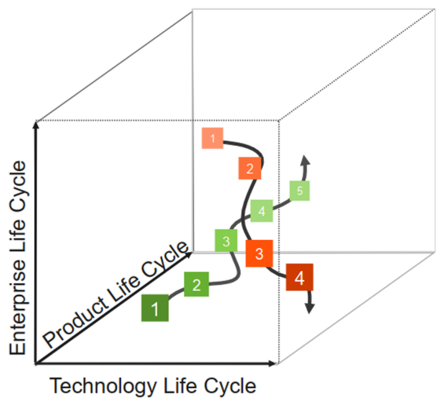


FIGURE 2.17: *Enterprise engineering solution space[29]*

Product life cycle

The product life cycle (PLC), shown in figure 2.18 is the mapping of a product's entire life cycle from its conception, throughout its design, to production, distribution, support, and eventual disposal [29].

Technology life cycle

Similar to a PLC, the technology life cycle provides us with a model of the life cycle of technology. The Gartner Hype Cycle, covered in section 2.13, is an example. A generic life cycle involves the early innovators, adopters and visionaries, early pragmatists, late conservative implements and the late sceptics.

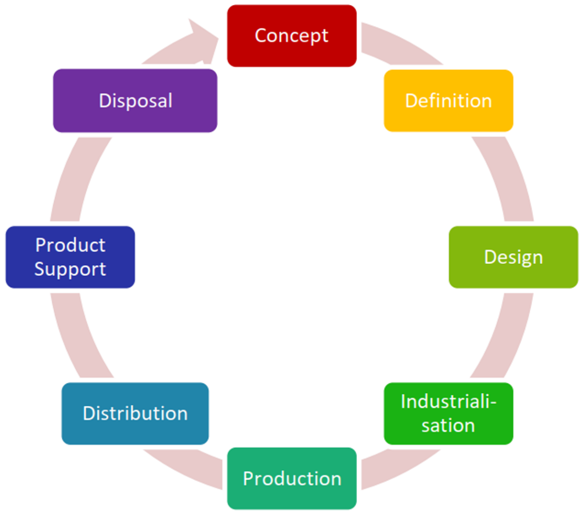


FIGURE 2.18: *Product life cycle[29]*

Enterprise life cycle

The Enterprise Life Cycle form the basis for the majority of Enterprise Reference Architecture and represents the entire life cycle of the enterprise, as shown in figure 2.19, typically including the identification of a need, the concept, the design, the implementation and operation of a firm to the eventual decommissioning of the firm.

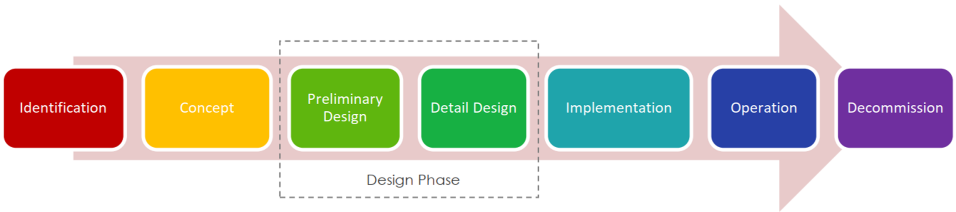


FIGURE 2.19: *Enterprise life cycle[29]*

2.10.4 Technology roadmapping

Technology roadmapping is navigation within the enterprise engineering solution space [29]. It involves strategic and long-term planning by using the interconnecting of the involved life cycles [29] [77]. The future-oriented roadmapping framework, developed by Phaal et al. [95], is an example of a technology roadmapping tool. Figure 2.20 shows the tool and the interaction between the various components of an enterprise. A roadmap generally represents time in a forward view, thus representing an integrated strategy with a holistic framework; by extending the timeline to the past, the emergence map concept in this tool can map the historical evolution of complex industrial systems [95].

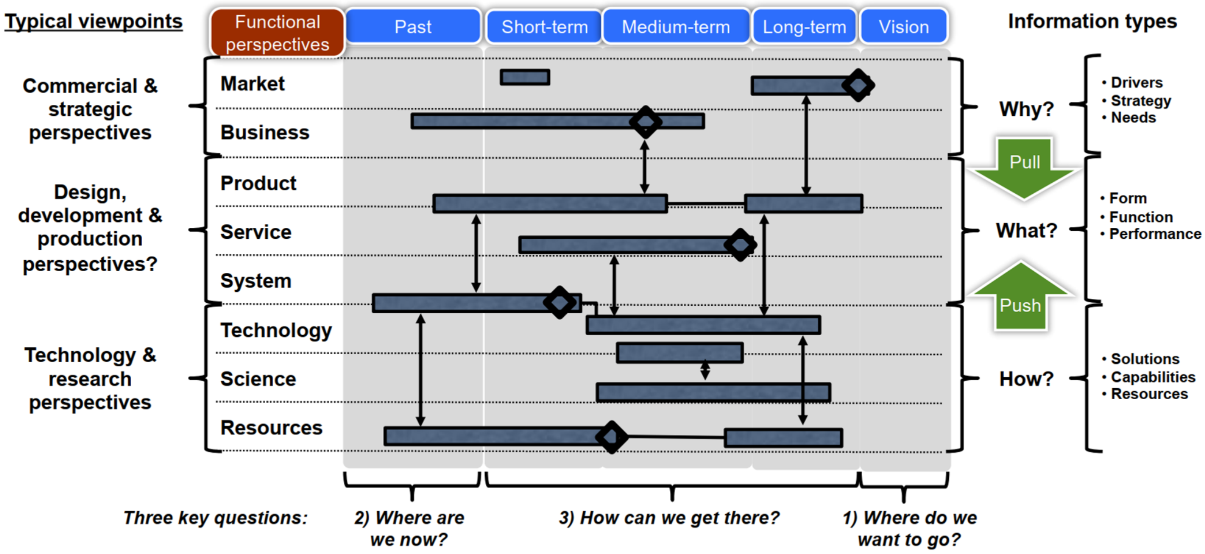


FIGURE 2.20: *Future-orientated roadmapping framework [95][29]*

2.11 Enterprise architecture

Like many other disciplines and numerous areas of research in this chapter, the concept of enterprise architecture evolves continuously [36]. Generally, an enterprise architecture (EA) refers to the practice of conducting enterprise analysis, design, planning and implementation of a holistic perspective for organisational strategy development and execution[36][134]. An EA provides an enterprise-wide view and applies principles and practices to guide organisations through organisational changes necessary to execute their strategies[134][29].

The goals of an EA are to guide an enterprise to understand its current operations, aid them in finding its desired future states, align the business with its information technology and facilitate organisational change.

Du Preez et al. [29] explains that there are two types of Enterprise Reference Architectures (ERA). **Type 1** ERAs deal with the design of a physical system, such as the manufacturing system part of an enterprise or the complete structure of the enterprise. **Type 2** ERAs deal with developing and implementing a project or program as an enterprise engineering program [29].

ERAs can be applied in numerous ways. The following are a few applications of ERAs according to Du Preez et al. [29]:

- A reference for planning the design or reducing of an enterprise/project.
- To find appropriate methods and tools to use during enterprise (re)design.
- As a repository structure for storing and managing project-related documentation.
- To develop a roadmap for a specific design or redesign, to guide users on what to do.
- For training purposes.

An enterprise reference architecture is a valuable tool for roadmap development as it can map out the organisation's current and potential future state.

2.11.1 Layers of enterprise architectures

There are various types of reference architectures with different levels of complexity. Due to the scope of this research, it would be desirable to limit the complexity of such a reference model in the case of a reference architecture development. Du Preez et al. [28] compares different ERAs in their textbook. Typically, these ERA dimensions use different life cycles, phases and layers to implement the design and redesign of an enterprise.

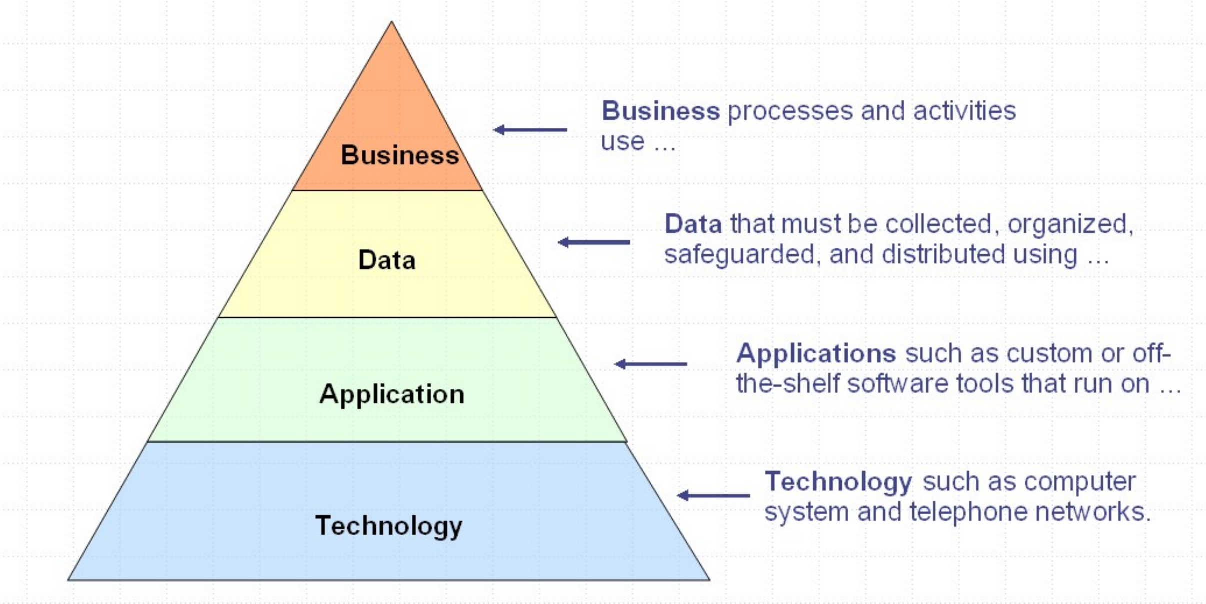


FIGURE 2.21: *USDA guidance on ERA layers [46]*

A simplified approach by the United States Department of Agriculture recommends the following four layers in an enterprise architecture, seen in figure 2.21 [46]:

1. **Business layer:** The top layer includes the processes and activities that an enterprise use to conduct its business, business strategy and organisational management.
2. **Data:** The second layer highlights the importance of data collection, organisation and making data-driven decisions towards enterprise design.
3. **Application:** This layer indicates the use of the data in a value-added manner, i.e. through commercial or custom software to approach everyday problems.
4. **Technology:** Finally, this layer comprises the technology used in the application, such as a computer or ICT systems.

Numerous enterprise reference architectures can be studied, adapted and implemented to use in this paper. A paper by Nakawaga et al. [78], where various Industry 4.0 reference architectures and the future of Industry 4.0 reference architectures are discussed, is briefly covered in section 2.12. Adaptive Inc's Enterprise Reference (AER) architecture, a reference architecture used in industry, is briefly discussed below.

2.11.2 Adaptive AER

As seen in figure 2.22, the AER represents the relationship and positioning of all enterprise domains that are required to run and subsequently transform firms [3]. It involves the modelling of a current state to understand the firms and subsequently perform an analysis of how the transformation would aid and affect decision-making [29].

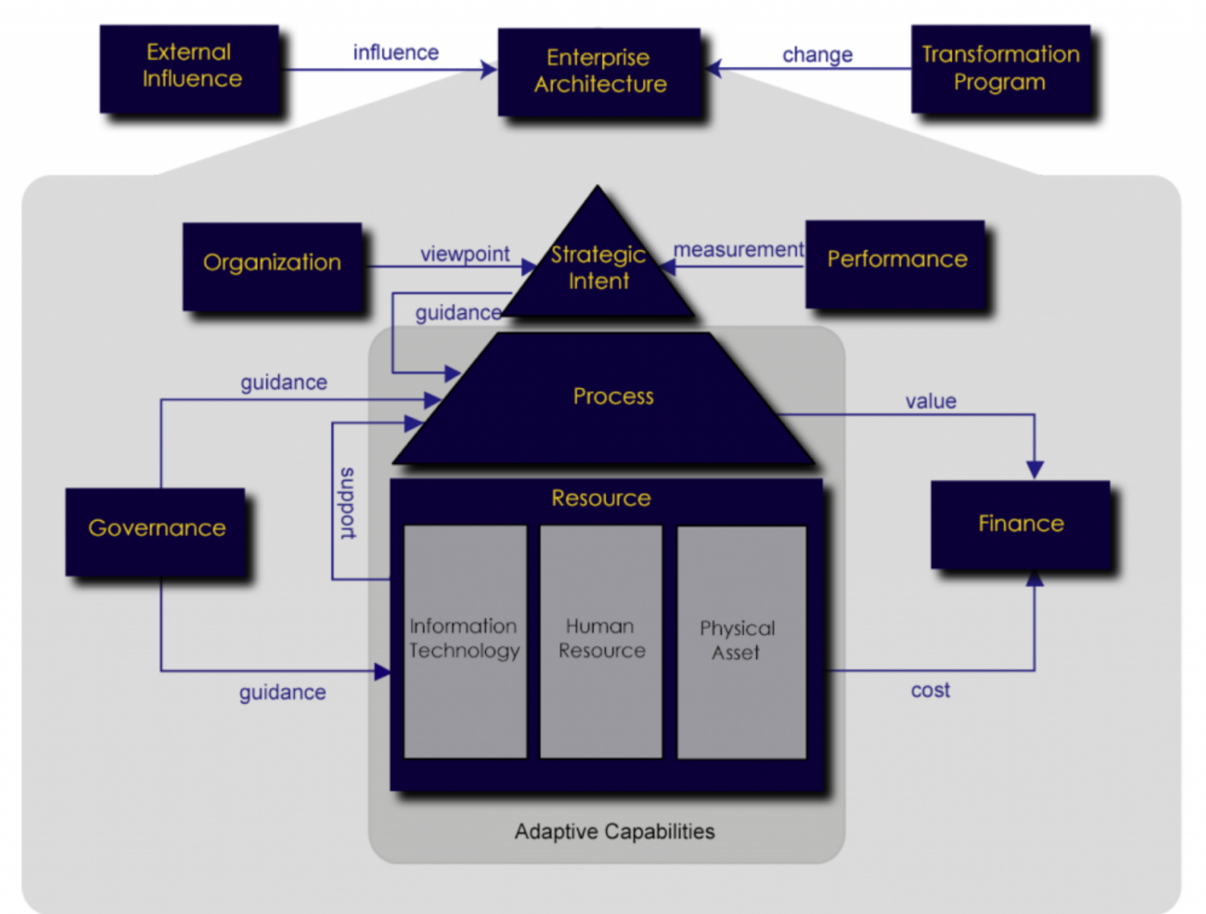


FIGURE 2.22: *Adaptive enterprise reference model [3]*

Adaptive Inc.'s model comprised 11 domains [3][29]. The External Influence Architecture is focused on the firm's context, analysing its environment and laying the foundation for its strategic intent. The Transformation Program Architecture revolves around all projects throughout the context of the enterprise's strategic intent (thus being relevant to any Digital Transformation operations). The Strategic Intent Architecture is the firm's reaction to external demand, providing the direction and targets for the firm. The Process Architecture covers all business processes, involving all inputs, outputs, management etc. The Organization Architecture represents the organisation structure, whilst the Governance Architecture aligns the operations with all types of governance, i.e. laws, policy, guidelines etc. The Performance Architecture and Financial Architecture represent the collection of all performance metrics and criteria and the financial framework for the enterprise, respectively.

2.12 Summary comparison of Industry 4.0 reference architecture levels

Various Industry 4.0 and Digital Transformation reference architectures exist, and a brief analysis of these architectures to develop the researcher's architecture could be beneficial to investigate the state-of-the-art approaches to such a development. Nakagawa et al. [79] mapped out various industry 4.0 reference architectures to the industrial automation pyramid, which contains five levels of automation, which they adapted to suit digitalisation. Each of the five levels listed and analysed below are different reference levels that can be used to map out an enterprise, and the relevant areas and solutions in its transformation journey, where six Industry 4.0 reference architectures have been appropriated to [79] :

1. **Enterprise level:** This level consists of the enterprise or business planning and resources of the firm, which entails the general business plan and operation. Solutions include enterprise IT, enterprise resource planning (ERP) systems and other business functional logic to support the business processes.
2. **Operation level:** This level includes the management, monitoring and optimisation of the operations of an environment. Solutions here consist of manufacturing execution systems and monitoring the entire manufacturing process.
3. **System/Process level:** The level controls field devices in a combined manner. This level includes data acquisition and control solutions.
4. **Control level:** The level controls single devices and assets at the field level.
5. **Field level:** The level includes the physical items in the environment, such as assets, machines and other physical entities. This could include components of Industry 4.0 that digitally support the environment.

Nakagawa adequately compares the six different architectures, and although each reference architecture is different, they equate appropriately to each level of the automation pyramid.

Essentially, each Industry 4.0 architecture has a similarity where they map each entity, area and relationship on levels similar to the automation pyramid, similar to the levels investigated in section 2.11.

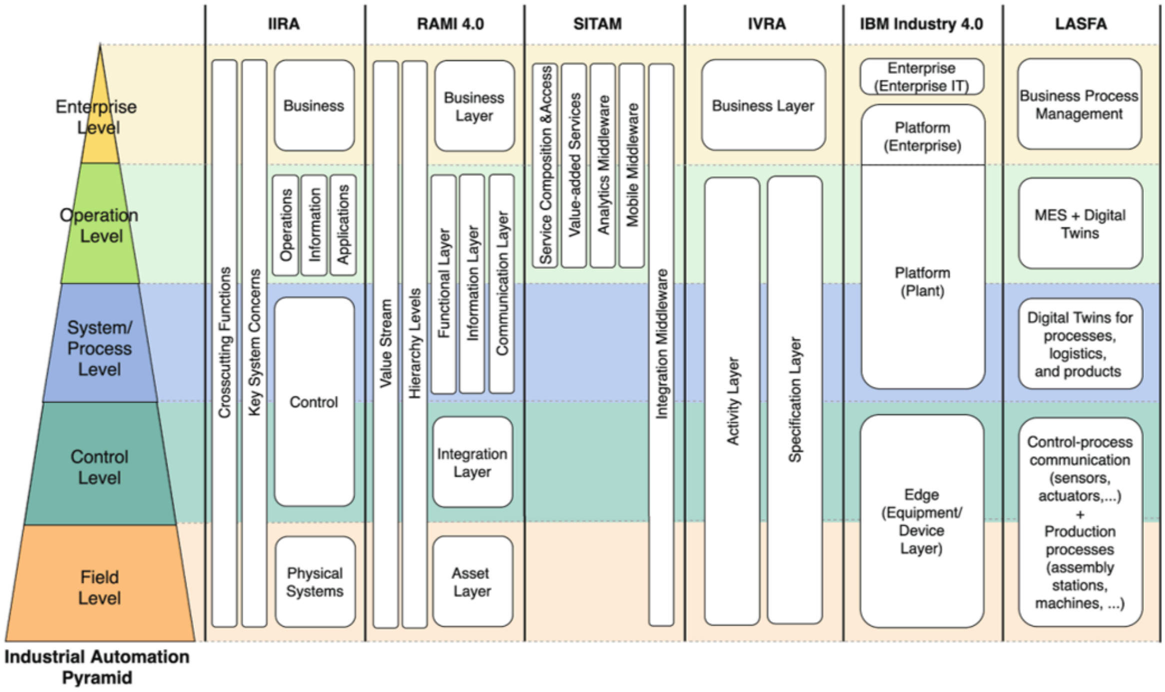


FIGURE 2.23: *Mapping of Industry 4.0 reference architectures to the industrial automation pyramid by Nakagawa et al. [79]*

Nakagawa et al. [79] also discuss the actual the use of Industry 4.0 reference architectures, pointing out that they are often insufficient for actual industrial use because they are not customisable enough and are rarely documented in actual use, only in literature.

From their research, Nakagawa et al. [79] find that more customised solutions are desired. However, reference architectures can drive the combination of software, physical technologies and the tools required for Industry 4.0 shop floors.

Finally, future architectures should detail precisely how communication and relationships occur among Industry 4.0 components. They conclude that reference architecture development should continue to increase maturity and sustainability to ultimately become a key element in the realisation of Industry 4.0

2.13 Hype cycle for emerging technologies

The Hype Cycle for Emerging Technologies, colloquially known as The Gartner hype cycle is a graphical representation of the adoption and maturity of specific technologies over time, developed by American technological research and consulting firm, Gartner [38]. The cycle was developed to aid firms in understanding the prevalence of emerging technology in the modern environment and is a valuable tool for organisations to aid in the development and employment of their Digital Transformation and Industry 4.0 adoption strategy, specifically toward the use of emerging technology within the strategy [38]. The firm releases a new cycle every year, and within the context of this thesis, the implementation progress and popularity of various emerging technologies can aid in developing an approach to DT. These cycles can be used to understand where various technologies are at a particular time and which technologies promise opportunities in the years to come.

Garter [38] recommends the use of their cycle to user organisations to be educated about technology use within their industry context. The cycle exists out of 5 key phases that emerging technologies cycle through [38]:

- **Innovation Trigger:** The breakaway point of the technology. This stage represents the start of the technology life cycle, involving proof of concept, media interest and other publicity. Usually, this stage offers no usable products, and there is a lack of viability within the industry.
- **Peak of Inflated Expectations:** Publicity of the technology produces success stories - alongside failures. Select firms proceed to take action.
- **Trough of Disillusionment:** Interest in the technology fall as implementations/experiments fail, bringing down producers of the technology along with it. Investment only continues in a select amount of successful producers.
- **Slope of Enlightenment:** An increased amount of successful implementations arise, bringing with it an increased usage of the technology and increased implementation and product or service development.
- **Plateau of Productivity:** Mainstream implementation. The technology is now widespread, clearly defined and used within the broader market.

The various phases can be seen in figures 2.24 and 2.25, where each phase is illustrated graphically.

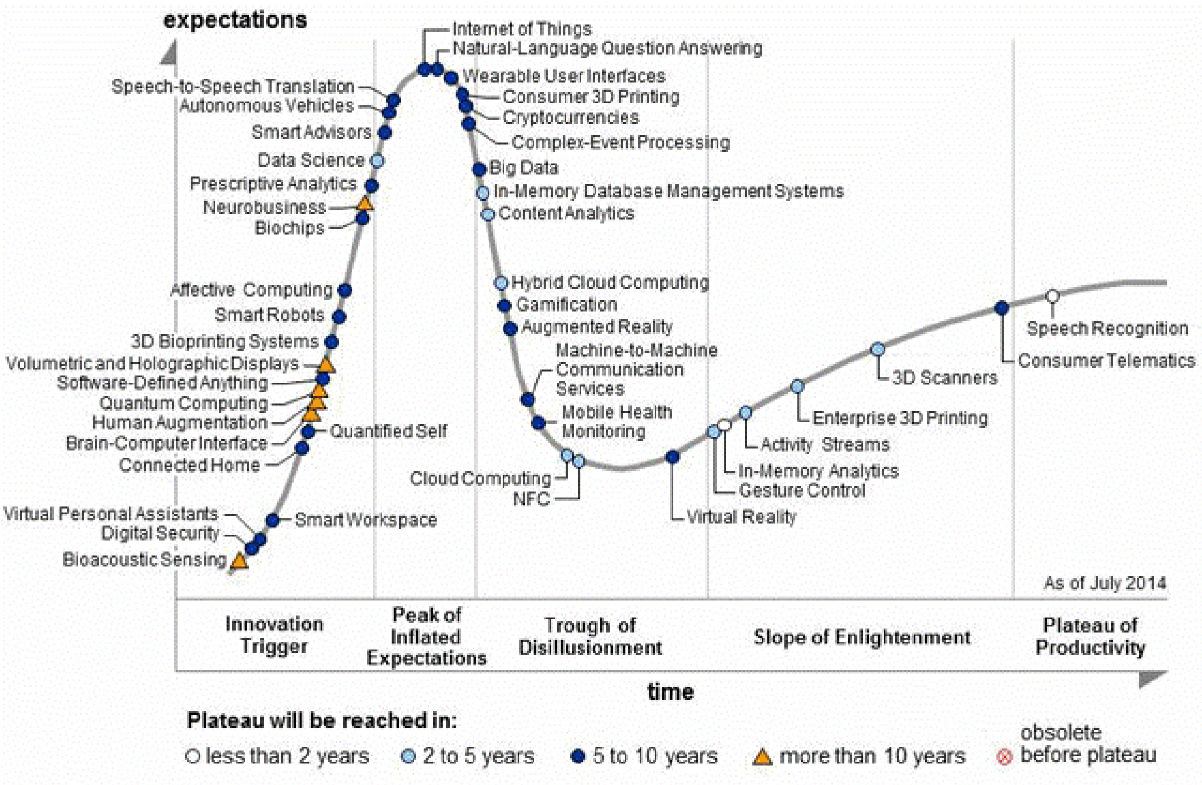


Figure 2.24: *Hype cycle for emerging technologies 2014 [38]*

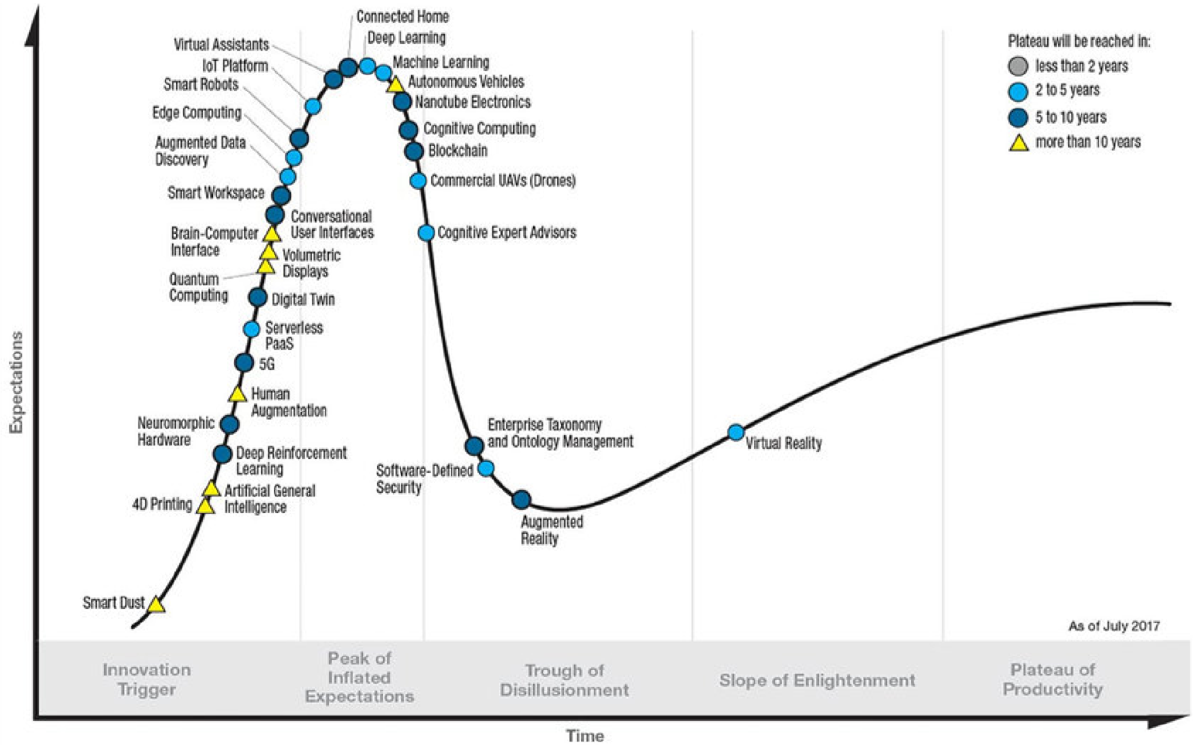


FIGURE 2.25: *Hype cycle for emerging technologies 2017 [139]*

To understand how the hype cycle can benefit firms, the researcher selected two hype cycles released by Gartner. The first, seen in figure 2.24, represents the hype cycle in 2014. A lot of Industry 4.0 technological components are at the cycle's peak, such as IoT and 3D printing, with others such as M2M technology and augmented reality steadily into the disillusionment trough and virtual reality starting to progress. Compared with the hype cycle of 2017, in figure 2.25, the technologies have progressed, with new emerging technologies receiving the hype and others starting to fall, whilst components such as virtual reality and augmented reality have moved through or are entering through the trough, as the technology starts to develop. Here, technology such as IoT, M2M etc., is more widespread these times, as described in the previous sections of this chapter.

In their technology report, Yang and Mejabi [139] of Wayne State University describe the current state of Industry 4.0 adoption in 2021. They find the widespread implementation of IoT use, where intelligent machines and cyber-physical systems are connected through wireless technology such as 5G, AI, Big Data and Augmented reality. The technology is now widespread and more affordable, and the implementation and use of these technologies are standard, in some instances even essential to everyday business operations [139], where in the past they were rarely available for use. Figure 2.26 shows the hype cycle as of 2021, where, based on Gartner [38] and Yang and Mejabi [139], it is safe to assume that all the technologies above and components of industry 4.0 have reached productivity plateaus and new emerging technologies - such as Nonfungable tokens (NFT), which are currently atop of the hype cycle.

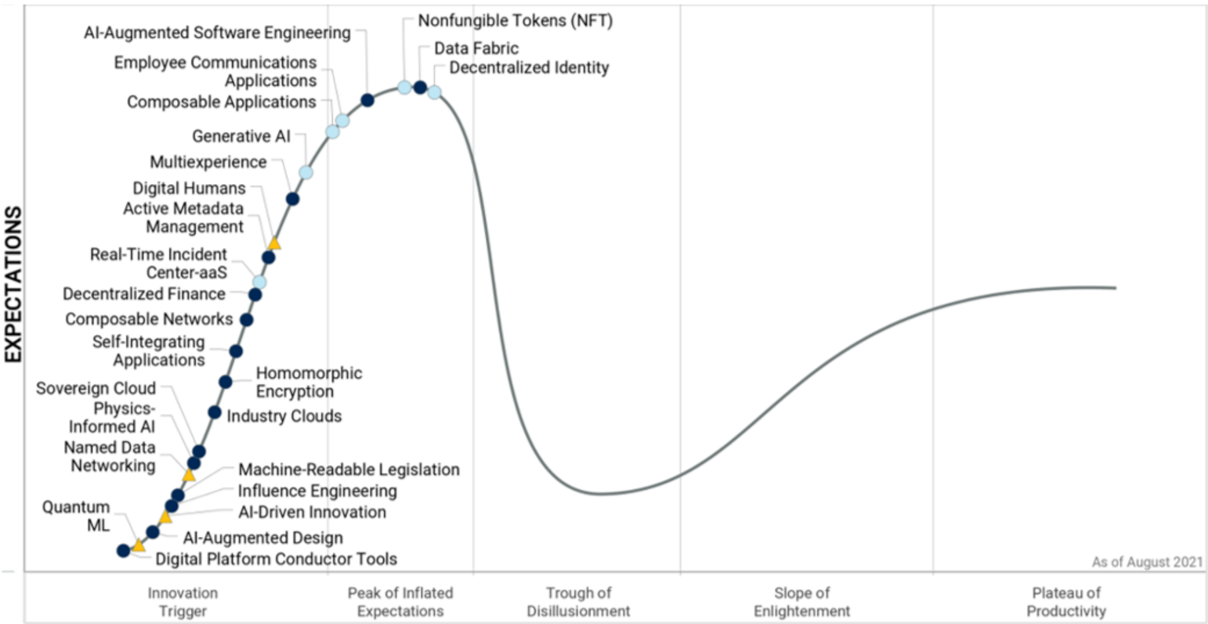


FIGURE 2.26: *Hype cycle for emerging technologies 2021 [38]*

2.14 Selection of a suitable model towards Digital Transformation within a labour-intensive environment

Several research design methods exist in the literature to aid in the quest for Digital Transformation. This section outlines the various methodologies, and a suitable methodology is selected.

Based on the description in table 2.4, the literature reviewed in this chapter, and the nature of a typical labour-intensive environment (the problem at hand), two implementation methodologies were identified as potential structures. Firstly, a framework is suitable as it effectively covers the requirements to implement a Digital Transformation - various broad-based and specific Digital Transformation frameworks have already been developed - proving that a framework is a suitable methodology to use.

Secondly, using a roadmap can be beneficial as it aids in giving organisations a vision of getting from where they are now to where they want to be [75]. Roadmaps can be a suitable approach to outline steps for an organisation to start the process of Digital Transformation. It is especially the case for firms that are not as technologically or digitally mature as competitors and surroundings firms, of which labour-intensive firms are a regularity.

The concepts of models and toolkits were eliminated due to the simplicity of both methodologies - they are not suitable to be the overarching implementation methodology of the thesis - both methodologies may be used within the scope of the thesis but not as the primary methodology.

TABLE 2.4: *Summary of methodologies investigated*

Methodology	Description
Model	• A model is an abstracted manner of classifying a process. [2] • Includes information input,-processor and output [2]
Framework	• Frameworks are a set of rules, ideas, or beliefs which you use to deal with problems or decide what to do [37]. • Frameworks act as foundations for all constructed knowledge for a research[119]. • They provide an underlying structure to support collective research efforts [119]
Roadmap	• High-level strategic overview of an organisations vision and direction [75] • Guiding document to align stakeholders, vision and goals of an organisation [75]
Toolkit	• Set of procedures, guidelines etc. to ensure the desired outcome or solve problems [40].

2.14.1 Roadmaps

Kostoff and Schaller [56] describe roadmaps as a layout of paths or routes in a particular geographical space. Roadmaps are used as high-level strategic overviews to aid organisations in industry, government and academia in their decision-making process. Roadmaps give direction by clearly defining where the organisation is, where it wants to be, and the plan to get there. The three fundamental questions of roadmaps can be seen in table 2.5

Various Digital Transformation roadmaps have already been developed; this section briefly looks at three roadmaps that have been developed to aid in the Digital Transformation of various environments. Considered briefly, the three roadmaps that are presented in table 2.6 are explicitly aimed at an environment. Two roadmaps are master's theses, completed at the University of Stellenbosch, and the third is an industry roadmap developed by the management consulting group McKinsey & Company.

TABLE 2.5: *Fundamental questions for an effective roadmap [77]*

Question	Description
Where are we going?	This represents the vision, mission, objectives, goals and targets that the roadmap would be achieving
Where are we now?	This represents the current state of technology development, products and market development
How can we get there?	This represents the policy measures, actions plans, research and development programs and strategies (both long- and short-term) that need to be implemented to achieve the vision, goals, objectives

The first of the three roadmaps, titled *A Roadmap to support SMEs in the SADC Region to Prepare for Digital Transformation* by Kretzschmar [57], is a roadmap specifically aimed toward Small and Medium-sized enterprises (SMEs) in the Southern African developing community. This area has limited industrialisation and is underdeveloped by today's standards. The research uses Digital Transformation principles to emphasise the quality of products, environment responsiveness and the importance of new technology adoption and optimising business processes [57]. Kretzschmar's roadmap aims to develop a Digital Transformation roadmap that aids SME management surrounding the most important factors that need to be considered in a Digital Transformation approach. They provide a structured approach that incorporates various tools and techniques that can be broken down into manageable tasks for SMEs to start Digital Transformation. Their roadmap provides 12 steps for SME leadership to develop a Digital Transformation plan. The roadmap was developed as part of a double degree programme by Stellenbosch University and ESB Reutlingen, which is the same programme as this thesis.

The second thesis that was investigated, *Development of a Digital Transformation Roadmap (DTR) for the upstream oil and gas industry,* by Botha [15] is also aimed at a specific environment, and serves as a solution to Digital Transformation in upstream gas and oil industries. This roadmap, developed as a continuous process for the constantly evolving and adapting conditions in the industry, created a detailed plan for such industries to digitally transform in an area where companies need to be more prepared and guided on how to implement such transformation [15].

TABLE 2.6: *Comparison of Digital Transformation roadmaps investigated.*

Title:	**SMEs in SADC**	**DT for oil and gas industry**	**A roadmap for digital transformation**
Author:	Marion Kretzschmar	D.J. Botha	Tanguy Catlin, Johannes- Tobias Lorenz, Bob Sternfels, Paul Willmott
Institution	University of Stellenbosch, ESB Reutlingen	University of Stellenbosch	McKinsey & Company
Aim	Roadmap to develop a Digital Transformation plan of Small and Medium-sized enterprises	Digital Transformation roadmap for oil/gas companies to guide in the process of digital transformation	Digital Transformation for an insurance company to harness the power of Digital Transformation
Steps	12 steps incl. Analyse - Establish Goals - Propose - Create DT Project Plan	Future vision - Current state Challenges - Strategy Execution -Evolve	Define value - Launch and acceleration - Scale up

Finally, a corporate Digital Transformation roadmap was investigated from a management consulting perspective, i.e. a corporate perspective that is actively used by a consulting firm to aid their customers. Mckinsey & Company [22] use this roadmap to guide insurance companies to harness the power of digital technology to re-evaluate all aspects of an organisation. There are three primary stages, with ten guiding principles for Digital Transformation. The first stage, defining value, involves three steps: secure senior management commitment, set clear targets, and secure investments. In this phase, Mckinsey & Company emphasise the need for organisations to understand the endeavour they intend to undertake.

The second phase is named the launch and acceleration phase. They describe that it is easy to launch initiatives but often challenging to keep them afloat. They emphasise the need for companies to consider projects and the necessary support carefully. This phase involves four steps. Firstly, start with lighthouse projects - projects with significant rewards with manageable risks, then appoint a high-calibre team, organise the promotion of new, agile ways of working and then nurture a digital culture[22]. The final phase, scaling up, involves three steps sequencing initiatives with quick returns, building capabilities and then adopting new operating models.

Based on the brief overview of the three roadmaps, a roadmap could be a suitable model to start the process of Digital Transformation for labour-intensive firms. All three roadmaps set clear and value-adding steps for their respective markets, and involve gradual implementation.

2.14.2 Frameworks

As outlined in table 2.4, a framework is a set of rules, ideas or beliefs used to deal with problems or decisions [37]. Frameworks provide an acceptable way to address the implementation of Digital Transformation by gaining conceptual and theoretical knowledge to aid organisations in making decisions. There are three types of frameworks which were investigated by the researcher as possible methodologies to address the problem statement:

- **Theoretical framework:** Framework consisting of an overarching structure of ideas combined with larger assumptions, used to analyse text or a phenomenon in a theoretical manner [141]
- **Conceptual framework:** Framework that includes the combination of ideas and research to define research and evaluate data [141]
- **Decision-making framework:** a framework that facilitates and enhances decision-making by providing conceptual structures, concepts and principles to integrate all dimensions (economic, social, ecological, legal etc.) of decisions [80]

Three existing Digital Transformation frameworks were examined to investigate the use of a framework to address this thesis's problem statement and objectives. Similar to the previous section, two master's theses from the University of Stellenbosch and a categorical framework for Industry 4.0 in manufacturing were used.

The first thesis that was examined, titled *The development of a conceptual framework for enabling a value-adding Digital Transformation*, Rautenbach [103], is a conceptual framework that uses conceptual knowledge of Industry 4.0 and Digital Transformation, and relevant concepts. The thesis conducts a systematic review to review relevant models and frameworks comprehensively. The framework development uses capability maturity models to find value-adding methods of Digital Transformation. This framework is a more theoretical approach to Digital Transformation and involves two phases. Phase 1 provides user organisations with concepts that require consideration through the process, with five sub-phases: industry disruption, customer needs identification, customer value design, digital capability assessment and challenges assessment [103]. Phase 2, which comprises the sub-phase: assessment report, value equation, and challenges index, aims to integrate the outcomes of phase 1. The research aims to aid user organisations in decision-making and education in Industry 4.0 [103].

Secondly, Du Plesis [28], created a framework titled, *A framework for implementing Industrie 4.0 in learning factories*. This approach also investigates concepts of Industry 4.0 to aid SMEs and learning factories in their implementation. The framework was developed to be used in three ways[28]. Firstly for new learning factories, secondly for enhancing traditional operations in SMEs or showcasing Industrie 4.0 in learning factories. Finally, the framework can be used for redesigning learning factories or SMEs to a more Industry 4.0-centric approach [28]. The

Table 2.7: *Comparison of Industry 4.0 and Digital Transformation frameworks investigated.*

Title:	**Value-adding digital transformation**	**Indsutrie 4.0 in learning factories**	**Categorical framework of manufacturing for Industry 4.0 and beyond**
Author:	Willem Johannes Rautenbach	Carl Jan du Plessis	Jian Qin, Ying Liu & Roger Grosvenor
Institution	University of Stellenbosch	University of Stellenbosch	Cardiff University
Aim	To aid user organisations in decision making and education in Industry 4.0.	Industrie 4.0 implementation of learning factories and SMEs.	The improvement of Industry 4.0 in production systems, and present the common opinions of Industry 4.0 and manufacturing.
Approach	Phase 1 - industry disruption, customer needs identification, customer value design, digital capability assessment, challenges assessment. Phase 2 - assessment report, value equation, challenges index.	6 Layers: Technology/Software Objects, system nodes, methods, Industrie 4.0 application and competencies.	Categorical approach using two levels - automation and intelligence, broken down into the control, integration and intelligence of machines, processes and factory in different levels of complexity and intelligence.

framework has six layers: technologies and software, objects, system nodes, methods, Industrie 4.0 applications and competencies. This framework is also potentially a suitable practical approach to Industry 4.0, as it uses technology implementation in learning factories.

Finally, returning to Qing et al.'s [99] *A Categorical Framework of Manufacturing for Industry 4.0 and Beyond*, where they used different levels of technologies and automation. The two levels are broken down into other levels ranked in complicity and intelligence, including the control, integration and intelligence of machines, processes and the factory, with Industry 4.0 readiness as the final goal. The framework also emphasises the data collection from sensors, machines and production lines to emphasise the decisions making and further steps in the subsequent layers.

2.14.3 Methodology selection

Based on tables 2.7 and 2.6, the conclusions were drawn that a roadmap approach would be most effective in addressing the requirements set out in Chapter 1, as a list of instructions could aid in the Digital Transformation process. The frameworks in table 2.7, although effective, are a broader approach to Digital Transformation or Industry 4.0 implementation, whereas the roadmaps in table 2.6 are more specific, covering topics such as SME Digital Transformation, insurance firm Digital Transformation and oil and gas industry Digital Transformation.

2.15 Conclusion

Chapter 1 established the need for Digital Transformation for labour-intensive environments to prioritise the adoption and implementation of technology alongside a human workforce. This chapter defined and contextualised various concepts relevant to Digital Transformation, including Digital Transformation, Industry 4.0, and Industry 5.0 and all their components and sub-components.

The drivers and principles of Digital Transformation and Industry 4.0 were discussed alongside the various technologies that could aid organisations' Digital Transformation.

After that, the literature surrounding labour and the typical challenges of labour-intensive environments were investigated. Several previous approaches were discussed, and the need for further research in the Digital Transformation of labour-intensive environments was highlighted.

The literature review also included a summary of Elkington's [32] triple bottom line approach before contextualising the relatively novel concept of Industry 5.0 and key supporting technologies of Industry 5.0 were defined and researched.

The use of enterprise engineering literature, Gartner's Hype Cycle and reference architectures were also briefly discussed before finishing the chapter with the model selection. It was concluded that a roadmap approach is a suitable tool to address the problem statement, meet the objectives and attend to the research gap in the given limitations.

The following chapter investigates various environments to understand the typical labour-intensive environment to find common areas, processes and resources, and relationships in these environments.

CHAPTER 3

Investigating different forms of labour-intensive value-creation

This chapter examines the five primary types of manufacturing systems to better understand the precise amount of labour required in various manufacturing systems. The environments that depend the most on labour are then examined in two observational case studies. The case studies are done to acquire a deeper understanding of a developing context, like South Africa, where the full effects of the Digital Transformation of the labour market have yet to be seen. After that, the various general areas, challenges and cause-and-effect relationships of labour-intensive value-creation are explored. Here value-creation refers to the product or service delivery in such an environment.

3.1 Different types of manufacturing systems

Standard manufacturing systems are examined in this section to group them according to the amount of labour they demand. All forms of value-creation can contain labour, although certain settings depend more heavily on it to produce their goods or services. Environments ranging from single and continuous flow production to high-mix, low-volume production are investigated and ranked according to labour.

Gradually, with the progression of modern industry, various manufacturing systems have been developed, driven both externally and internally. Production systems can be catered to suit various needs, such as the assembly of standardised parts to standalone custom systems. Generally, there are five broadly defined types of manufacturing systems, classified in terms of volume and flexibility [51][81][42].

- **Project manufacturing**: Creating unique products, usually at the project location, with no flow. The system is highly flexible, with high labour and variable costs at a low volume. One of the case studies investigated later in this chapter uses project-based manufacturing in one of their assembly areas.
- **Job shop:** A flexible operation with several activities that produce a wide variety of products. Usually highly flexible, with high levels of labour.
- **Batch process:** The sequence of activities are usually in a line and less flexible, where products are produced in batches to fill specific orders. Depending on the facility, these systems are usually moderately flexible, with several products and moderate labour requirements.

TABLE 3.1: *Comparison of process structures and characteristics, adapted from NetMBA [81], supported by literature from Jacobs FR & Chase RB [51]*

	Project	Job Shop	Batch	Assembly	Continuous Flow
Flow	None →				Continuous
Flexibility	High →				Low
Mix of Products	High →				Low
Variable Cost	High →				Low
Labor Content	High →				Low
Labor Skill	High →				Low
Volume	Low →				High

- **Assembly line process:** Fixed sequence production where an assembly line connects activities and paces them. These facilities are often not very flexible, with few products and low reliance on labour.
- **Continuous flow process:** Fixed pace and fixed sequence production, where products are produced in a continuous flow, with very low levels of labour.

The first three in the range of the five production systems above are quite dependent on labour, with their product delivery being more geared toward a high-mix and low-volume form of output.

Job-shop manufacturing (and, briefly, project-based manufacturing) are investigated in further detail in two observational case studies in sections 3.6 and 3.7. These studies analyse labour-intensive environments in practice and learn more about a developing context, such as South Africa, where the full consequences of Digital Transformation have not yet been realised. Before using case studies to obtain further understanding, supporting literature on each of the five production systems is reviewed.

3.2 Supporting literature: Workings of a project-based manufacturing system

Most production in project-based manufacturing systems is centred around the product, which (usually) stays in a fixed place. [51]. Project-based environments are of a high-mix and low-volume nature, where the types of products differ often, but the output volume is very low, often with just a singular output [81]. These environments are heavily labour-dependant and often use a skilled workforce, where a set of skills are needed to finish the tasks and where tasks are often very specific [51][42].

Project-based systems often make use of project management principles and techniques. Jacobs FR & Chase RB [51] define a project as a series of related tasks or jobs directed towards a major output that requires a significant period to perform. Project management is defined as the planning and controlling of resources, such as people, equipment and materials, to meet the required output of a project.

Examples of such environments include specialised tailor-made manufacturing solutions, such as in the case study in section 3.7, construction sites, metal fabrication, aerospace engineering and construction environments.

3.2.1 Labour-intensive construction to illustrate project-based value-creation

In their book, *Productivity in Construction* Dozzi and AbouRizk [26] outline a framework to understand the productivity improvement of a construction project. The framework, seen in figure 3.1, consists of different elements such as materials, management and equipment, with the output being project-based production. An in-depth explanation of the construction framework is not covered due to the constraints of this study. Still, it was briefly studied to illustrate a project-based value-creation environment. Dozzi and AbouRizk [26] break construction projects into three primary categories: labour effectiveness, management principles and material timeliness.

Similarities in their framework and illustrations of other production systems, such as the two case studies in this chapter, are apparent. Examples are labour management, data collection, scheduling, layout and material handling. These similarities demonstrate that all labour-dependent systems have a consistent pattern and use similar components in their value-creation.

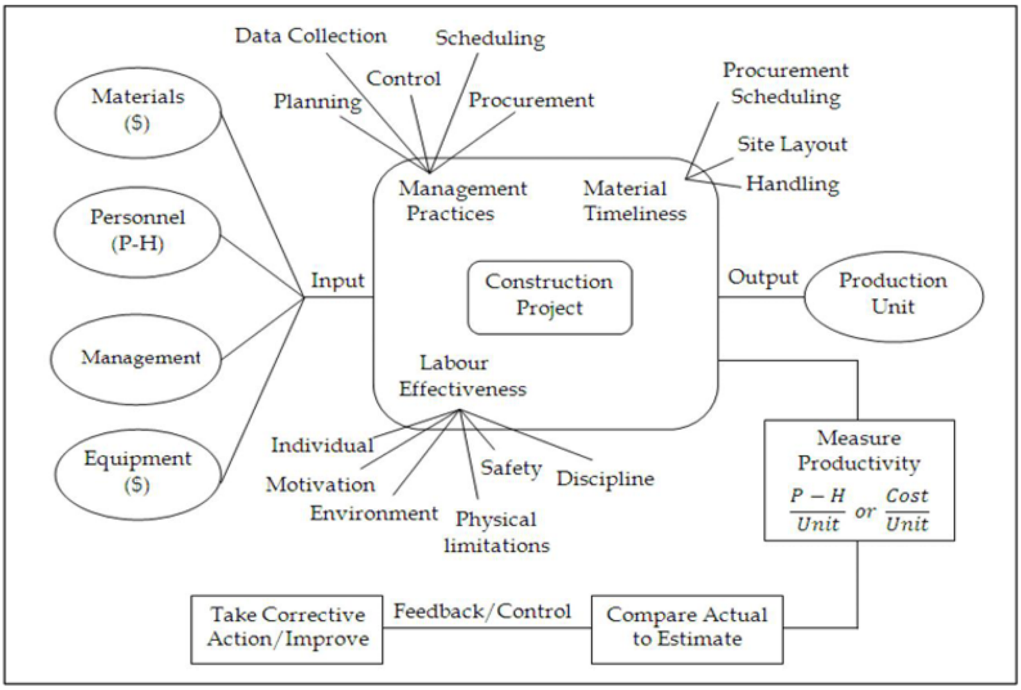


FIGURE 3.1: *Framework for productivity improvement [110][26]*

3.2.2 Challenges facing the project-based manufacturing

Due to the labour-intensive nature of these environments, supply chain management, skill management, rising costs, and changeable client needs are some of the industry's most significant difficulties [24][45][94].

Labour-insensitivity, shortages and training

Acquiring and retaining skilled labour positions, especially skilled employee's experience with precise tolerance training and modern certifications, such as AWS, are an increasing challenge that metal fabricators face [94][45]. Furthermore, digital implementations, although of increasing importance and utilisation, are not always effective in fabricating ultra-precise tolerances and complex parts and welds, emphasising the reliance on labour [94].

To address labour shortage and training, fabricators are emphasising the use of in-house training, improving workplace culture and providing attractive benefits [94][45]

The value-creation of these environments, including labour-intensive manufacturing, again supports the idea of adding methods of digital support to aid labourers in their task fulfilment. The use of cyber-physical systems, machine-2-machine communication and methods of digital guidance and quality control are all potential supportive measures.

Increasing customer demands, flexibility and customisation

Demands of modern manufacturing are gradually shifting the industry's focus to the customer's voice and demands. Customers in the 21st century have an increased desire for custom, and tailor-made solutions [24][48]. Furthermore, customers want their products quicker, more affordable and with real-time information, [24].

Increased cost and supply chain management

Due to the resource costs in the industry, the fabrication industry is directly and increasingly influenced by tariffs and trade wars on the global scale [94][24]. The Covid-19 pandemic still has lingering effects on acquiring steel and other raw materials. The majority of fabrication companies in 2022 report that leads times are increased when compared to pre-pandemic levels [94].

3.3 Supporting literature: Workings of a job-shop facility

A job shop is a type of manufacturing system that can handle modest orders for make-to-order items [51][125]. Small fabrication orders, goods with custom designs, and repair work are typical value-creation processes in these environments [125]. Before a work order is finished, products go through various processes. Repair shops are an example of a job shop environment and are covered in greater detail in section 3.3.1 and the case study in section 3.6.

3.3.1 Household appliance re-manufacturing process

The re-manufacturing process of household appliances is investigated to explore typical job-shop environments further. In their 2001 article, *An Economical and Technical Analysis of a Household Appliance Re-manufacturing Process*, Sunden [120] conducts an economical and technical analysis of a household appliance facility in Motala, Sweden. At the time of the investigation by Sunden, the facility repaired microwave ovens, washing machines, stoves and fridges. Although Sunden's analysis suggests improvements in the technical and economic regard, the purpose of this study within the context of this research is merely to support the clarification of a repair facility due to the job-shop system used. The re-manufacturing process of the household appliance facility can be seen in figure B.1.

A product that cannot be repaired on-site is delivered to the Motala facility by truck. Once on site, the products are unwrapped and registered in the computer system. After registration, whether an item is to be repaired or used for spares is decided. Parts selected for re-manufacturing undergo a testing procedure to determine the damage. After testing, these parts are either sent to repair or to spare part storage. Different errors cause different repair times, and spares are either taken from the spare part storage or ordered by the Motala facility - leading to the possibility of longer lead times if products are kept waiting for their spares. After the repair, they are cleaned, wrapped and placed in storage, ready to be delivered to retailers [120].

As this is also a repair facility, the process involves using maintenance specialists that are experts within their re-manufacturing environment, making it an environment that is highly dependent on labour.

3.3.2 Challenges in a job shop environment

Process variety, skill management and machine downtime are a few challenges faced in a job-shop type environment [125][51]. In general, job shop environments are more challenging to manage, as they are categorised as high-mix, low-volume production environments [125].

Variability

Each job can have different routing and process time requirements in these environments. Even if jobs are similar, the assigned artisan's labour can differ from work order to work order. As machines break down and other unforeseeable instances arise, the routing, requirements and process can often change, thus also creating changing bottlenecks over time [125].

Additionally, some equipment have sequence-dependant setup times, and jobs can sometimes last days, thus using different workers in different shifts [125].

Skill management and labour-dependency

Workers in these situations typically possess a variety of skills due to the high degree of variation, and it takes time, and money to ensure that they continue to gain knowledge and experience [30][125]. Additionally, some work orders cannot be fulfilled when workers are not present since they require the expertise of both labourers and machine operators.

Additionally, the environment's efficiency is often directly linked to the relationship between employees and management, where morale and motivation in the business impact the service delivery [30]. Due to the increased reliance on labour in these contexts, there are more labour-related challenges than in continuous or batch manufacturing.

Long lead times

Another challenge is the time required to complete jobs. Lead times are often long, and depending on the work order, uncertain materials, external vendor's operations, and changes in customer demands in existing orders or some factors which contribute to time management issues in these environments [125].

3.4 Supporting literature: Workings of a batch manufacturing system

An overview of batch manufacturing systems is provided below. In a batch manufacturing system, products are moved in groups or batches, and each production process is applied simultaneously to the entire batch [93][43].

In certain manufacturing systems, batch production is the only realistic option. Examples include the production of perishables, such as in a sandwich shop and a clothing line where various garments are produced, and the line is changed depending on the garment going through the production line [43][93].

Typically, batch production is very flexible, where items go through each production stage simultaneously, and quality checks can typically be carried out between batches [51][43]. These systems are common in small and medium-sized enterprises (SMEs), where reasonable inventory volumes are maintained, and downtime between batches is frequently possible. Additionally, batch manufacturing enables the reduction of expenses like machining (due to downtime) and wastes (since there is typically greater space for error), and the systems are typically more responsive and flexible to a change in demand [93].

Smaller batch systems, or such systems in developing countries, often rely on labour to move items between production stages and in the actual production of products [43]. Challenges facing batch production systems include downtime, underproduction and waiting wastes [93]. Furthermore, batch production can be expensive with higher storage costs and the lack of specialisation and customisation towards a specific customer demand [93][43].

In their article, *Process flow improvement proposal of a batch manufacturing system using arena simulation modelling*, Rahman and Sabuj [100], collect and analyse data to build an accurate model of a UPS manufacturing line. Their existing model analysis, shown in figure 3.2, describes the process flow of a typical uninterruptible power supply (UPS) device manufacturing line. Parts are processed in batches and subjected to various operations and assembly, including cleaning, painting, assembling, testing, and inspection. Similar to a job shop, these processes require a worker to carry out tasks. They include similar areas where other production processes are done, such as PCB board making, sheet metal fabrication and transformer production.

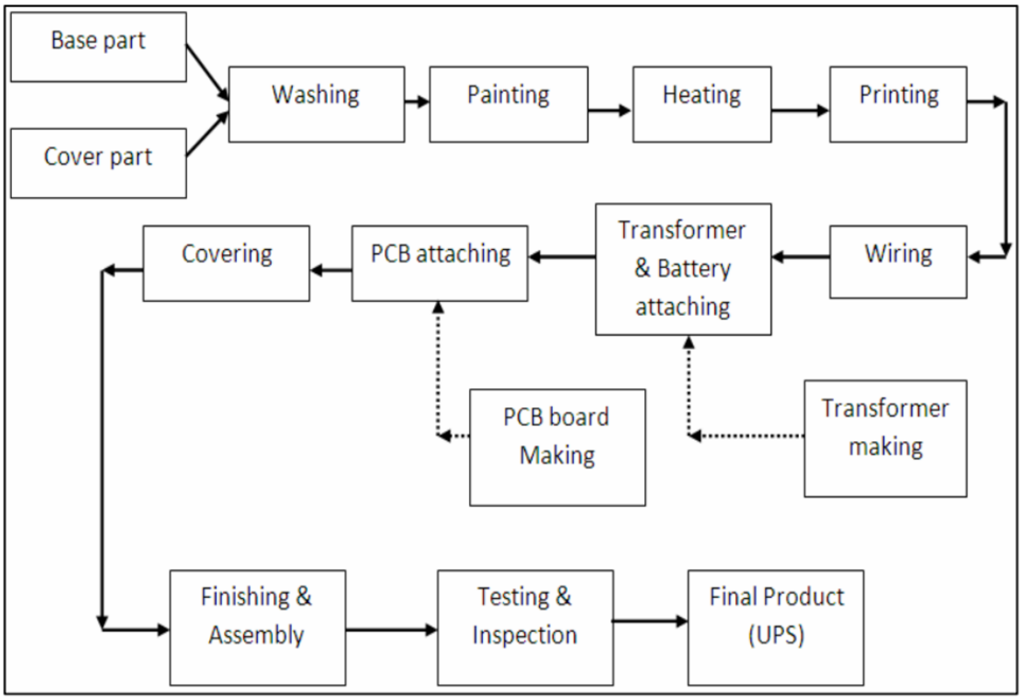


FIGURE 3.2: *Flow chart of existing UPS manufacturing system used in Rahman and Sabuj [100].*

The use of simulation in Rahman and Sabuj [100] demonstrates the potential for digital support in batch productions. The reliance on labour in these products can rationally open up the challenges and solutions illustrated by Mckinsey & Company [41] in section 2.7.2, such as the needs for data collection, transparency, and other cooperative methods.

3.5 Supporting literature: Workings of an assembly line and continuous flow manufacturing system

The previously examined manufacturing systems involved environments with various products and outputs of moderate to low volumes. In this section, production systems that are designed to produce the same type of product in large quantities are briefly examined.

Generally, a continuous flow environment is used in more developed environments, such as those that are more technologically advanced and have a lower reliance on a labour workforce [90][81]. Continuous-flow manufacturing is regarded as the pinnacle of standard production. Generally, it consists of strict line production, with a high volume of products and a low combination of product types. [90][51]. However, the low dependence on labour is not always the case, as a continuous assembly with a labour workforce does occur, especially in developing nations [90]. With the advent of Ford's assembly line, the automobile manufacturer employed more than 40 000 workers in one facility [84] and was aimed at simplifying the production process, primarily consisting of a labour workforce, by implementing standardised processes and an assembly flow process.

In the 21st century, however, continuous and assembly line production environments are increasingly digital, and Industry 4.0, where cyber-physical systems, IIoT and other I4.0 components are aiding in or have even entirely taken over production [17][89]. In their conference paper, Pacheco et al. [90] explore continuous flow in a labour-intensive environment, the type of environment they describe as a "low-tech" industry, where the demand for labour is of increased importance.

An assembly line, utilising machines that are not complex and of a labour-intensive production process, is investigated by Pacheco et al. [90]. The assembly line is of an international curtain manufacturer in Lima, Peru. Briefly, the assembly line, before their proposal, consisted of 39 processes, where 820,2 seconds were required to finish a single product. Pacheco et al. [90] use a methodology to standardise and optimise the process flow of the environments. They implement basic lean and standardisation principles, such as cycle time, work scheduling design and takt time and redesign the production line into an assembly line consisting of 4 workstations, where each workstation continues on assembly of the previous to produce the curtains. Finally, they conclude that due to the little reliance on complex machinery and the labour-intensive environment, the redesign of production towards a more continuous flow can be inexpensive as most value-creation is due to manual assembly.

The rationale behind the inclusion of Pacheco et al. [90] is twofold, first to describe a typical continuous assembly line environment and second to investigate the standardisation and use of basic lean and other manufacturing principles to standardise a production process before implementing methods of digital support. Generally, it is recommended that for digitisation and eventual Digital Transformation to be effective, standardisation must come first [98][83]. Furthermore, the potential of digital support to aid in these standardisation processes, such as time and motion studies and work sampling, could be used as a new approach to standardisation and process design.

3.6 Case Study 1: Observational study at inner-city bus service unit repair shop in Epping, South Africa

From section 3.1, it is evident that labour-intensive manufacturing or value-creation systems frequently produce many goods at low production levels. Due to this, observational case studies were carried out at partner institutions using low-volume, high-mix value-creation environments. Job-shop environments are practical examples of these environments.

A practical example of a job-shop setup is a repair facility, as mentioned in section 3.3. These environments usually have long cycle times and variations in their labour, and they rely heavily on labour to diagnose and fix various products.

The researcher conducted the first case study to understand the distinctive value generation in this type of labour-intensive industrial scenario. In particular, an observational case study was carried out to analyse how such an environment practically functions and entails looking into how labour in the environment and the workflow relate to one another. Additionally, both the current aim of the organisation towards Digital Transformation and the general reception and use thereof was investigated in the case study.

The case study was conducted at a research partner in Cape Town, South Africa. The primary focus of the study's investigation was the electrical and transmission departments of the facility's unit repair shop, primarily a hand labour repair facility. This unit repair shop is the section of the facility that diagnoses and refurbishes units that must be removed from a bus, including gearboxes, engines and smaller transmission or electrical compartments.

3.6.1 Case study 1: Description

The case study included observational time on different works-orders and informal discussions with employees and management to understand the environment within the repair facility.

Most of the time was spent studying two departments: the electrical department, which is in charge of the buses' electrical components, including lights, looms, and starters, and the transmission department, which is in charge of the buses' gearbox and general transmission. The researcher investigated the labour-intensive process of units of various sizes in these departments, which repair units of all sizes, from larger items such as gearboxes to smaller items like indicator systems. This wide range of processes provided a wide variety of processes to analyse and visualise a general labour-intensive process.

All repairs are done by hand, requiring trained artisans and technicians to strip (disassemble), clean, re-assemble, and test the units before delivering them to a store that houses finished or repaired units. Besides the labour-intensive component, the environment also involves using supportive processes, such as machining, cutting, and drilling from other departments, to complete a work order. Furthermore, during the study, the researcher was able to observe the current digital landscape of the environment and get valuable input from artisans regarding challenges in the workshop.

All work orders in the facility follow the same work process flow, shown in figure 3.3 and outlined in section 3.6.2.

3.6.2 Case study 1: Activities and process flow

All unit repair departments of the facility use four different types of employees. Firstly, qualified diesel mechanics or electricians (both referred to as artisans) with predominantly highly skilled hand labour use their hands and hand tools to work on unit repairs. They are qualified to test and approve units for use after assembly. Interns or trainees also accompany most artisans that the artisans train to become skilled, qualified diesel mechanics or electricians (The repair facility is also a training facility for these artisans). The interns are responsible for supporting work, such as disassembly, and inter-department responsibilities, such as fetching parts from the machining department. Each department also uses technicians who are qualified to work on specific units and are semi-skilled. The roles of technicians also include disassembly without supervision from the artisans. Finally, the workforce is supported by general workers, unskilled employees who also fetch spares, clean the workshop, clean the units and assist artisans and technicians.

Figure 3.6.2 illustrates the general work-order process flow of repairs within the transmission shop at the repair facility. In summary, the unit is repaired by one artisan, with cleaning shop employees aiding periodically to clean when available. Firstly, a depot's maintenance staff identifies a fault with the unit, extracts the faulty unit, and delivers the unit to the unit reception at the repair facility to check if there are any available spares. If spare units are available, they are supplied to the depot to minimise the waiting time for a bus that needs repairs (as soon as a spare unit is available for the depot, the unit is sent to the depot). The faulty unit is then captured on their system using a UNIX system at unit reception. Unit reception then accesses the company interface system, known simply as an online maintenance system, or OMS and generates a work order and job number. The leading hand checks "report 23", a company report that stipulates the current job numbers with the assigned artisan. In the meantime, the unit is moved to the transmission department from the unit reception. An unoccupied artisan is then assigned to the unit to start the repair process. The artisan starts by stripping the unit and inspecting the unit to determine the fault at hand. Once the inspection is completed, the artisan puts in an order for all needed spares. This order is delivered to the primary parts store by the artisans— the receptionist at the spare parts store captures the required spares on the OMS System. The store spares for each unit, and if spares are unavailable, the buyers order the required items. After ordering, the artisan or a cleaner from the cleaning shop (if available) proceeds to clean all working parts of the unit. Once all spares are available, the artisan starts the assembly process. After assembly, the unit is tested to ensure that all parts are in working order, and finally, the artisan closes the job and assigns a delivery note to the unit spares shop. This process flow is not always followed, and work is frequently begun on units before all the necessary spares have been received. As a result, there are a lot of incomplete open work orders. The seven in-detail steps are described below:

1. Unit receiving

The unit reception is the starting point of a unit for repairs at the repair facility. The unit reception sectary receives the unit from the delivery vehicle at the reception area. The units from each depot are delivered to the unit reception, where the secretary checks the received unit to the received unit paper bill. Each unit is received with a paper bill containing all the information that the secretary then enters into the UNIX and OMS system of the inventory store, where a work order and job number are created.

2. Job assignment

The leading hand in the transmission department prints out "report 23"—a list of all open jobs—looks at the units that need to be finished and chooses the artisan for the work. The artisan is then assigned to a job .to the OMS system by the leading hand. The leading hand establishes a reasonable time for the employee to complete the task. The leading hand's subjective experience alone determines the artisan and time used. This may apply to each sub-task individually or the entire work order, depending on the length of the task. The artisan conducts a visual inspection before the disassembly of big parts. The artisan then uses their tag to accept the assignment on the OMS system. The OMS system does not produce in-detail task data, and most captured data is in an unusable form.

3. Disassembly

The artisan strips the part, inspecting parts of the units to investigate the fault by comparing the requirements to a checklist. During the stripping and inspection stage, the artisan notes which parts are required for the unit's repairs. The part is stripped entirely and added to a parts tray. The disassembly process for such big items involves semi-skilled labour. The employee must be skilled enough to disassemble the unit with due process without potentially damaging the unit. The inspection requires a high skill level, as the artisans are trained to know which parts of the item are at fault. The stripping and inspection process is time-consuming and could take multiple working days.

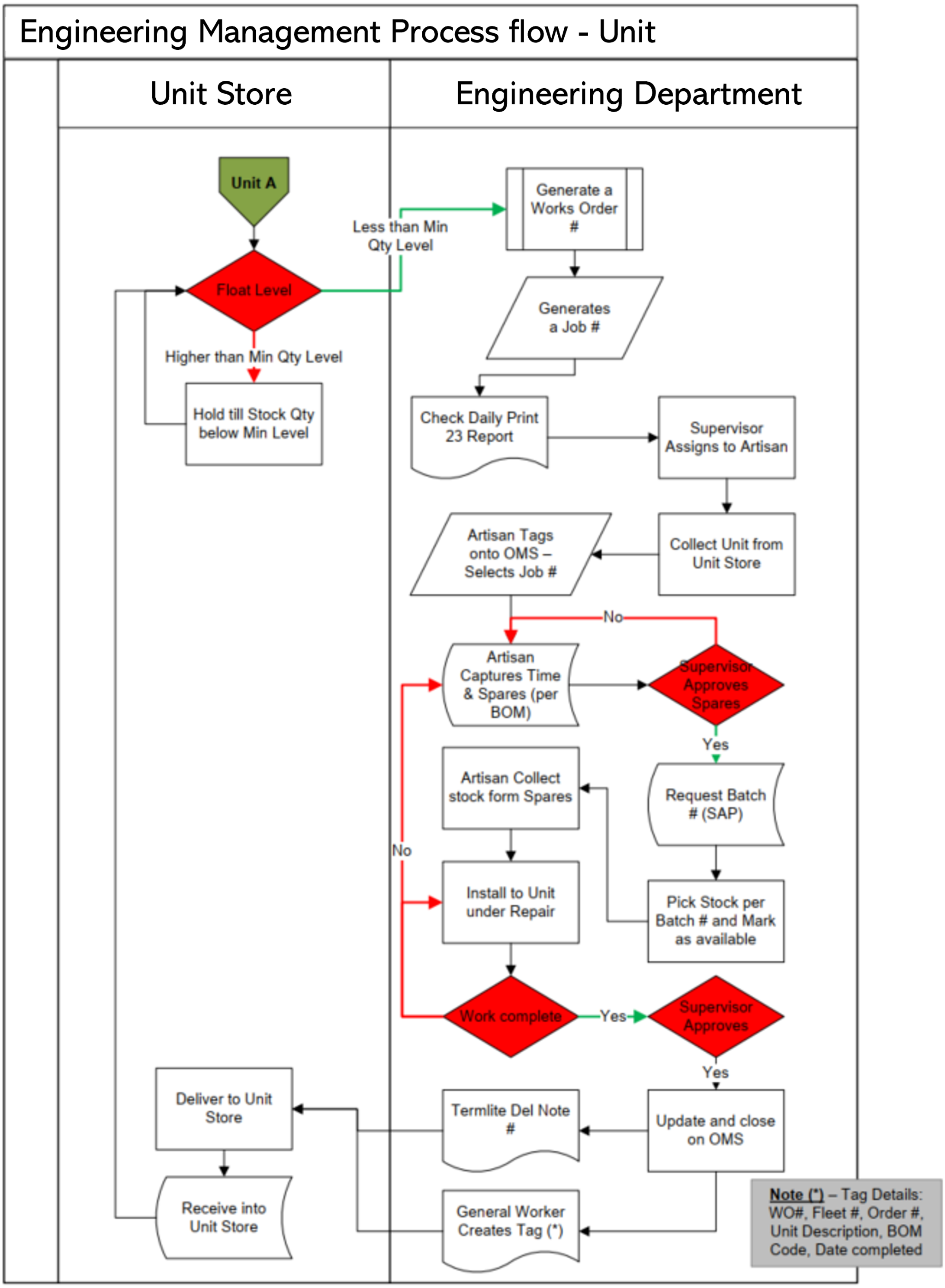


Figure 3.3: *Case Study 1: Engineering management process flow [34]*

4. Order

The artisan proceeds to order the parts that are required for the repairs. Ordering is done by paper orders delivered to the spare parts reception. At the spare parts reception, the required spares are captured on the UNIX system.

If the parts are in stock in the parts store, the parts will arrive at the transmission shop. The procurement department then orders parts that are out of stock or not kept in stock. Every unit repaired in the facility has its repair kit. These kits contain small spares such as seals, electrical parts and screws. A calculated number of these kits are kept in the spare parts storage, but no precise demand forecasting is done, and only a sizable amount of safety stock is kept. Additionally, because each unit's diagnosis is unique, each work order needs a distinct spare. There is no method of anticipating any unique spares, nor are special spares held in-store.

5. Cleaning

Stripped parts are then moved to the cleaning bay, where they are cleaned by the artisan or a cleaner, depending on availability. The cleaner uses multiple cleaning equipment to clean the unit, and the labour involves unskilled labour, although the employee is required to ensure that no parts go missing or are damaged.

6. Assembly

The artisan is assigned to re-assemble the unit as soon as all spares are available. The process is time-consuming as the artisan uses skilled labour to assemble the units to industry-conforming standards outlined in the manual, which is occasionally consulted.

Unit assembly, especially larger units such as the automatic gearbox, often depend on supportive manufacturing from other departments. These supporting processes include machines in the machining department, such as tubes, gears, cylinders, and other parts which require machining, drilling, or other subtracting work. The process often involves changes in tolerance and requirements from another department, such as the machining department, to ensure the proper fitting of spares. The artisans regularly move between their workbench and the machining department.

Depending on the task, the artisan would also move between their workbench and the tool shop to collect specialised tools. If tools are unavailable, the artisan would occasionally look around the shop to find the tools from another artisan, or the work would be halted and moved to another task/order until the task could be continued.

Artisans can access physical instruction manuals where all units' standard operating procedures (SOP) are listed if a rare unit needs to be repaired.

7. Testing

The re-assembled item is then tested on a testing bench to ensure that all requirements are met to allow the unit to be used and placed back into a working bus. After testing, the unit is then delivered to the unit store and a delivery note is created by the artisan on the OMS system, signalling the completion of the work order. Suppose a unit fails a quality test check on the test results. The unit is returned to the assembly, where the artisan completes the desired rework or is stripped for further diagnostic.

3.6.3 Case study 1: Discussion

This section briefly classifies the results of the various observations done in the case study into sub-areas within the observed departments, where each area's relationship with the process is described, and further challenges and opportunities are identified. This section discusses and presents three observational studies for large transmission items, small transmission items, and electrical items, respectively.

The previous section, section 3.6.2 highlighted the actual process flow of three unit repair processes within the unit repair shop of the facility. The study of small units in the transmission department can be seen in figure 3.4. All three of these processes followed a similar flow and gave the researcher a good overview of the repair process. Visualisation of each observational study can be seen in figures B.3 and B.4 in the Appendix B where the route in red represents the reception, disassembly and cleaning process, green represents the assembly process, along with its supporting processes, and blue represents the testing and delivery process. The route colours were chosen as they represent different reasonable standard times given to artisans by leading hands for larger items. For continuity, they are used in the smaller two-item processes as well. The numbers of the three figures are as follows:

1. **Online maintenance system:** One of many online maintenance system access points where an artisan signs into and receives a work order.
2. **Unit reception:** Represents the area where a unit is received by unit reception and then collected and visually inspected by artisans.
3. **Disassembly workstation:** Represents the area or workstation where a unit is disassembled.
4. **Cleaning bay:** Represents the area where units are cleaned.
5. **Repair workstation:** Represents the area or workstation where a unit is re-assembled. With **5a** representing the machining shops where parts are machined, drilled etc., for units and **5b** where parts are collected or delivered to the artisan
6. **Testing area:** Represents the area or workstation where a unit is tested to ensure usability.
7. **Finished Unit Storage:** Represents the area where finished units are stored and collected by or delivered to depots.

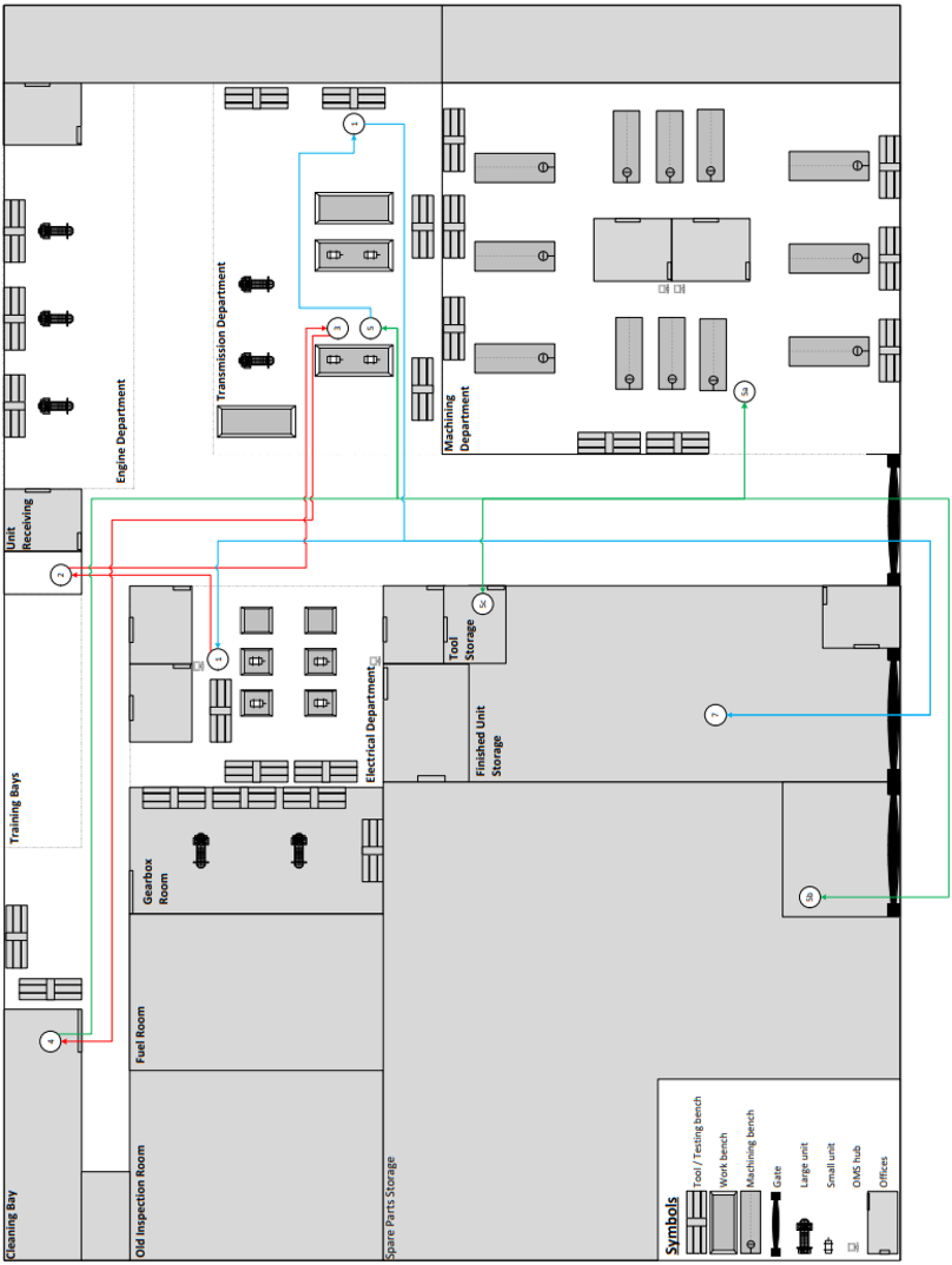


FIGURE 3.4: *Observational study for small units in transmission.*

Based on the case study, the following stand-out areas with recurrent concerns were discovered:

Repairs:

The repair process is the actual value-creation of the environment. Defective units are repaired and follow a process flow, as seen in figure 3.3.

Certain steps and relationships found in the observational studies are not presented in the process flow. For instance, much of the time spent on a task is moving around the workshops, from searching for tools and delivering order notes to spare parts storage or waiting on parts from the supportive machining department.

Certain methods of guidance and collaboration within the labour-intensive process can also be highlighted. Artisans use certain equipment, such as hydraulic presses and testing benches, to simplify tasks. Employees who need guidance can access a manual or consult other employees or the leading hand.

The value-creation also relies on additional manufacturing methods that are not necessarily part of the labour-intensive assembly process, such as the machining, welding and drilling of parts required for the unit repair process.

The labour-intensive repair process varies from job to job, even if the same items are repaired; thus, the facility lacks effective standardisation. Most repairs depend on the skill and labour of the artisan, whose repair procedure is rarely documented. This is a problem since, in some circumstances, other artisans never get the chance to gain experience with these products, which causes continuity concerns and extra training costs down the road.

Furthermore, there is a lack of adequate data collection, thus creating a lack of a data-driven approach, which hinders the modelling process and the existing process management system, i.e. is the whole process understood by management?

The only forms of process modelling or performance management are done via time and motion study data collection, and obtaining usable data from the OMS system proves inefficient due to the format.

Labour management

Given the sensitive nature of labour, the actual human resource management area is briefly discussed, focusing on the area's actual subsections that directly influence the repair process. Broadly the area consists of the task allocation process, the training of employees, safety, recruitment and remuneration, with the latter three subsections not being within the scope of this thesis.

Currently, employees are trained in conventional ways. Interns shadow artisans and learn from them, but artisans are often overburdened by the amount of work and training responsibilities. Tasks are allocated primarily by the leading hand and based on their experience with their workforce.

As mentioned above, most repairs depend on the expertise and labour of the craftsman, whose repair process is infrequently documented. This is a problem since, in some cases, subsequent artisans will never have the chance to work with these items, which raises questions about continuity and adds to the cost of future training.

Equipment and machine management

The management of tools and equipment is one of the main priorities of the labour-intensive process. As artisans cannot complete their work without standard tools, tools are essential to value-creation. Additionally, special tools and equipment are needed for some aspects of value production, such as testing and, in particular, the dismantling of bigger units.

All artisans are responsible for their tools at their workstations, including the management and security of their tools (To work in this facility, skilled artisans must first obtain their tools.). Every department has a few supportive tools supplied by the facility, such as trolleys, testing benches, industrial lifts and pneumatic-powered tools. There is also unused equipment from past value processes in the facility.

Furthermore, an additional tool storage facility is located in the workshop, where employees can collect specialised tools on sign-in bases, primarily a paper-based system.

A paper sign-in system manages departmental tools at the tool facility. The ability to regulate company tools is extremely limited, and it frequently happens that artisans are kept from their tasks while they wait or look for equipment.

Finished unit storage

New or repaired units are kept in the finished unit storage facility of the repair facility.

Depending on the safety stock of the finished unit storage, the facility either offers a replacement unit upon a depot's request or repairs the depot's damaged unit. In a make-to-stock production approach, all work orders are, in theory, driven by the inventory level requirements from the finished unit storage. Due to the frequent orders for larger items such as engines, gearboxes, and axles, the plant must resort to a make-to-order method and use the finished unit storage as a holding space before processing depot deliveries.

Even though artisans and management are aware of some seasonal patterns, there is an absence of forecasting based on the observational studies. When evaluating the finished unit store, there are several apparent challenges. These include using different strategies for larger items, frequently prolonged order fulfilment waiting times in different seasons, and holding large amounts of stock for specific items, even with infrequent requests.

For example, brake caliper orders are more common in winter due to the Cape winter, where the moisture causes corrosion. Still, the same caliper stock is kept throughout the year, even though artisans have more of these jobs in winter. Additionally, vast amounts of stock of smaller items such as seats, electrical systems and hydraulic systems, even with infrequent orders, are kept in storage.

Furthermore, communication between unit reception and finished unit storage is limited to the outdated UNIX system and audited on a paper delivery bases. Physical items are identified only by delivery notes and handwritten serial numbers, and no barcodes, QR or digital identification systems are present.

Management of finished units is done similarly, where finished units are tagged with paper tags, with a handwritten description and job number, before being entered into the UNIX system by the inventory staff and creating the relevant paperwork for delivery when being collected by depot drivers.

The method of taking stock involves manually counting the inventory and inspecting the paper tags every week by comparing the actual products in the facility to a printout list from the UNIX system.

Finally, there is minimal security, with only the recent construction of a gate to restrict access and only physical security methods.

Spare parts storage

Since the facility prioritises expensive part security, only limited access was permitted to the storage of spare parts during the observational studies. Despite this, the process for storing spare parts is very similar to storing finished units. The main distinction is that work orders drive spare part orders, and the facility for storing spares is much larger than that for storing finished units, which makes it even more crucial to control, secure, and forecast the location.

The allocated artisan places orders for spare parts using a delivery note, which is then recorded on UNIX at the spare parts reception. Employees in the spare parts storage print up a list of the necessary spares, and during collecting runs, they combine the spares from various work orders.

Kits for specific jobs, everyday replacement items and other items such as consumables and uniforms are also kept in the spare storage. The supply of spare parts storage is managed by procurement, and there is minimal forecasting. Ordering spares in advance is only done by procurement on request from a department's leading hand with upper management approval.

The significant reliance on paper, the storage area's limited transparency (i.e., lack of control), and the lack of effective forecasting are common issues this area faces or creates. These issues frequently result in incomplete units remaining in the repair areas, which creates waiting times and inventory waste.

Supply chain communication

Given that this study's focus was primarily on value-creation within a labour-intensive setting, the supply chain and logistics of incoming and outgoing parts and units were not comprehensively studied.

In short, finished units from the unit storage are managed by the sales, or unit management, department, which is responsible for the forecasting, supply and information of these units. They depend immensely on the facility's value-creation and supportive areas, as they are responsible for all relevant communication with the depots surrounding their requested units. Similarly, the procurement office is responsible for all relevant areas of the procurement of spares.

3.6.4 Case study 1: Adoption level and overall reception of Digital Transformation

Concerning digital support or any digital implementation, their processes are supported by their online maintenance system (OMS) for work order management, i.e. information about a maintenance task, artisan assignment, and process outlines for completing that task. All incoming and outgoing units and parts have a UNIX system that enables the communication between departments and depots.

Access to the UNIX system is only limited to the unit reception and spare parts reception, where paper-form orders are delivered by artisans and captured by the receptionists in these areas. Essentially, all information is manually captured or drawn from the UNIX system. Departments also heavily rely on printouts from the UNIX system to function. The facility employs an old printer and has a supplier create paper specifically for them as it is no longer commonly used in industry.

The OMS system collects data that cannot be used because it is not in CSV or excel format and would need extra coding and work to make it usable. Once again, aside from clock-in hours, when employees are given employment tags, all data in the OMS system is recorded or drawn manually. The firm does not make data-driven decisions, and work orders are not as transparent to management.

Finally, the concept of Digital Transformation is generally not received well by the staff, where concerns of potential work obsolescence are raised, and any changes are generally not immediately received well.

3.6.5 Case study 1: Conclusion

Case study 1 presented a labour-intensive job-shop environment, where the service delivery is the physical repair of units from buses. The process was described, along with the findings of the observational studies done in the repair facility. The complex relationships between different elements and areas in the labour-intensive environment presented many challenges and opportunities for Digital Transformation. Compared to the traditional manufacturing of similar items, a repair shop is even more labour-intensive, as artisans must manually disassemble, diagnose, clean and repair a faulty item. This labour-intensive value-creation method does bring extra challenges but also more room for improvement and the opportunity to implement solutions that can make a considerable difference.

3.7 Case study 2: Observational study at tailor-made manufacturing solution company in Paarl, South Africa

Organisations in the metal manufacturing sector and client-specific project assemblies are two other examples of labour-intensive workplaces. With larger items, these facilities also employ job-shop settings or project-based manufacturing. Again, many products are produced in these settings, with low or singular (for projects) volumes.

A custom manufacturing solution that provides both services was used to conduct a second case study. The plant, based in Paarl, South Africa, specialises in metal fabrication, offering customers metal products, assemblies, and projects. The facility is divided into two sections: an assembly line for projects and assemblies and a unit line for metal fabrication. The unit line uses folding and cutting to create straightforward metal parts, assembled and standalone products. The assembly area is a project and job-shop assembly workspace. Smaller-to-medium metal assemblies are completed under contract, and large project assemblies are completed for larger, more distinctive products requested by customers. Both the produced metal parts from the unit line and the sourced components from suppliers are used in these assembled products.

3.7.1 Case study 2: Description and logic

The brief observational case study included an in-depth tour of the facility's value-creation with management. The study showed the various lines, their tasks, and any technologies or machinery used in the facility to the researcher. After that, the researcher was given access to both lines, where observational periods and informal discussions with line managers were used to understand the environment.

The facility makes extensive use of labour, with the only actual non-labour manufacturing being the laser cutting stage, where metal sheets are cut using a laser for unit production. Similar to case study 1, the environment employs different levels of skilled labour, where artisans do complex assemblies and are supported by general workers to complete work orders.

The process flow of the facility can be seen in figure B.5 in Appendix B. It shows the actual process flow and its connection to their online tracking system, which is a good visualisation of two levels frequently occurring in the reference architectures in section 2.11. The process flow is primarily for the unit line, where assemblies are indicated by the ”subsequent assemblies” stage and have their online management system.

3.7.2 Case study 2: Activities and process flow - unit line

The results of the observational case study are summarised in the process flow, shown in figure 3.5, where the entire value-creation chain of the facility is visualised. The organisation is a tailor-made manufacturing solution where the product requirements are defined and designed with the customer.

All in-house parts are drawn by the drawing department in collaboration with the customer. After that, the programming department adapts and converts the drawings to be sent through the system into laser cutting and folding machines.

The unit line manufactures simple metal products for end users or further assembly. Depending on the order, the line includes folding, laser cutting, or a combination of both. In this operation, semi-skilled workers manually feed sheets into folding machines and hold them there while folding, and other workers use laser cutting devices to cut the sheets. After the value-creation process, quality control examines finished units before issuing distribution instructions.

The assembly section is a typical job shop, where assemblies are done with parts from folding, laser cutting and subcontracted parts. Skilled artisans are used here to assemble these complex parts. Depending on batch size, artisans conduct quality checks and sample inspections conducted by the quality controller before approving delivery. The process can be seen in figure B.5 in Appendix B, which is the actual process flow used by the environment, with an in-detail process flow showing each value-creation step shown in figure 3.5. The four primary areas in the value-creation are used to map the process flow, with off-page reference (in orange) referencing the flow of information and parts of finished units from the value-creation areas to other departments, such as sales or procurement.

The facility makes use of a few digital implementations. There are two types of online management or tracking systems used by the facility. The tracking system, also shown in the company process flow, is used to aid in tracking and managing units in this line. The other online system is similar to the OMS system of case study 1, where work orders for assemblies are tracked and managed. Additionally, the facility also makes use of a Power-Bi system for the analysis and management of orders.

In addition to the job-shop assembly area, a project-based assembly area is used to produce larger designs. Sub-assemblies or sourced components are installed on the stationary projects in this section, which also serves as the assembly area.

1. Sales & drawing

Communication with the customer and drawing are summarised together, as limited access was available to the researcher, and the focus is more on the actual manufacturing or value-creation.

Customers who need custom parts, assemblies, or products tailored to their needs make use of the facility. Sales and engineers engage with the customer to establish the requirements for their product. The drawing department then completes this by using CAD software to create 3D drawings of each assembly and separate drawings of each item and sub-assembly. Engineering designs can be extracted using CAD software and transmitted to the programming division for production setup.

Each sale is different and can be major project-type products, which could take months to complete, smaller batches of customer items or only simple folded or laser-cut parts.

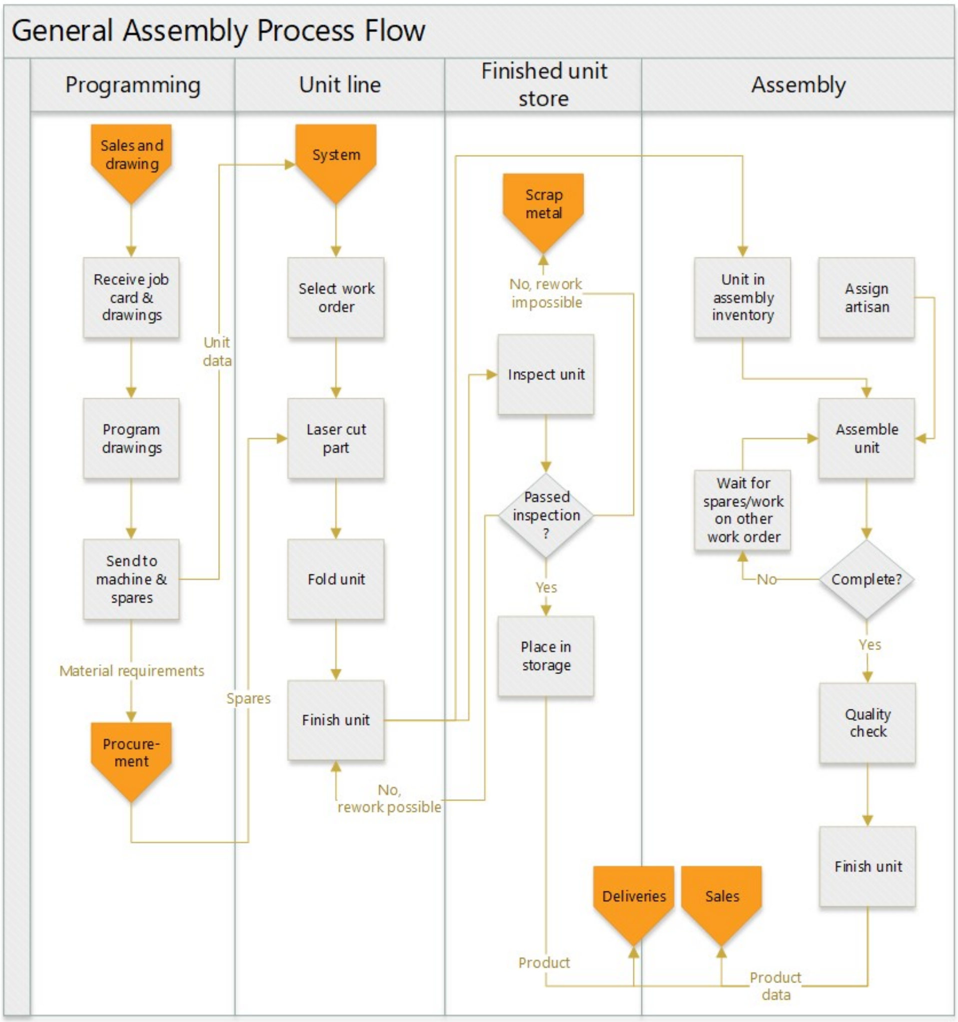


FIGURE 3.5: *Case study 2: General process Flow from observational case study*

2. Programming

Programming receives physical and digital copies of the engineering drawings for part fabrication. Here the entire flow of the product is decided on, i.e. which processes will be used in manufacturing the part. The programming department creates an entry on the PowerBi and tracking software.

The programmers adapt the digital drawings to ensure compatibility with the laser cutting software and machines and the available metal for nesting in the parts storage. Nesting is when a group of parts are designated to be cut together, either on one work order or multiple. The tracking system sends the information and drawings to the machine area, and the worker receives the physical job card. Work orders are generated by the programming department and essentially initiates and directs the entire value-creation (which assembly requires which product and from what machine or labourer).

3. Laser cutting

If laser cutting is required for the part, the cutting requirements are collected via the system by the responsible employee from the programming department who initiates the laser cutting on one of the two machines.

Machines are loaded manually or with a forklift. The process is relatively simple, and the responsible employee selects the cutting order and initiates the machine to cut the nested parts to their desired specifications.

Each laser cutting station has a QR printer, where part information is printed on a sticker, thus ensuring the tracking of the item and the physical job card are sent with the part throughout the remainder of the process.

4. Folding & finishing

The metal components are folded using commercial folding equipment to achieve the appropriate specifications.

Firstly, the responsible employee scans the sheet. Depending on the part specification requirements, folding machines of various sizes are used to fold sheets. Work orders are classified by deadlines, allowing employees to select their desired work order as long as it is completed by the given date.

The folding process necessitates lengthy setup times, the retrieval and delivery of parts, and manual labour in which workers feed and hold metal sheets for the folding machines. Work cannot be performed without the assistance of semi-skilled workers who direct the folding process.

A nearby PC is used to access the tracking system, where the process is selected and finished. It is the responsibility of the employee to enter their times into the tracking system.

Depending on the part specification, parts are frequently finished by buffing, polishing, cutting, or painting. After folding, certain components are done. Pallets with completed parts are ready to transport for the final inspection.

The parts are then sent to their designated areas for assembly if they are needed in subsequent assemblies, such as those utilised in the project or assembly area (not to final inspection)

5. Final inspection

Depending on the size of the part, parts are transferred by hand, pallet jack, or forklift to the final inspection table or area. An employee proceeds with manual quality inspections here, checking for dents, scratches, and other flaws on the surface and comparing measurements to technical drawings. The number of sample pieces chosen for examination depends on the batch size.

Products that do not meet requirements are placed on a quarantine table, where it is decided whether rework is feasible. The parts are shipped back to the finishing section, where imperfections are removed, and finishing is touched up if the rework is possible. Parts that are folded or laser-cut but do not conform are scrapped.

Finished unit storage and delivery

If the final inspection is successful, the part is then transferred to the storage area for finished parts. The data is communicated via PowerBi and the tracking system, where delivery is planned as the facility completes its delivery.

Finished parts are listed as inventory on the system and are verified twice through manual inventory checks.

3.7.3 Case study 2: Activities and process flow - assembly line

For assembled units or projects, a supervisor assigns an artisan/general worker or a team of employees. The "assembly line" area is separated into two designated areas, one for project-based manufacturing and the other for job shop-based production. Both areas change as the product requirements change; thus, when moving from one project to another or adapting job shop stations to a new unit, setup times take considerable time. There is also a parts inventory for parts from the unit line and subcontracted parts, tool storage with specialised tools, consumables, and access to the parts store, where metal sheets and other parts are stored.

Assembly work orders are managed via the alternative online management system, and the unit line tracking system is not used in this area.

1. Subsequent assemblies & projects

Parts required for an assembly are placed together in a designated area for an assembly of a new work order. The assembly receives a job card and unique job order, and every part required for assembly is also placed with its original job card.

The employee or team of workers will then build the item using welding, manual assembly, and installation, either around the item in the project area or the flexible assembly line between work benches. The artisans check measurements and assembly requirements regularly to ensure quality.

Teams work together on the projects, where assigned artisans are responsible for their installation or assembly to a project unit.

2. Finishing

Following assembly, the goods are finished using different supporting techniques such as painting, trimming, buffing, and grinding before the quality controller inspects them.

3. Quality check

The quality controller then performs the final quality check, where the results are compared to the results of the artisan's quality check. Assembly and measurement quality checks are performed on paper with the assembly job card.

3.7.4 Case study 2: Discussion

This section presented the outcomes and findings of case study 2. Time constraints prevented timely and thorough observational assessments of an entire work order, such as in case study 1. The researcher conducted a quick observational study, accompanied by informal discussions and a tour of the industrial environment and online services. For the researcher to understand how the environment creates value and the extent to which it has undergone Digital Transformation, the management of the facility presented the following key components of the facility to the researcher:

1. **Programming:** The environment division that converts engineering drawings into functional models for laser cutting and folding.
2. **Laser cutting and folding:** The laser cutting and folding of parts for further assembly or simple units.
3. **Tracking system:** The new online tracking system that the environment uses.
4. **Assembly:** The job-shop welding and assembly of complex units.
5. **Project assembly:** The project-based assembly of larger custom items for customers.
6. **Inventory & Asset Management practices:** The inventory, tool and asset management systems for spares, finished products, consumables and specialised equipment or tools.

The process flow in figure 3.5, with the accompanying activities and process flow description, has already covered the majority of each component, where the challenges and opportunities of these areas were categorised as follows:

Production:

The environment's value-creation is delivered in the form of production -specifically in the form of folded and accurately cut metal fabrications, as well as the assembly of small to medium-sized metal objects. Larger projects tailored to a specific client are also done. Labour in the form of loading and assisting with cutting and folding machines and manual assemblies are present in the environment. Non-labour-intensive methods of manufacturing are also present to aid in the fabrication, as in the case of laser cutting machines, which significantly reduce the labour needs for the environment and open up room for employees to continue with other tasks. Software on the folding machines guides employees in the setup and re-setup of machinery.

The metal fabrication process demonstrates the usual operation of three production settings: project-based manufacturing, job-shop manufacturing, and even batch manufacturing. It is incredibly labour-intensive, with very few machines completing operations.

Project and job-shop production occur during the assembly process, where various components are put together at workstations at low volume and high quantity rates. The environment's laser cutting and folding process is an example of a batch-based manufacturing process. The line is built up individually for each product with long setup and changeover periods.

Transportation and motion wastes are still present in case study 2, but due to parts, tracking is reduced compared to the previous case study. Additionally, assemblies still rely on labour to be completed, the environment is still heavily reliant on a paper-backed system for their value-creation and refined data collection in the assembly process can still be improved.

The tracking system, PowerBi, and management system have enhanced data collecting, allowing management to make more data-driven decisions, particularly in process modelling and procurement management.

Human resource management:

Currently, employees are trained in conventional ways. However, it is not as continuous as in case study 1, with periodic in-house and occasional outsourcing training, depending on the current process design.

The job assignment in the unit line is unique, as employees can choose their tasks in the unit line as long as items are completed before a given date. Supervisors assign assembly and project jobs.

The interaction of labour and the new tracking system also allowed the researcher to investigate a recent digital implementation. Generally, management and employees struggle with the implementation of the system due to the system being a sizeable prototype system still in development and due to the limited flexibility of the system.

Additionally, the general attitude of the labour force toward Digital Transformation is consistent with expectations; employees are less excited about digital support, particularly when there are major changes.

Asset, equipment and tool management

The use of tools, machines and assets, such as folding machines and laser cutting machines, are used extensively in the environment.

Similar to the repair workshop, artisans are responsible for their tools as each employee receives a locker for their tools, where they can be stored and locked.

Specialised tools and consumables can only be supplied with authorisation from the tool storage supervisor, where a barcode registration controls all tools in the tool storage facility. All tools are linked to an online register, thus ensuring better control and transparency of tool usage.

The tool's user, sign-in, and sign-out times are recorded in the online register, a basic database. Such a tool is viewed as a type of Digital Transformation compared to the paper sign in case study 1.

Finished unit storage

The delivery department is in charge of the finished unit storage. Finished units are captured on the PowerBi and online tracking system, and a barcode scanner controls inventory management.

Each part and assembly has a barcode sticker on with all the information about the product, ensuring swift communication with the system and rapid transportation of the items throughout the unit storage.

The finished unit storage is not separate from the manufacturing environment and has limited safety features, but the facility uses CCTV systems for security reasons.

Spare parts storage

The spare parts storage is similarly managed to the finished units. When a spare component enters the facility, it is marked with a physical sticker and a QR code that provides all the necessary information about the part as it goes across the facility.

Specialised tool control (as mentioned in equipment management above) and consumables are also managed through spare parts management. Similar to the tool system, consumables use a database sign-in system where reception manages the signing-in and out of consumables.

Different cuts are nestled on each page by the programming department, and any remaining cuts are sent back to storage to be reclassified.

Quality control

Quality control is highly important for this environment. Regular quality checks are conducted in each stage, and all items or batch samples are checked to ensure they conform to customer requirements. The quality control process is entry labour reliant, and an assigned quality controller does all checks.

The value-creation process uses two types of quality control. Designated artisans perform in-process quality checks after each sub-task or end assembly. These quality checks include checking all tolerances, parts, and sub-assemblies using a paper quality control checklist attached to the job card. Depending on the size of the operation, a designated quality controller performs after-process quality control, checking tolerances, surfaces, and finishing in chosen samples or the entire job.

Supply chain communications

The company's fleet makes deliveries to the Western Cape's major metropolitan centres. The delivery department manages delivery notes and the fleet and is also in charge of finished unit storage. Schedulers use the PowerBi system to enable order delivery by allocating jobs to vehicles. For order fulfilment, the department collaborates closely with sales.

The online system facilitates procurement management, and a supervisor's approval is required before purchasing a part. This method of procurement is semi-automatic.

3.7.5 Case study 2: Adoption level and overall reception of Digital Transformation

Similarly to case study 1, management and supervisors have limited information about the actual labour-intensive process, thus opening up the means for similar data collection methods as suggested by McKinsey & Company [41]. The increased data collection, however, has enabled management to make more data-driven decisions, especially in process modelling and procurement management.

Although this environment's digital maturity is more advanced than the organisation in Case Study 1, the tracking system's installation is not without problems. The tracking system depends on the labour force to collect data, and lengthy processing times and non-value-adding movements after task completion skew the data collection. The implementation also potentially causes time wastage in data entries from labourers next to their workstations.

Additionally, since work orders can only flow in one direction via the tracking system, it is more difficult for managers and employees to approve the bypassing of a work order., such as in the case of rework.

Brief informal discussions regarding Digital Transformation were held with staff and management in the environment. Overall, most people in the environment are keen on Digital Transformation. There are, however, concerns about potential obsolescence and disruption of product delivery. The latter can be seen in the swift implementation of the tracking system in the entire unit line, where the overall reception and collaboration with the system are not yet satisfactory, as mentioned above.

3.7.6 Case study 2: Conclusion

Case study 2 presented the researcher with a unique opportunity to understand three types of labour-intensive environments that will enable the adequate development of the reference architecture and roadmap.

The increased use of digital support methods in the labour-intensive value-creation of case study 2 also allowed the researcher to engage with a labour workforce to investigate general feelings towards Digital Transformation and Industry 4.0 of the everyday labourer.

The general findings in case study 2 are similar to case study 1, reaffirming the findings in case study 1. Furthermore, the new digital tracking system's unique challenges are notable and can support the idea of an incremental approach to Digital Transformation in such an environment.

3.8 Cause-and-effect relationships found in a labour-intensive environment

The case studies and the supporting literature, in general, covered comparable areas. This section divides each component of value production into categories that apply to most labour-intensive workplaces. Following that, each area's everyday problems and opportunities are examined, along with how each one relates to the others. The study explains the cause-and-effect relationships using Fishbone diagrams (Ishikawa). Since only the value-creation process, these categories are limited to the product or service management aspect of operations management in such situations. Based on the study above, the following categories were identified in the value-creation:

1. **Product or service creation**
2. **Human resource management**
3. **Asset, equipment and tool management**

4. **Finished unit storage**
5. **Spare part storage**
6. **Quality control**

3.8.1 Product or service delivery

Primarily, the area that defines a labour-intensive environment is such an environment's product or service delivery. Most industries make use of a certain degree of labour. Still, in some organisations, especially in the case of developing countries such as South Africa, labour is often the primary value contribution method. Therefore, technology cannot simply be used as a labour replacement for the challenges and operations of such an environment but can be used to simplify the value-creation process.

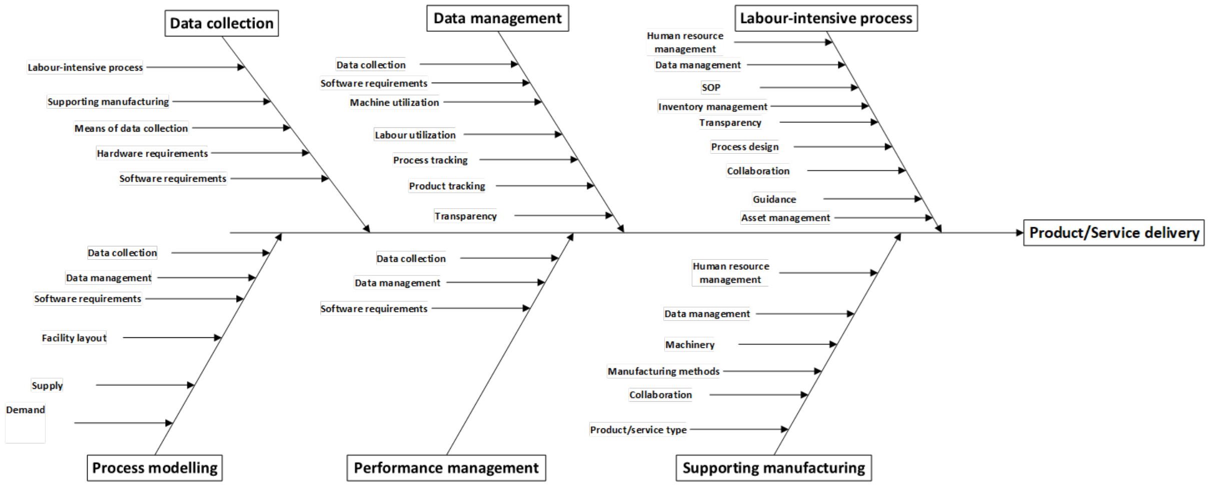


FIGURE 3.6: *Cause-and-effect diagram: Product or service delivery*

Various cause-and-effect relationships can be found in product or service delivery. The impact of the actual hand or other labour in the labour-intensive process, the other means of production such as machining, drilling and sub-assemblies that are less reliant on labour and the actual modelling of the process and the drive behind the modelling are all noticeable. Figure 3.6 shows the cause-and-effect relationships for product or service delivery.

Primarily, the output is reliant on the labour-intensive process. This process is directly influenced by the labour employed in the environment. Transparency and standardisation compliance also impacts the manner of production. For instance, a labour process can variate in each cycle, as an employee's experience grows, as independent challenges arise and as each unit differs, especially in high-mix low-volume environments. The need for, and compliance, with a standard operating procedure for a labour process can significantly impact the production and directly impacts wastes in motion, transport and waiting. Furthermore, guidance and collaboration within the labour process also impact the level of value-creation. An example, as seen in case study 1, would be the use of an instruction manual for employees when a new challenge arises and how equipment is used to aid in the labour-intensive process, such as the use of test benches and hydraulic presses. Effective asset and tool management also impacts the labour-intensive process, as time spent searching for tools, repairing equipment or waiting for equipment could have been spent on value-creation.

Supporting manufacturing processes, such as the machining in case studies 1 and 2 and transformer assembly in the UPS system by Rahman and Sabuj [100], include processes that are not the primary labour-intensive production process and only form a supporting role. The type of machinery and manufacturing process, such as subtractive or additive manufacturing, and the standardisation compliance and transparency of these environments directly impact the labour-intensive process because a fallback in these processes results in wastes, like the waiting wastes that were observed in Case Study 1. These processes can also be labour-intensive, similar to the previous primary cause, but are distinguished from the labour-intensive production process.

The importance of data is highlighted in the investigations done in this chapter. Data collection is a major challenge in a labour-intensive environment; McKinsey and Company's findings highlight this [41]. Effective data collection is needed to enable these firms to make data-driven decisions in data management, process modelling and over-performance modelling. All the environments have data-collection methods with varying opportunities for improvement. When implementing data collection, such environments would have to consider their data collection means and the hardware and software requirements of collecting the data. The data type is also a concern, as seen in case 1, where non-usable data is being collected.

The management of data is also essential. Case study 1 does collect data, but minimal decision-making is centred around data. Data collected in all processes can reveal important measures and statistics surrounding machine utilisation, labour efficiency and product tracking, all of which could aid in the transparency of the value-creation process and lead to effective process modelling and compliance in standardisation in the process. Finally, the facility's layout can affect every area mentioned above and can be supported and changed through data collection and process modelling, thus affecting the other value-creation processes.

The management of the product or service delivery is also aided by the process modelling of the environment, i.e., the design of the value-creation process and measuring and managing performance. Various software and cyber-physical systems, as mentioned in section 2.3.1, exist, but here, data collection and management have an impact, as inadequate data collection leads to inadequate management.

Case study 1 primarily uses quality controllers to measure the environment's performance and model the process with minimal aid from the OMS system. The tracking system in case study 2 allows for some modelling and measurement.

3.8.2 Human resource management

The human resource management of such an environment is essential. Employees' education, training and motivation can directly impact how value is created. Labour is required for such an environment; thus, effective human resource management, leading to a healthy and productive environment, is a primary area.

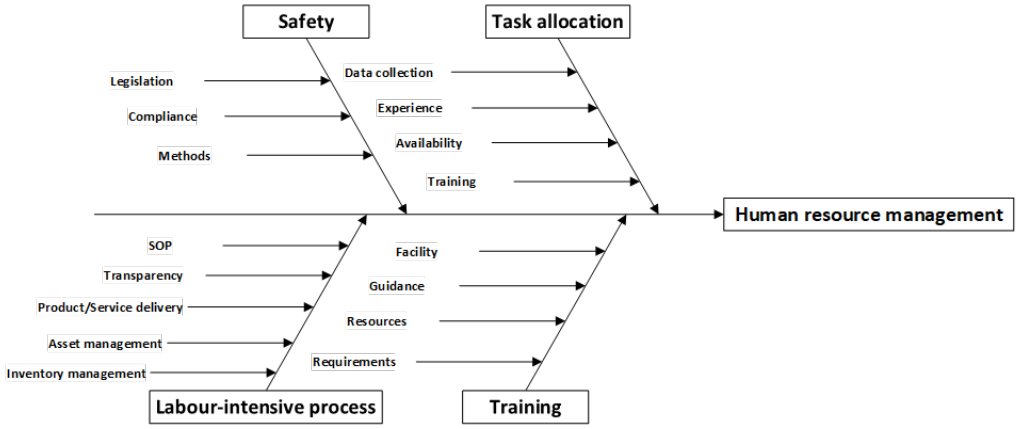


FIGURE 3.7: *Cause-and-effect diagram: Human resources*

Human resource management involves the task allocation, training, safety and implementation strategy of labour in the value-creation process.

Here, once again, data collection's importance comes to light. In case study 1, employees are allocated tasks based mainly on a foreman's subjective reasoning. The primary allocation rationale is the foreman's actual experiences in the artisan's training, experience, and independent thinking ability. As previously mentioned, this is quite beneficial. Still, the use of data, appropriately collected and protected per local legislation, could aid in the task assignment, thus directly impacting the value-creation of the environment.

Furthermore, the importance of training is evident; the means for alternative training methods, as highlighted in section 3.2.2, can aid in value-creation by reducing the need for repetitive training and under-utilisation wastes and empowering employees with modern training skill development.

Finally, there is always room for improving workplace safety, and safety measures and methods impact human resources management. Human resource management can also include remuneration, recruitment and employee relations. However, due to the sensitive nature and limitations, i.e. the primary focus on value-creation, these areas are not investigated as thoroughly.

The other areas also impact labour effectiveness. For instance, employees often have to wait for tools or spares in the case studies and are required to do their value-creation process according to the SOP of the environment. All these and other reasons impact the labour-intensive process and labour efficiency.

3.8.3 Asset, equipment and tool management

A significant source of waiting, defect, transportation and under- or over-utilisation is the ineffective use of resources used in the value-creation process. In case study 1, an example of waiting waste due to the search for tools is revealed. Effective asset management has significant cause-and-effect relationships with value-creation. How tools are assigned, used and stored impacts the labour production process, which could cause or reduce waste in these environments.

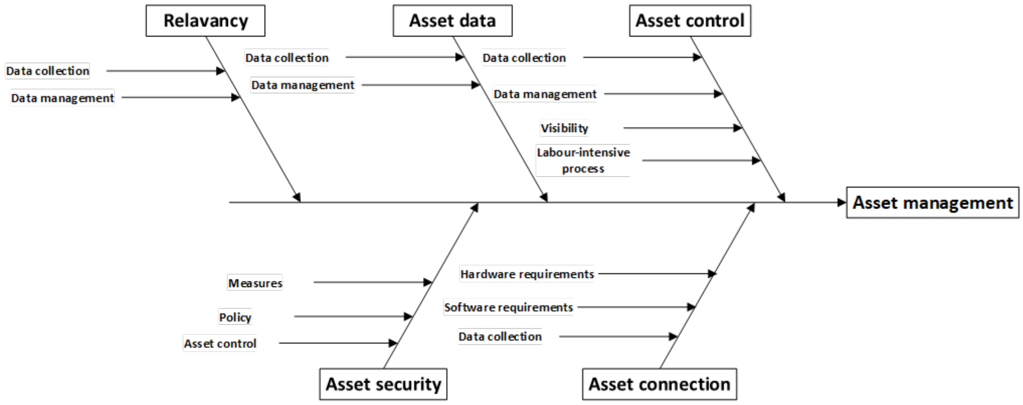


FIGURE 3.8: *Cause-and-effect diagram: Asset, equipment and tool management*

Here, once again, data collection could aid in determining the relevancy of these resources, managing the control and assignment of and having an impact on the connection potential of the asset, where an M2M system could be a potential source in data collection, management and process design.

Both case studies mention the usage of space by underutilised or irrelevant machines, which could aid facility optimisation and optimise the value-adding process through de-cluttering.

Finally, asset security is also relevant to asset management, as missing tools and equipment affect waste in value-creation. Effective policy, measures and control could reduce this effect, thus reducing the associated wastes.

The control of tools and equipment is also impacted by the actual labour-intensive process, as missing tools currently in use by other employees affect the control and can cause waiting wastes. There are inventory control methods such as M2M, RFID or IoT systems (see section 2.3).

3.8.4 Finished unit storage

Inventory management is a significant part of any manufacturing system. Effective inventory management can reduce costs, save time, improve customer service, and improve demand accuracy for optimal stock levels. Effective management of finished inventory can also increase transparency using inventory tracking, reduce unnecessary waste, and improve business planning. It can aid in optimising inventory flow, creating an agile system and aiding marketing and operations in planning and operation.

Finished inventory is present in the case studies and supportive literature discussed above. Based on the two case studies, it is evident that conventional inventory management systems have much room for improvement. Under-utilisation wastes are present in case study 1, when artisans and technicians do manual stock count each week, which could quickly and cheaply be achieved by other means, and eliminate the need to cut back productive time from a workforce.

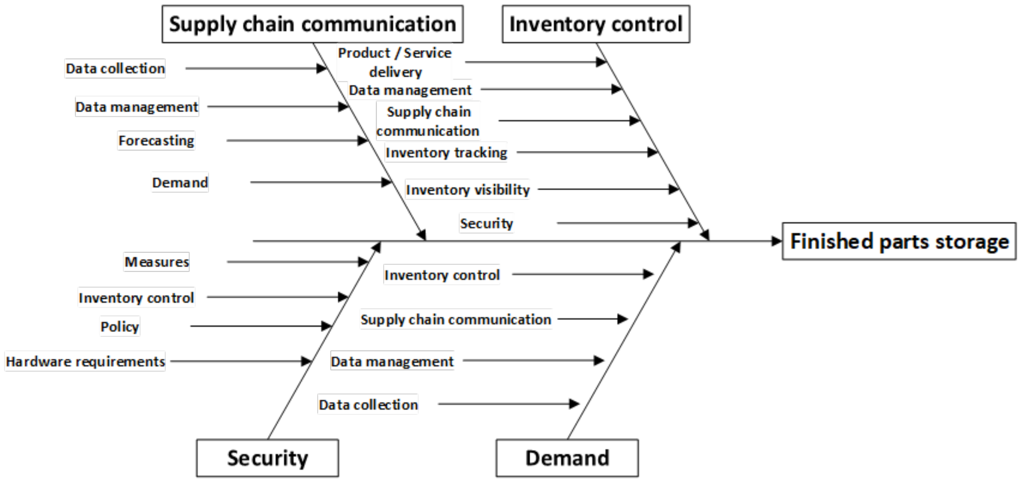


FIGURE 3.9: *Cause-and-effect diagram: Finished unit storage*

Various labour-intensive environments - especially in developing nations, such as case study 1 above- still use a paper-based system, where all information is captured and transferred on paper delivery notes. The lack of real-time tracking is also evident, and case study 1 has no means of data collection, thus limiting all the potentials listed in the first paragraph of this section.

The finished products are the output of every manufacturing environment; the design of each system, the process flow of each system, and the output requirements are all defined by the system's needs, i.e. the finished goods or services. As a result, any delays upstream in the value-creation process can affect inventory control and cause orders to be delayed.

Any aiding methods or tools used in finished unit storage can also improve the security of a labour-intensive environment. Finished units are the output of the value-creation process, and finished goods sales drive some or all of the operations within such an environment. Reducing the likelihood of theft or damage to finished goods can reduce costs, increase transparency, and reduce the need for rework, putting less strain on human resource management and the value-creation process.

Specialised inventory management can aid in optimising the remainder of the environment, both in process and digital enhancement. Conventional forecasting methods can be replaced with digital systems and aid an organisation's sales and upper business management in their business planning and operations.

3.8.5 Spare parts management

Similar to finished unit storage, the management of spare parts in a labour-intensive value-creation process can affect the value-creation process. As mentioned in case studies 1 and 2, ineffective spare management can cause waiting and under-utilisation wastes when artisans are waiting for spares to resume repair and assembly processes.

On a technical side, many of the relationships and elements of spare part management are similar to that of finished units but reversed, as spare parts form part of the inputs of the value-creation process. Spare parts management is affected by the product or service delivery of the environment, as labourers take stock out of the storage; thus, new stocks are required. The need for data management and collection is quite evident, as effective requirements management can optimise requirements forecasting, and stimulate every downward process in value-creation by increased security, reduced waiting times and transpiring.

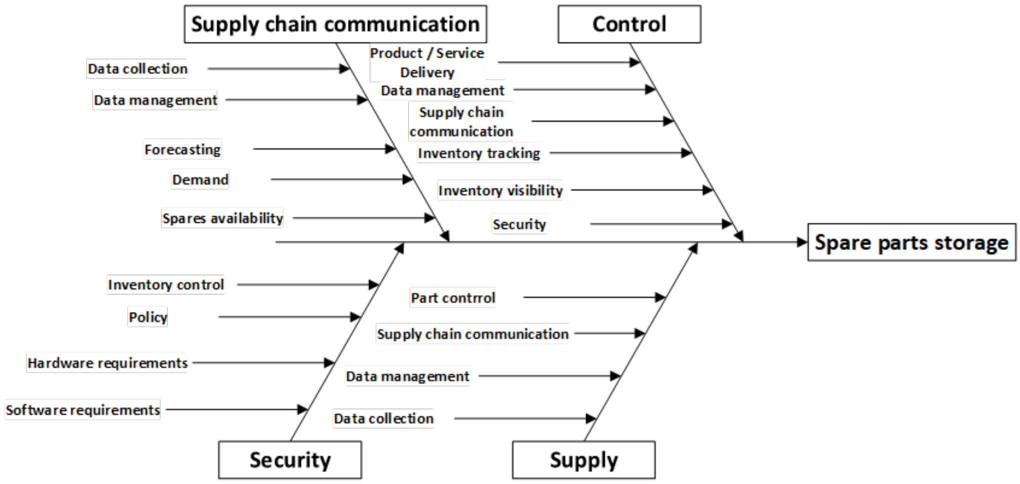


FIGURE 3.10: *Cause-and-effect diagram: Spares management*

Finally, having a specialised parts inventory management system can optimise digitally and conventionally by stimulating procurement and supply chain communication. It can also aid in the cost reduction of spare parts requirement, thus also affecting procurement management and the upper business management in such an organisation with business planning and operations.

3.8.6 Quality control

Quality control is needed in all forms of product or service delivery. Inadequate quality control leads to poor delivery and can lead to extra costs, both financial and reputation, for these environments. Quality control measures are added to ensure that the product or service is delivered well. Both case studies briefly cover quality control, where both in and after-production quality control is present in case study 2 and quality control in the form of testing is used in case study 1.

Quality control can be carried out manually or with equipment and technology. Issues with quality control might result from faulty tools or measurement errors made by quality controllers. All earlier jobs in the labour-intensive process will affect the quality since quality control is the last step in the value-creation process. Similarly, the product type also affects the value-creation process and the output quality of the environment.

The supply chain impacts the output quality in terms of both supplier selection and the quality of the sourced components or materials.

Finally, as with all areas identified in these environments, data management and collection can affect quality output by identifying problem areas or products and by analytics, where quality control measures can be improved in value-creation aspects most needed. Another example is reducing quality control measures on products where fewer issues are often found, which can also be improved by quality control.

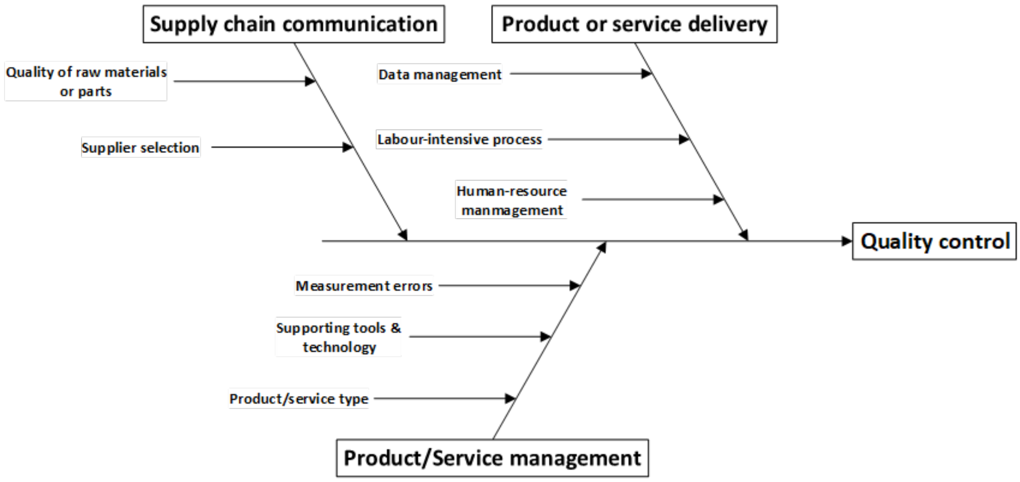


FIGURE 3.11: *Cause-and-effect diagram: Quality control*

3.8.7 Business management and supply chain management

The business management and organisational structure also affect the value-creation. For instance, in Case Study 1, while maintenance is not the organisation's primary objective, a repair shop is set up to assist with bus transportation operations. Therefore, a repair shop might no longer exist if management and the organisation's business plan decide that it is unnecessary, that new units or parts could fill the demand, or that all repair work should be outsourced. Additionally, funding for these areas also comes from upper management, and any projects or changes usually have to approve by the business's management team.

The research in this thesis is not as detailed in these areas due to the focus on value-creation. They are still considered, where improvements and relationships from within the value-creation are researched and transformed, which would affect these areas.

3.9 Conclusion

This chapter began by examining five primary types of manufacturing systems to better understand the precise amount of labour required in various manufacturing systems. Following that, two observational case studies were carried out to investigate the environments that rely the most on labour. The case studies and supporting literature were used to categorise various areas, processes, and systems commonly found in labour-intensive environments. The cause-and-effect relationships within and between these areas and joint issues and challenges were then studied.

The following chapter applies the research and findings from chapters 2 and 3 to create a reference architecture and technology roadmap methodology used in the chapter 6 roadmap approach.

CHAPTER 4

Solution approach: Development of labour-intensive Digital Transformation reference architecture and technology mind map methodology

The first two chapters reviewed relevant academic writing on Digital Transformation and attempted to comprehend how a typical labour-intensive environment functions. Research objective 1.3 is to create a reference architecture based on the findings of the previous two objectives, i.e., the potential areas and their relationships. In this chapter, the literature and findings are used to create a reference architecture for a general labour-intensive environment's operations, with a specific focus on the value-creation processes of the operations. The reference architecture maps and classifies current processes and an organisation's digital growth. A technology mind mapping methodology is developed to address research objective 1.4. The mind-maps are designed for use on the reference architecture and to identify potential digital or technological support methods in a firm's DT endeavour.

4.1 Reference architecture development

Each labour-intensive setting is unique; thus, each would employ a unique set of Digital Transformation strategies. This section develops a reference architecture for a general labour-intensive environment. The RA is used to map the value-creation operations of such an environment and understand the different areas, analyse any existing digital potential and identify and develop new digital potentials using the mind map methodology in section 4.5. In a roadmap methodology (see table 2.5 in section 2.14.1), the reference architecture seeks to visualise the existing environment and respond to the second fundamental question of an effective roadmap - Where are we now?

Du Preez et al. [29] mention two types of ERAs described in section 4.1.Components of both type 1 and type 2 architectures were used to develop the architecture. The focus is on both the current structural arrangement of the physical system of an operations management part of an enterprise (type 1), and in the roadmap using the structural arrangement of the development of a DT endeavour in an enterprise is used (type 2).

First, the various levels of the architecture are developed using the literature in chapter 2. After that, the levels are populated based on the findings in chapter 3, where the categories used in the cause-and-effect study findings are adapted to the different areas of the reference architecture.

4.1.1 Levels of the architecture

Sections 2.11 and 2.12 investigate the use of enterprise reference architectures in general and in Industry 4.0-specific implementation, respectively. In both sections, various levels exist where the different levels of an organisation are listed.

The objective of this reference architecture is within the value-creation levels of an enterprise, where specifically, the operations management of such an environment is the subject of the reference architecture.

Operations management is the management of systems or processes that create goods or provide services [51] i.e. the value-creation of the firm. The reference architecture's levels focus primarily on mapping each process in the operations of an environment towards a certain level, where the focus is not on the business approach, strategy or general means of business.

The point of the architecture is, however, not to limit the business level of an organisation. If used correctly, it could impact the business intent of the organisation by impacting the firm's operations affecting these areas in a bottom-up approach.

A challenge in section 2.12 is the usability of reference architectures, which often lack adequate flexibility and are rarely used in industry. To address this issue, the reference architecture is developed to be as simple as possible and to be used together with the mind map methodology in section 4.5 and roadmap in chapter 5. In section 2.11, Du Preez et al. [29] explained that reference architectures can be used to guide users on what to do in a roadmap design or re-design. The reference architecture is designed to function in this manner.

The roadmap aims to only look at the Digital Transformation of the value-creation of these types of environments, employing a company perspective on Digital Transformation (see section 2.1.1). The roadmap aims to visualise processes, cyber or physical technologies and data collection and management in these environments. Similar to the USDA's [46] recommended layers in section 2.11.1, four levels are used in the reference architecture with the focus on the information, application and technology levels as they concentrate on the operations of the environment, where value-creation occurs. The different levels - enterprise and business, information, application and technology with their relationships, can be seen in figure 4.1.

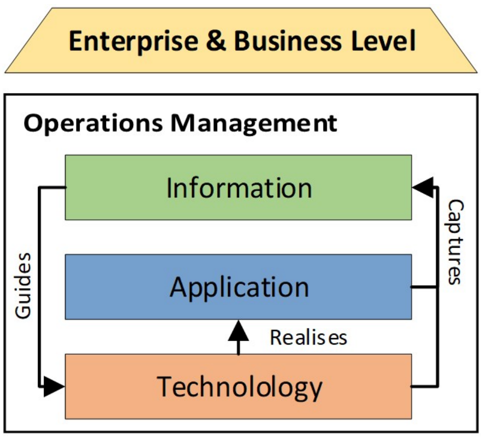


Figure 4.1: *Levels in labour-intensive Industry 4.0 architecture*

Business and organisational Level

In each ERA discussion in this thesis so far, the top level of the architecture is the business or organisational level, where the business and organisational management and strategies and their processes and activities are included. As the desire and support for Digital Transformation usually come from a business level, this level remains atop the reference architecture, where potential methods of digital and technological support could emerge from the outcomes of the lower levels and in potential further research on this subject. The reference architecture focuses on the operations management of these firms, so these levels are not populated. However, it should be noted that any transformation in a company's operations would impact these levels.

Information level

A significant challenge in both case studies, and found frequently in research, is using digital information (data) in a labour-intensive environment. The capturing, analysis and usage of data in labour-intensive organisations is under-utilised in most labour-intensive processes.

Every reference architecture in section 2.12 and the USDA ERA layers (section 2.11.1) all make use of a data level or layer, where data is collected, organised, secured, distributed and analysed. The second level of the reference architecture, and the first operation level, is the data level, which deals with collecting and analysing information about the value-creation processes outlined in the application level.

Application level

Primarily, the desire for digital and technological support is to aid firms in adding value to their operations, explicitly aimed at the various processes and activities in the labour-intensive environment. The application level of the architecture refers to these activities, their current state, and how certain technologies can be used to collect information from these processes or how technologies can be applied to aid these activities by adding value. The application level is the third level of the architecture (2nd operational) and outlines all the application areas. The value-adding process and technology implementation is applied at this level.

This level is where any digital or technological implementation is applied specifically towards an area in the value-creation of a labour-intensive organisation. For example, an RFID system collects motion data from a labour-intensive assembly process. The data is then sent to a server (information level) for management and analysis.

The application level is where the reference architecture is slightly different to other architectures or approaches, such as those in section 2.12. Nakagawa et al. [79] mentioned that one of the significant challenges in Industry 4.0 ERAs is their usability and how information and communication flow between them - this is especially challenging in larger architectures. Most architectures investigated by Nakagawa et al. [79] attempt to address every level and every component in detail within an enterprise. The reference architecture developed in this chapter only focuses on the application level, where the actual processes and physical systems exist, and the technology and information relationships describe the cyber-physical element. The architecture is similar to the adaptive capabilities in the Adaptive ERA [3] of section 2.11.2, where it physically looks at the processes and resources an environment, which is, in this case, a labour-intensive environment.

Technology

Technology is needed to collect data and create a cyber-physical system. The final level of the architecture is the technology level. This level includes all hardware and software requirements for data collection (information level) and the value-adding application of technology (application level).

This level shows the actual digital or technological support methods, where the technologies are applied in the value-creation process at the application level and used to collect information for the information level about the various activities and processes. Technologies included are IoT, M2M, AR and VR in section 2.3 and cobots, digital twins, cloud and edge computing software in section 2.9.3

4.1.2 Describing the relationships between the levels of the architecture

A level of digitisation is required before digitalising the labour-intensive process. Digitised products and their collected information drive other digital operational processes. Digital information must be captured from a process, product or system or converted from analogue or paper-based information.

The importance of data collection and management in Digital Transformation, specifically in a labour-intensive setting, has been mentioned on multiple occasions before; see sections 2.1 and 2.7.2.

If a certain level of digital support is desired in an environment, qualitative and quantitative information is required to ensure a sustainable implementation without wasting resources.

For example, if an organisation desires to add a new workstation or machine for a process (technological or not), they would not blindly add another workstation without researching their entire value-creation process and confirming that a prospective implementation is cost-effective and adds value before implementation or change.

The relationships between the data and technology levels are similar to the 5C cyber-physical system architecture described in section 2.3.1. Technology is used to collect data via smart connections (level I of 5C) and to provide visual support for decision-making at the cognition level (level IV of 5C). The application level refers to the actual use of cyber-physical systems, that is, the implementation of a cyber-physical system (technology level) on a value-creation process or area (application level) to collect and analyse data (data level).

Furthermore, results from the data level are used in a value-added manner (similar to in section 2.11.1) through technology.

The levels of the reference architecture are structured in such a way, which can be seen in figure 4.1, that the application level communicates with the information level, where data is collected from the various processes, managed and analysed to then select a suitable technological implementation from the technological level. The technology is then applied in the application level on the specific process, area or product, where the process restarts.

4.2 Populating the levels of the architecture

The three levels need to be populated with various elements or reference points to enable the use of the reference architecture for labour-intensive operations. The architecture is explicitly developed for labour-intensive environment use, where the various areas identified in section 3.8 are adapted to the elements identified for Digital Transformation. The areas in the architecture are purposefully kept to a minimum to improve readability, to be broad enough to allow for industry-specific adaptation, and to focus on the areas that stood out the most in chapter 3.

The architecture is developed in such a manner that a user environment can adapt it to their environment. The centre of the architecture describes the value-creation (the product or service delivery) of the environment, where the user environment lays out its value-creation process in process flow format, similar to figure 3.5 in case study 2. A workflow process shows the relationships between areas (at least towards the value-creation delivery) and the general flow of value throughout the environment. Elements, resources and processes from these areas are then categorised in the different areas of the architecture.

4.2.1 Populating the application level

In section 3.8, the project or service delivery, human resource management, equipment management, finished unit storage and spare parts storage are all found in the case studies and literature. These areas include all activities, systems and processes used in the operations or value-creation of a labour-intensive organisation.

Value-creation

The areas in the reference architecture are centred around the value-creation of the environment to represent the manufacturing of products or service delivery (of physical items). This area, involving the actual labour-intensive manufacturing processes and flow of products through the environment production, also includes how the entire process is applied to the manufacturing system, where the process design and synchronisation of the process are presented. Finally, means of guidance or collaboration in the value-adding process are included. The value-creation subsection is designed so that a user can include their manufacturing type, i.e. batch, project, in the centre of the reference architecture and categorise around it, both in the application level's components and the information and technological level.

Based on the relationships and areas identified in section 3.8, the actual value-creation category is where the most cause-and-effect relationships were found. Every other operational area, process and resource in the architecture supports and enables the value-creation of the environment.

Physically, these environments have two types of manufacturing or value-creation processes, as seen in the cause-and-effect relationship of product and service delivery. They are the actual labour-intensive process in which the method of value-creation is labour delivery, as well as supporting manufacturing processes such as machining. In terms of Digital Transformation, both of these processes can be transformed in a variety of ways, ranging from data collection methods for labour-intensive environments, as mentioned in section 2.7.2, to additive manufacturing (see section 2.4.3) for supporting measures.

Furthermore, as mentioned by Oztemel and Gurzev [89] in section 2.3.1, Digital Transformation enables the use of digital process modelling and integration (which can also be related to the data level) to improve the entire process by creating or re-engineering it and synchronising it with other areas. The element, process and synchronisation, refers to combining all processes within the value-creation, i.e. the synchronisation of the labour processes with the supporting processes and the eventual synchronisation of all processes in the operations management.

Finally, all processes in value-creation can be simplified through digital and non-digital guidance, as well as collaborative approaches to DT, such as the use of cobots or other methods of collaboration between labour and cyber-physical systems (human-cps collaboration), which is one of the proposed core components of Industry 5.0 in section 2.9.3.

Every process in the value-creation of an environment can be improved by calculating efficiencies, finding and eliminating wastes and optimising the process. Digital support methods can simplify a process for an employee by guiding an employee or collaborating with an employee in the form of human-CPS collaboration. The process can also be designed, re-designed, changed and improved through digital and technological means. The use of other machinery in the process and the synchronisation and communication between man and machine are often a source of waste, and digital means, such as RFID tracking, can simplify the transparency of the process and reduce these long waiting times.

Labour management

Various labour or human resource management areas can be included, where firms can extensively research the need for labour. However, the goals of this thesis include contributing to a sustainable transformation where the employee is not threatened by or replaced by any methods of digital support. Three areas within labour management have been identified that could be supported by digital implementations:

- **Task allocation:** Data collection and analytics can be used to simplify task assignment, allowing managers to spend less time on task allocation.
- **Training:** Digital training methods can be used to simplify training, where the need for other employees or outsourced training can be reduced to save both costs and non-value-added time for skilled employees. For example, virtual reality or augmented in section 2.3.7 can simplify the training process and reallocate artisans to more demanding areas.
- **Safety:** One of six design principles of Industry 4.0 (see section 2.5). The safety of employees is of utmost importance in such an environment for both the employee and the operation. No one in an organisation wants someone to get injured, and often an employee is a critical component of the value-adding process - where the process cannot continue without them. All improvements should be designed with safety in mind. Additional improvements in digital or technological support specifically for safety, such as automatic shutdown or safety systems, can reduce injury on duty.

Apparatus management

Wastes in the labour-intensive process are often a result of searching for or waiting for tools and equipment that are required in an assembly or manual labour task. Furthermore, as an environment's output develops, its process and resources should develop around it. The facility in case study 1 is filled with unused equipment used on previous units, is in disrepair or is outdated. Apparatus management is simplified in such a manner to include tools, equipment, consumables and all other non-human resources that are required in the labour process or supporting process.

From this, three relevant areas for resource management were identified. Firstly, the control of a resource or tool. Case study 1 has increased control and reduced waste in their waiting times for specialised tools. An online system supplies transparency of tool use, where supervisors and employees know exactly where each tool is at a given time. Controlling assets and resources has a significant opportunity to be improved by digital means. Secondly, the security of resources is also essential and is associated with the control. There are, however, manners in which the security of expensive items can be improved. M2M is an example technology that links the application of machines and data collection to and receives feedback from the data level (see section 2.3.5).

Finally, the relevancy of the resource should also be considered and includes the operation of the equipment, how a resource adds value and whether or not the resource is redundant in the current working environment. There are various machines and equipment in case study 1 that are out of use and can be replaced with modern solutions that aid in both the labour-intensive and supporting processes.

Inventory management

Inventory management of spare parts and finished parts has been addressed separately in the research up to this point and is mainly managed by different departments in these environments. Challenges and opportunities in these two areas are similar. Digital Transformation can be applied, where forecasting in finished units is for operations output requirements and spare parts are for the input requirements.

Three primary areas have been selected in inventory management, which is apparent in the case studies and seen regularly in the literature. Inventory control is grouped and refers to how inventory is controlled in its visibility, tracking and inbound and outbound storage method. Often, time is wasted on inventory as employees are required to manage and store items. Furthermore, paper-based systems are still heavily used, and this could be seen in case of studies 1 and 2. Digital Transformation can reduce the need for paper, where suitability and cost-reduction are highlighted, and it can reduce the need for the employee to do frequent stock checks, which can be used to add value to other processes in operations. Digital support can also aid in stock security, similar to resource management mentioned above.

Finally, these environments' stock and output requirements can be simplified and optimised with increased digital forecasting. An example is in case study 2, where the tracking system automatically identifies parts requirements, and someone is only required to sign off on the purchase.

Product and service management

In the 21st century, the voice of the customer is of increased importance. The product or service of a manufacturing environment is centred around customer requirements. Including this area in the reference architecture is primarily for the operations part of the product or service, as the result of the operations is the product. The entire value-creation is designed around the product or service output of the environment; thus, the type of product, its design and its requirements both impact the entire value-creation and any subsequent improvements in this can aid in increasing the output of the environment. The type of product and how the value-creation adapts customer requirements into a product can both be aided by digital methods. CAD software is an example of how product designs through digital modelling requirements can be simplified by creating digital product design models.

Quality control is also an aspect of product or service management used in most production environments. As seen in case study 2, in labour-intensive environments, quality control is often done manually by a quality controller with the aid of tools.

Effective use of Industry 4.0 could benefit these industries by improving the quality of the value-creation process, as mentioned in section 2.6. Any digital or technological aids in quality control could also potentially improve the quality by reducing quality control needs (as explained in section 3.8.6). Product quality control can be a time-consuming endeavour, where digital and technological methods can significantly reduce the complexity and simplify the process for an employee.

4.2.2 Populating the information level

The importance of data in a labour-intensive environment is evident, and the other levels of the architecture cannot function appropriately without data. The information level represents the data collection and management used to select and apply technology in each area of the application level. Furthermore, the level also includes the connection within the environment to enable real-time connection (if possible) and capture the historical state of the environment.

The data collection tops the elements of the level, as retrieving data from a labour-intensive process is apparent in the research of this thesis. Before managing and applying data, it has to be collected.

Each area in the application level has the potential for data collection, which can be analysed and applied to introduce digital and technological support methods. The importance of data collection has already been discussed in 2.7.2, and the lack of adequate data collection has been discussed in case study 1.

Data management, which allows performance management and process modelling based on the acquired data, represents the second element. The four sub-elements of data management are communication, performance management, process improvement, and analysis of the labour-intensive operational environment. Understanding the data and attempting to use it to enhance procedures or assess performance is referred to as analysis. Any level of communication, or the act of sending and receiving data, is communication. As DT requires data and connections and gives instructions to the software and hardware in the technology level, the data level serves as the foundation of the architecture. The latter two sub-elements are autological.

The information level is also supported by the methodology developed in section 4.5, where a focus on the data collection and application is used to assess the processes of an environment and stimulate the search for additional DT support methods. Additionally, in the roadmap in the subsequent chapter, where incremental implementations lead to real-time connection and the connectivity and information management of the environment, emphasis is placed on the importance of data collection. For example, suppose an environment has sufficiently implemented a data collection and management system. It can move on to a more advanced method, such as a cloud-based system or digital twin (see section 2.9.3).

Additionally, as in the CPS 5C architecture in section 2.3.1, the connection of physical assets can aid in data collection, analysis and real-time tracking. Finally, the data level can also use software in the technology level to create digital assets or simulations, such as digital twins. This, alongside general data management, can be used in process modelling and analysing the performance of the processes.

4.2.3 Technology level

The technology level is the simplest in the architecture and is populated by the user. There are two sub-levels in the technology level, the software and hardware infrastructure. The technology level is the field level, representing the technology used and applied in the environment, such as robotics, sensors, IoT systems and more.

The application level uses physical technology and software in this level to apply each of its elements. Various technologies and implementations that firms can use for applications are discussed in the components of Industry 4.0 and Industry 5.0 a Chapter 2. The method for choosing the physical, technological or methods of digital or technological support (DT support methods) is described in section 4.5.

4.3 Explaining cause-and-effect relationships between areas and elements

Any digital or technological support methods that are implemented in an area would have an impact on another area. For instance, implementing guidance and collaboration could also improve the overall process and synchronisation between the different areas, simplify employees' training and task allocation, reduce inventory or apparatus control challenges and lead to an enhanced quality product.

For this reason, a user environment must understand their operational environment. The roadmap is developed in chapter 5 to use the reference architecture, and the technology mind maps in section 4.5 to progress in a user operations DT endeavour incrementally. The importance of the cause-and-effect relationships between areas is discussed in both.

4.4 Digital Transformation reference architecture for labour-intensive value-creation

The various levels of the architecture, developed and populated, are combined in the Reference Architecture for digital and technological support methods in the operations management of general labour-intensive environments, which can be seen in figure 4.2. The reference architecture is developed so the user can adapt the elements to cater to their specific requirements based on their goals and industry-specific environment.

User organisations can use the reference architecture to map their current environment. First, the architecture should be accompanied by a process flow of any other visual or detailed document on the business processes of the environment. The accompanying document is studied in detail. The business processes are extracted to the reference architecture, where each sub-process, resource, various apparatuses and the current digital climate is listed in the reference architecture format. Table 6.3 lists how to generally map and categorise elements on the reference architecture. Briefly, the method to map the environment on the reference architecture is as follows:

1. **Identify business process:** The accompanying process flow, SOP or other detailed document is used to identify the various business processes in the operations.

2. **Extract sub-processes:** All sub-processes, resources, apparatus and digital/technological connections are listed from the business processes.

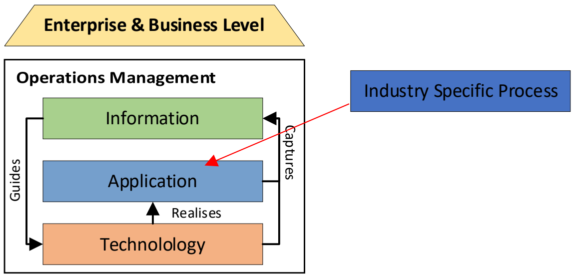
3. **Categorise:** The primary business processes and all accompanying business processes are categorised into the different areas of the reference architecture

The Digital Transformation reference architecture for labour-intensive value-creation can be seen in figure 4.2. The remainder of this chapter develops the accompanying technology mind mapping methodology that is used together with the RA on the roadmap to implement various digital or technological support methods.

TABLE 4.1: *Reference architecture categorization template*

Architecture Guideline

The DT reference architecture for labour-intensive value-creation was developed to help such an organisation visualise the value creation in their operations. The organisation's operations or process management employees can then combine a process flow or description of their work environment in the centre of the reference architecture.



1. To understand the operations of the labour-intensive environment, the following information is required:
   a. Industry-specific process: A process flow or similar diagram is used to visualise the flow of work in the environment, involving each area of the environment and used to populate the different levels. If there are no such visual flow charts or tools, they can be developed using tools such as:
      i. MS Visio
      ii. MS Office alternatives
      iii. Additional third-party or online flow chart applications.
   b. Data level: How is data being collected, stored, managed, and applied in the environment, and is there a relationship to the application layer? For example, an online maintenance system for tag-in times.
   c. Technology level: What are the current hardware and software technologies used in the operations of the environment, and how are they applied, i.e., UNIX data management system, 3D printers, PC service points?
   d. Application layer: Understand the different areas of the labour-intensive environment:
      i. Value-creation: Which steps are required in the value-creation of the environment? This includes labour, machinery usage, and other manufacturing or service delivery forms. Furthermore, what are the current operating procedures and support methods in manufacturing or service delivery?
      ii. Human resource management: How is the current labour workforce managed? This is specifically towards their role in the value-creation, i.e., how are they assigned to tasks, how are they trained, and what forms of safety are used in the operations of the environment.
      iii. Apparatus management: How are resources, such as assets, consumables, tools, and machinery, controlled, stored, and managed in the value-creation environment? This includes the security measures or methods in the process and the relevancy of the resources in the environment, i.e., is a specific machine being used?
      iv. Inventory management: How are inventory inbound (spare parts) and outbound (finished units) managed? This includes controlling stock into and out of inventory, security measures and requirements forecasting for the demand and supply of inventory.
      v. Product/Service management: Understand the outcome of the value creation, i.e., the product or service delivered and how and why the product is produced based on the customer or operations output requirements. Furthermore, what quality control methods does the environment employ to ensure top-quality products?

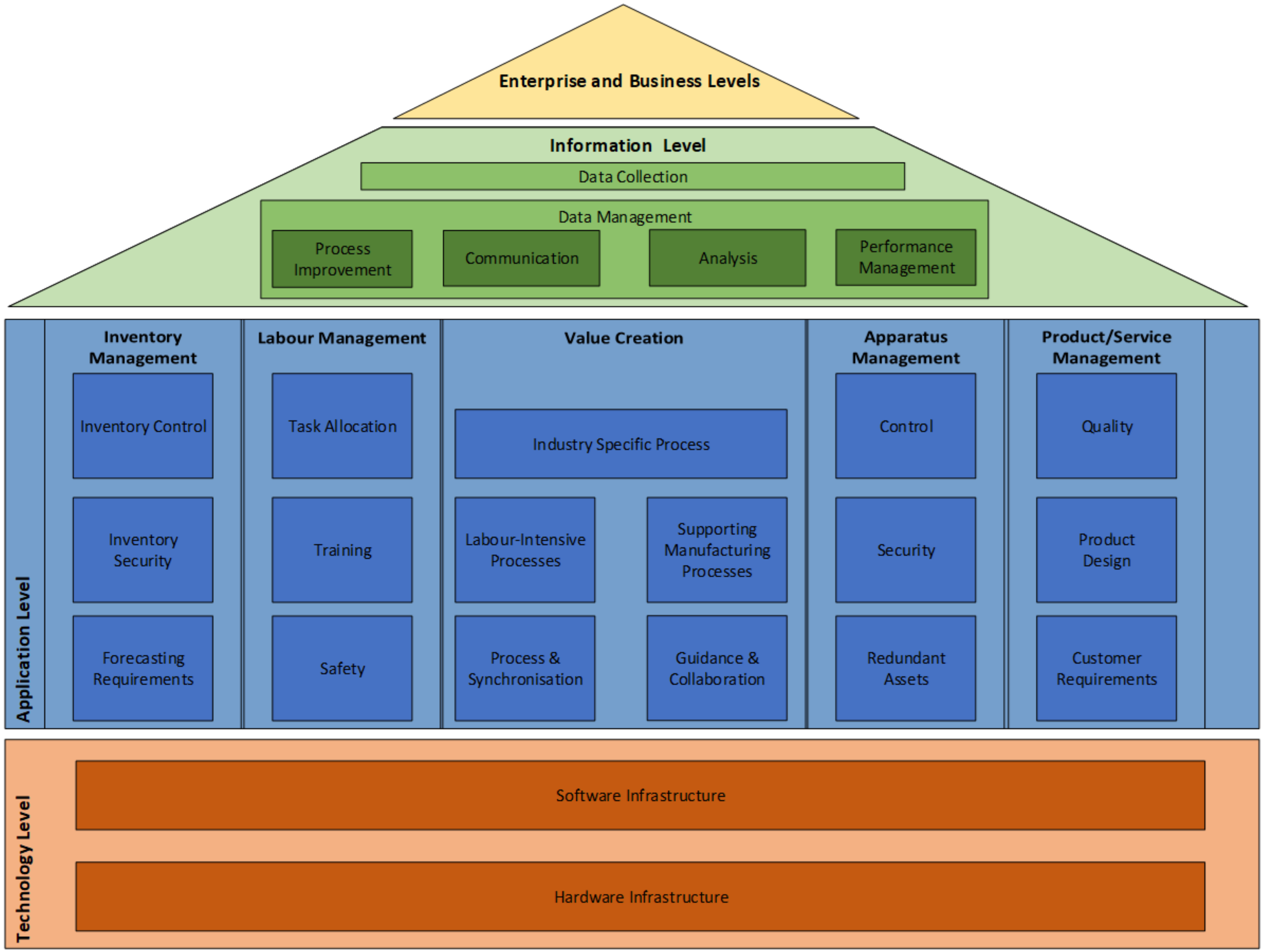


FIGURE 4.2: *Digital Transformation reference architecture for labour-intensive value-creation*

4.5 Methodology for creating user-specific technology mind maps from the reference architecture.

Instead of identifying several digital or technological means of support, a methodology to generate user-specific mind maps is developed due to the uniqueness of each environment. Regardless of how they create value, any labour-intensive setting can use the roadmap in chapter 5 to their advantage. This section develops this methodology based on brainstorming principles, the reference architecture and catered towards labour-intensive environments.

Used together, the architecture and the user-specific mind maps are guiding tools to aid user environments to practically answer the physical goals of the second fundamental question - Where are we going?

4.5.1 Technology mind maps: Brainstorming and mind maps

Minds-mapping is a form of brainstorming where ideas are generated as potential solutions to one of many problems in a topic [124]. The technique of mind mapping was created to help with idea generation. A mind map is typically created by beginning in the centre of the page with the main topic or concept and then working outward in all directions to form an expanding diagram made up of keywords, phrases, concepts, facts, and numbers [124]. Mind maps can be an appropriate method for generating and selecting ideas.

In the user context, mind maps are a valuable tool to ensure that all stakeholders can understand as they can be read and understood relatively easily. A mind map makes it easier to discuss options when choosing ideas from it since solutions can be visually compared. Additionally, creating a mind map is simple. It is also possible to use software like MS Visio, which makes it simple to create diagrams like mind maps for usage in user settings as digital and physical models.

4.5.2 Methodology to develop user-specific technology mind maps

Based on the areas of the reference architecture, various digital or technological support methods can be identified as potential solutions. The area is divided into each pertinent portion using the architecture and technology mind maps employed to choose these solutions. The relationship between the three operational levels of the architecture is used here, as users must find physical and software-based technologies that can be applied to the value-creation of the environment and collect or manage data to enable process improvement and further implementation.

Each area is selected as a set of two technology mind maps. Lower levels of digital or technological support are first identified in mind map form. After that, these mind maps are used to develop new mind maps to identify higher forms of support that build on the previous solutions. Technologies are selected according to two criteria, describing the technology level's relationships with the information and application level. Technology, both hardware and software, is used to capture information in the application level for the information level, and technology is applied at the application level to improve the processes in the application level.

The following process was utilised to create the mind maps, with the first three steps concentrating on creating low-level mind maps, which can be seen in figure 4.3.

1. **Reference architecture area selection:** Each part of the application level in the reference architecture, after environment analysis, is selected as the centre point for its own

two technology mind maps, with its sub-areas serving as subbranches.

2. **Architecture relationship branches:** Each sub-branch is broken down into further branches of data collection, data management and technology application.
3. **Root causes, challenges, and opportunities:** For each relationship branch, the various challenges, opportunities, or cause-and-effect relationships are listed. These subbranches indicate specific processes where various digital or technological support methods can be added to collect data and improve the process.
4. **DT brainstorming:** Utilising research and brainstorming techniques, solutions in the form of digital or technological methods of support are found to address the challenges or opportunities in the form of Digital Transformation.

After that, as shown in figure 4.4, the new set of mind maps makes use of the previous set by identifying new solutions that build on the previous set of solutions. The outcomes of the analysis of the first Digital Transformation is then used to decide on further DT support methods.

5. **Advanced DT solution brainstorming:** More advanced support methods are identified after analysing a previous implementation, either based on the previous set of solutions or the root causes and outcomes of step 3.

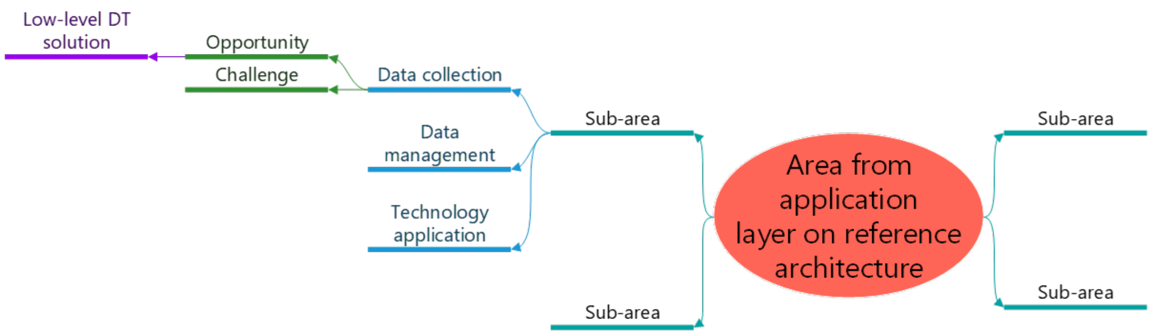


FIGURE 4.3: *Methodology to develop low-level technology mind maps*

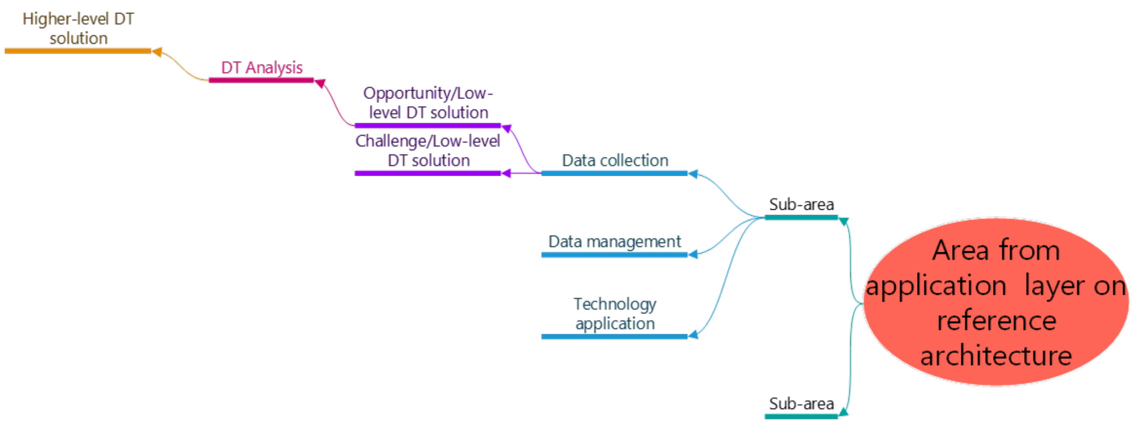


FIGURE 4.4: *Methodology to develop high-level technology mind maps*

4.6 Conclusion

The previous chapter investigated the value-creation process, relationships and typical challenges of labour-intensive environments. This chapter developed a reference architecture that these environments can use to map and categorise their current operations and digital progression. In addition, this chapter introduced a methodology to develop user-specific technology mind maps that these environments can use with the reference architecture to identify potential digital or technological support methods. The next chapter uses the architecture and mind map methodology in a roadmap approach for the incremental Digital Transformation of these environments.

CHAPTER 5

Roadmap development

This chapter expands on the reference architecture created in the previous chapter by creating a roadmap for Digital Transformation in a labour-intensive value-creation setting. The roadmap's function is to provide such environments with a visual tool for implementing digital and technological support methods in the various components of their operational environment as they start on their Digital Transformation journey. The roadmap helps labour-intensive environments effectively embark on their Digital Transformation path by utilising the reference architecture created in section 4.1 and mind maps of technology support developed in section 4.5 of the previous chapter. The roadmap document, outlining each step in detail, can be seen in Appendix C.

5.1 Approach and methodology for the roadmap

Innovation is the successful generation, development, and deployment of concepts that introduce novel or modified versions of current products, procedures, or business models that bring value to an organisation in any way [29]. Implementing Digital Transformation is a type of innovation associated with its own innovation life-cycle [53][29]. Firstly, this roadmap approach to Digital Transformation attempts to guide the user environment through the innovation life cycle of Digital Transformation by innovating on a process or product level. The focus is on the value-creation of the labour-intensive environment, with an incremental approach that limits the disruption of the labour-intensive environment.

Similar to how radical innovations fail more often than incremental innovations in customer delivery [29], where the customer's needs need to be thoroughly understood, innovation in the value-creation of a labour-intensive process can also have this difficulty. A radical change in the environment can disrupt both the value-creation of the environment and the morale or employee acceptance of the innovation, as seen in sections 2.3.1 and 2.7.2.

Secondly, this roadmap is developed to reduce the complexity of the user environment by giving a straightforward set of steps to achieve their Digital Transformation. The steps are intended to be easily readable, informative and interchangeable where the user environment deems necessary. Examples are often used to illustrate the document's use to the user organisation, where potential tools and methodologies are recommended in specific steps. An online google sheet spreadsheet accompanies the document with numerous templates and methodologies used in certain steps. The case study in Chapter 6 also illustrates a possible use of the roadmap for a user environment.

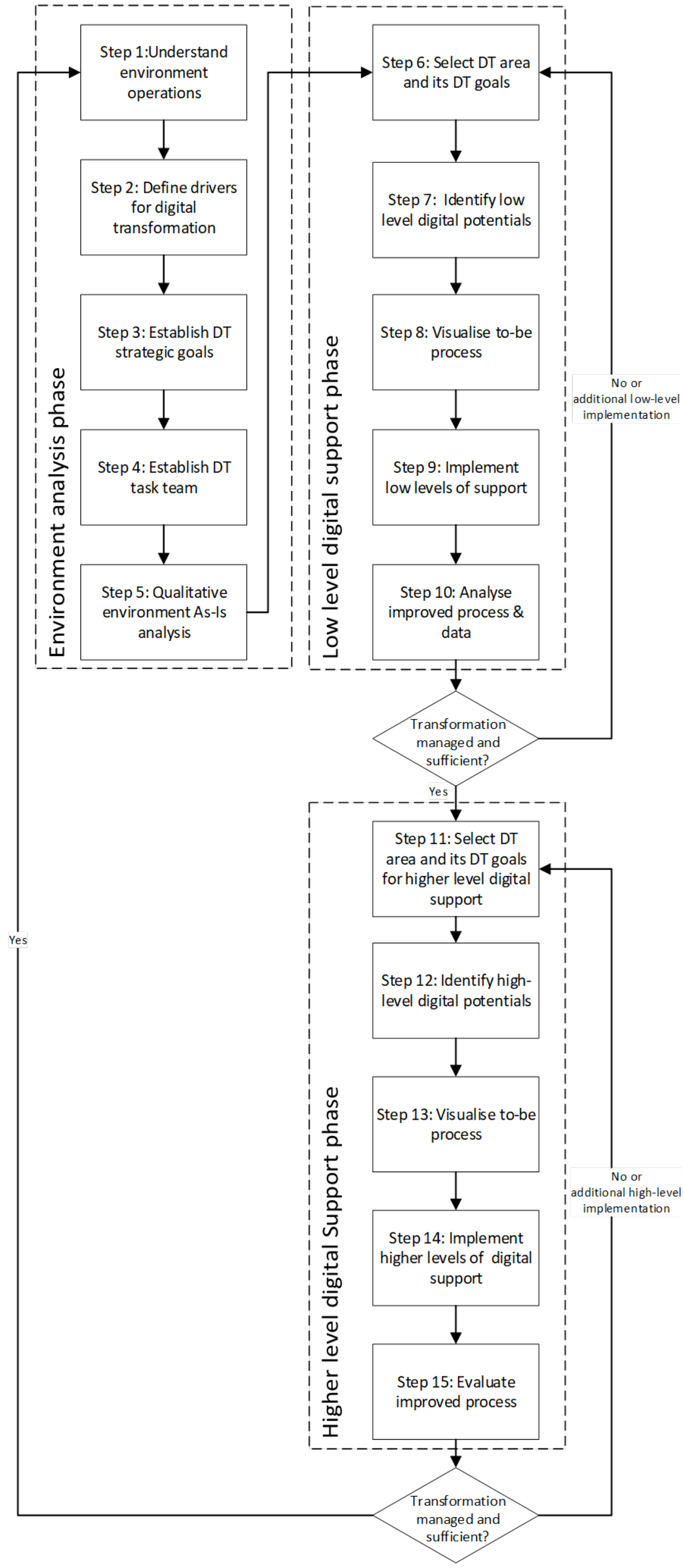


FIGURE 5.1: *A roadmap for the Digital Transformation of labour-intensive organisations*

Furthermore, the methodology of continuous improvement is incorporated into the roadmap design, where three feedback opportunities are presented to user environments in each of the three phases of the roadmap, i.e., the environment analysis phase, lower-level DT support phase and higher-level DT support phase. The reasoning behind the feedback is two-fold, firstly, to test innovations in certain areas and secondly, to ensure the continuous improvement of the value-creation within the labour-intensive environment. For this reason, when the task team feels that their Digital Transformation journey has concluded, the roadmap proposes that the organisation return to the need for innovation, or step one, where the task team and organisation should re-evaluate their environment, redefine their drivers and restart the roadmap. Similar to innovation, Digital Transformation is continuous, where drivers today are not the same as five years ago, as the three incarnations of Gartner's Hype Cycle for Emerging Technologies in figure's 2.24,2.25 and 2.26 prove.

By directing the user environment in the incremental Digital Transformation of their environment, the roadmap acts as an implementation strategy for the innovation that is Digital Transformation. The roadmap uses technology mind maps, as shown in section 4.5, and the reference architecture in section 4.4, to identify and implement potential low-level and high-level DT support methods.

The roadmap's goal is to serve as a guiding tool that encourages a practical and bottom-up approach to Digital Transformation. More emphasis is on implementing these digital or technological methods of support than on designing a Digital Transformation framework or point of view assessment methodology of an environment's digital maturity. However, to comprehend the possible breadth of Digital Transformation within organisations, frameworks or roadmaps like those created by Du Plessis [28], Rautenbach [103], and Kretschmar [57] have been employed to draw inspiration towards the roadmap. A similar template to Kretschmar's [57] roadmap was used.

Finally, the roadmap is developed to be modified to fit the user's demands.

5.2 Roadmap development: Environment analysis

Management must first define why they intend to embark on the DT process to initiate the organisation's Digital Transformation journey. Additionally, before exploring or implementing any method of digital or technological support, or DT support method, the organisation needs to define their strategic goals based on the Digital Transformation driver of its environment and create a task team to lead the DT endeavour. It would be the organisation's first responsibility to understand the environment where-after they can identify different potential levels of DT support methods.

The first step of the Digital Transformation roadmap is to analyse and understand the environment utilising the reference architecture developed in Chapter 4.

5.2.1 Using the reference architecture to understand the environment operations

The reference architecture created in section 4.1 is used in this step to map and comprehend the user environment's value-creation process. To understand the user's labour-intensive environment, users of the reference architecture and roadmap generalise the value-creation within their environment inside the reference architecture by classifying each aspect and area of their environment to each layer and element of the reference architecture. The detailed procedure for using the reference architecture is described in the roadmap in Appendix C with a link to the reference architecture's excel spreadsheet. It is the same process outlined in table 6.3 in section 4.4,

In summary, a detailed process flow of the user environment, or created by the task team using tools such as MS Visio, is centred on the reference architecture. Each step in the process flow is then classified into the areas of the architecture to find areas for the roadmap implementation.

5.2.2 Defining the need for Digital Transformation

After understanding the environment, the organisation needs to determine internally and externally why they wish to start a DT endeavour. It was stated in Chapter 2 that a labour-intensive environment's transformation hesitation, labour workforces, and lack of knowledge or expertise are reasons why the journey toward Digital Transformation is delayed. Nevertheless, as discussed in sections 2.3.1 and 2.7.2, the need for Digital Transformation in these environments is unavoidable, and the motivation for DT will come from both internal and external forces. For businesses to build and maintain a competitive advantage in a rapidly evolving and highly dynamic globalised world, innovation is critically important [29].

The next step that the company needs to do is define the drivers for Digital Transformation to direct the DT journey, decide what kind of digital methods of support the organisation will employ, and describe the general rationale behind and the direction of the DT.

There are internal drivers like the desire for the workplace and process improvement, cost reduction, or integration, as well as external drivers like competition, regulation, or industry innovation pushes, as indicated in section 2.1.2.

These drivers determine the overall course and results of the transformation; once they have been addressed, the organisation and task team must re-frame their drivers and then realign their transformation effort.

5.2.3 Establishing the Digital Transformation strategic goals

The drivers found in step 2 are used as the starting point for this phase. The task team must establish the boundaries within their scope on how they will carry out their transformation process and identify the overall outcome, i.e., what they hope to achieve with the change. The task team must establish their own Industry 4.0 vision and define Digital Transformation within its context.

They must decide how far they are willing to go in the DT process and what trade-offs the organisation is willing to make to succeed in the process to establish the boundaries of their transformation. Each user would have a unique set of objectives and constraints. An example strategic goal is a triple bottom line outlook, described in section 2.8 but this roadmap attempts to develop an environment that is human-centric, resilient, and sustainable, or an Industry 5.0 environment as stated in section 2.9.

This step generally involves determining what the task team and organisation want to accomplish with the Digital Transformation process, who and what they are taking into account, and how far they are prepared to go. The accompanying spreadsheet outlines the core commitments of an organisation, two potential approaches - the triple bottom line and Industry 5.0, and two example goal-setting methods. Goal setting is a significant component in business, and most organisations already have goal-setting strategies. User environment can integrate their core commitments and desired approach to defining new strategic goals, specifically towards their DT endeavour.

5.2.4 Establishing the Digital Transformation task team

It is clear from case studies 1 and 2, sections 2.7.2 and 2.9, that it is crucial to have everyone in the environment on board for a Digital Transformation journey. In the context of this roadmap, there are two reasons for creating a task team for Digital Transformation. First, the organisation needs planning and execution to manage the DT project to achieve an adequate transformation. Second, the task team, which is in charge of maintaining the cohesiveness of the entire value-creation team, needs to inspire and reassure personnel that the DT initiative would not threaten their positions within the business.

In addition, developing such a team would facilitate shared accountability, reduce the stress associated with the transformation, and promote group thinking, allowing DT decisions that take research and practical consideration into account before implementation. A varied group of people from all tiers of the value-creation hierarchy of the firm should be the organisation's goal. The general responsibilities of each task team member the user is advised to appoint are outlined in the roadmap document in Appendix C. These responsibilities are based on observational experiences in case studies 1 and 2 and additional research in chapters 2 and 4.

In summary, the operations manager, or equivalent individual, is responsible for the overall value-creation of the user environment and would lead the DT team. A representative from top management would support the operations manager job, depending on the size and hierarchy of the business, as in case study 1, by reviewing and approving modifications that only high management would be able to authorise. In a smaller firm, like case Study 2, the responsibilities are integrated, and the individual in charge of the firm's value-creation can make these changes independently.

The core Digital Transformation team, responsible for understanding the areas in the environment, analysing challenges, investigating viable solutions, and identifying partners to implement any digital support, then provides support to these persons.

The supervisors or members of middle management, i.e., those in control of the various areas in the environment, would function as supporting roles in the DT task team to verify the viability of the implementations, inspire the ground personnel, and receive input from the bottom up.

5.2.5 Analysis of the current environment

This roadmap's incremental approach to DT advises against trying a full-scale transformation and instead suggests transforming a small number of areas over time. Analysing the current environment is necessary to choose the areas that need to be transformed. The user team must utilise the available knowledge to extrapolate from the previous step and analyse the environment. The lack of usable data is evident in the majority of labour-intensive environments, according to both case studies, the supporting literature, and the data analytics model developed by McKinsey & Company [41]. For this reason, the best places for transformation are identified through a qualitative investigation of the surrounding environment. The task team can utilise any qualitative data-gathering method, similar to how the data was collected for the two case studies, to analyse, rate, and classify each component of the user environment. The analysis need not be restricted to qualitative analysis if quantitative data are available. Calculating efficiencies and quantifying wastes can also be done to analyse the areas.

The main goal of this step is to pinpoint the areas that need to change immediately so that the following step can be supported by observational studies, root-cause analyses, on-the-ground discussions, and other techniques. Templates in the roadmap include qualitative methods such as five why and fishbone root cause analysis and quantitative methods such as overall labour effectiveness and takt time analysis.

5.3 Roadmap development: Low-levels of digital support

The method for this roadmap is incremental, as described in section 5.1. Based on the environment analysis, the next phase in the roadmap is to identify, pick, and execute potential digital or technological support methods. Before moving on to higher forms of Digital Transformation, this roadmap phase chooses lower levels of support to evaluate the DT process, interaction, and cause-and-effect relationships from the implementation in the environment, particularly with the labour force. Additionally, the application of lower levels of DT support methods can meet the requirements above easily, affordably, and with little disruption, depending on the user drivers, strategic goals, and DT goals.

For example, suppose an organisation decides that their desired level of Digital Transformation only constitutes the implementation of cheaper, more straightforward or other lower levels of DT support. In that case, the user only needs to proceed through this phase.

Users are not constrained to the roadmap information and are encouraged to modify the DT process as they see fit. Based on the research in Chapters 2 and 4 and the reference architecture, examples of digital or technological support methods are listed in the mind map figures on pages 214 and 224 in Appendix D that act as potential solutions for common problems in a labour-intensive environment. These mind maps have some limitations and can and must be modified or tailored to the results of step 4. Additionally, specific methods become dated, more accessible, or less expensive when technology develops and should be replaced or introduced.

Using the Gartner Hype Cycle for Emerging Technologies, shown in figure 2.24, as an illustration, one can see how some technologies that may have been too difficult to implement in the past are now more possible. An example being the increased use of blockchain and cryptocurrency today, when compared to before 2017 (before the innovation trigger) or during 2018 and 2019 (during the through of disillusionment).

Users can also switch specific steps before deployments, such as testing or in-depth solution analysis. The four steps that make up this phase are: identifying low levels of DT support methods, visualising the new process, putting it into practice, and analysing it. Afterwards, the task team can either keep providing DT support at higher levels for that area or try to convert other parts of the labour-intensive environment.

5.3.1 Selecting areas for DT and defining their respective DT goals

The roadmap's incremental approach requires the selection of one or more areas in a low-level transformation of digital or technological methods of support before trying a more extensive and more sophisticated transformation based on the task team's understanding of the environment and their analysis.

Additionally, the user is encouraged first to choose areas for data collection, to analyse the area further, and to discover additional relevant means of digital support due to the apparent lack of data collecting and administration in a labour-intensive procedure. Once a certain level of data collection has been put in place, a quantitative analysis may now be used to streamline the choice of the DT method in the following stage of the roadmap. As a result, a feedback loop is returned to this stage, where decisions and implementations in the environment are made based on the outcomes of the next section of the roadmap.

If the implementation is deemed successful, the team goes back to this step, where they either implement additional support methods based on data collection or other results of the low-level implementation. The team can also choose an entirely new area before moving on to a higher form of digital or technological support.

This step chooses which areas to transform based on the results of steps 4 and 5, the strategic goals of the environment stated in step 3, and the results of step 5. Depending on their strategic goals, each user environment would choose a different area, with lower DT goals for each area. Examples of selection criteria include:

1. Selecting which area, based on the qualitative analysis, is the most obvious and where quantitative data may be used to advance the process. Due to the absence of data and a higher likelihood of discrepancies, it is likely that in the user environment, the labour-intensive or value-creating activity would be the most obvious, and the user would choose this to begin data collection before turning to other methods of support.

2. Selecting the area where data can be collected easily.

3. Selecting spaces or stations that are quantitatively inefficient.

4. Deciding on the least disruptive area to evaluate the viability of implementation and the effects of a DT implementation on all parties. As an illustration, inventory management could be used to demonstrate to staff that DT deployment is not always detrimental to their capacity to add value.

5. Selecting an area in line with the digital goals, such as selecting the labour-intensive process where a certain method of digital support can promote human-cps or human-robot collaboration.

6. Building on the outcomes of a previous area's implementation, such as using the data collected to implement an additional DT support method or adding additional lower levels of DT support to the process in a particular area based on outcomes proving that a support method works well in the process or well with the labour workforce.

The roadmap document uses a Pareto analysis, a tool for decision-making on and prioritising competing problems in the user firm's operation [51] [18]. In this case, the Pareto is based on amount of challenges in the different areas of the reference architecture and aims to select different areas for Digital Transformation.

5.3.2 Identifying potential low-level methods of digital support

Finding potential digital or technological solutions to the outcomes of the preceding steps, specifically for the chosen user environment area(s), is the first step in the actual transformation.

Following the DT goals for the chosen areas, lower levels of DT support are suggested as solutions for problems and opportunities for forms of digital advancements. The task team can study these less advanced DT support levels. The mind map methodology in section 4.5 can be used to identify these DT support methods and applied to many areas, opportunities, and problems of typical labour-intensive industrial environments and the reference architecture and serve as prototype DT support or a starting implementation to handle these areas.

Once more, the reference architecture is utilised to highlight the selected area and show how it relates to other levels and components. These solutions are chosen using technology mind maps based on the environment's data availability and collection, other DT support methods, and the implementation's desired results. The goal of low-level implementation is twofold: first, it should demonstrate to these kinds of environments that potential solutions, like DT support, can be implemented at low cost and minimal disruption and significantly affect value-creation; second, it should serve as a prototype for solutions where a higher level is advised, like a full-scale RFID or IoT tracking system.

The task team needs input in this section, particularly from the foreman or other team members involved in the administration of a specific area, to test the viability of proposed solutions and foresee the implementation's labour reaction and cause-and-effect links.

The data level stresses the use of quantitative data to research further the area in the architecture and the feedback loop in the lower level of this incremental roadmap for DT support methods and non-digital methods like standardisation, lean manufacturing, or process design and improvement. Therefore, it is suggested to concentrate on data collection before moving on to other digital or technological support approaches.

5.3.3 Visualising the transformed area

The DT task team should first attempt to comprehend the impact that the implementation(s) would produce, both within the area and within the general environment, before implementing the DT method(s) specified in the selected area(s). Additionally, charting the process' future state would help the task team adopt the DT support approach by enabling them to see the effect of the implementation graphically.

In this section, the implementation and areas are listed, the relationship effect is examined, and the interaction with human resources is given specific attention. Standard operating procedures (SOPs) are updated, or new SOPs are created if necessary to reflect changes to the relevant process flows. The reference architecture is expanded to include the anticipated effect and implementation.

The implementation's potential cost-benefit proposition should also be considered since it may determine whether the DT implementation is financially feasible. Using cost-benefit analysis, investment ranking, break-even analysis, and other cost estimates, such as energy usage, are examples of potential cost-benefit propositions.

The potential disturbance should be examined To assess the possible RST generated by the implementation.

The templates added to the roadmap show a few methods that user organisations can use for this analysis.

5.3.4 Implementing the methods of digital support

The next step is to put the solution into practice after researching the DT support methods and their effects on the surroundings. Most lower-level implementations are chosen for their low cost and negligible impact, at least according to the mind maps. The task team can purchase the hardware and software needed for the implementation after receiving approval from upper management (if required, based on the task team selection).

Either the team implements the solution, or a third-party company is engaged to implement the hardware and software, depending on the implementation.

5.3.5 Evaluating the transformation to determine further steps

Evaluation of the current process is the last step in the roadmap's low-level digital support phase. The roadmap's outputs define the subsequent actions the user organisation should take in their roadmap-based approach to Digital Transformation.

The new and enhanced process must be assessed to ascertain whether the transformation was effective, similar to step 5. To determine how the process improved, the task team would employ quantitative and qualitative methodologies in this situation. Again, in this instance, the middle manager or person in charge of the transformed area is consulted to assess the transformation. Each user environment would produce different results depending on their strategic objectives and particular area DT goal. Quantitative analysis for the break-even of implementations, energy savings and efficiency difference can all be calculated, as seen in the quantitative template in step 5.

The possible cost-benefit proposition of the implementation should also be examined because it may decide if the DT implementation is financially feasible. Once again, examples of potential cost-benefit propositions include cost-benefit analysis, investment ranking, break-even analysis, and other cost estimations, such as energy usage.

Finally, the disruption should be analysed to evaluate the potential RST created by the implementation.

Some examples are listed based on the example criteria listed in section 5.3.1

1. Is the DT support method collecting ample data that allows for further analyses of the labour-intensive process and implementation of other digital support methods?

2. Does the data collected aid in understanding the process?

3. Is a quantitative difference noted in station or area efficiency?

4. How disruptive was the implementation based on the feedback from middle management?

5. Is the task team satisfied that the DT support methods support a collaborative environment?

6. Does the new implementation address the challenges and opportunities played out by the previous low-level implementation/data collection method?

7. Do the benefits of the implementation out-way the cost?

After reviewing each implementation, the task team must choose the following stage in their DT project. They can choose to revisit low-level implementation in other environments, keep re-formulating higher DT goals for each area, or stop the transformation process if the task team and upper management deem it appropriate for the time being. Their decision depends on their strategic goals and specific area goals.

5.4 Roadmap development: Higher levels of digital support

To deploy higher and more extreme and disruptive levels of Digital Transformation, the following phase of the incremental roadmap builds on the findings, analysis, and knowledge gathered by the user environment from the lower levels of digital support.

The steps are carried out in a manner similar to that of lower-level implementations, where the higher-level goals for Digital Transformation are chosen first, followed by the identification, visualisation, and implementation of potential implementations. After that, the transformation results are tested, and the following action is chosen.

Each user environment is distinct, and just like the previous phase, each user environment can modify the processes in this phase to meet the requirements of their labour-intensive environment.

5.4.1 Selecting areas for higher forms of DT and defining their respective DT goals

High-level goals for the Digital Transformation of these areas are now specified based on the impact of lower-level DT support techniques, including the labour reaction, collaboration, and enhanced understanding of the labour-intensive process of each area transformed in the second phase of this roadmap. These goals are used to find, test, and practice higher DT support methods.

To choose these higher degrees of digital or technological support, the task team should, by this stage, have a more in-depth understanding of the numerous components in each area.

The feedback output returns following the conclusion of higher-level implementation. The results of this phase are once again utilised to guide future implementation and decisions in the user environment, similar to the previous iteration of area selection and DT goal-setting.

The results of the preceding ten steps are combined for each chosen area to generate new DT goals. Some sample criteria include the following:

1. Selecting the most apparent area for implementation based on the quantitative analysis of the area. For example, a lower level of data collection could have indicated that prototype tracking methods have worked to increase the transparency of the labour-intensive value-creation process. More advanced tracking and tracing methods can be used to optimise the process even further.

2. Selecting areas where previous implementations have been well received and a further implementation would be limited. For example, where DT support implementations have simplified the process by removing specific steps from the labour-intensive process, the worker can now focus on other more critical and stimulating tasks.

3. Selecting other methods of human-CPS or human-robot collaboration, for example, implementing human-robot collaboration, based on the reception of previous simple collaborative initiatives.

4. Building on the outcomes of a previous area's implementation, such as using the data collected to implement an additional DT support method or adding additional higher levels of DT support to the process in a specific area based on outcomes proving that a support method works well in the process or well with the labour workforce.

5.4.2 Identifying potential higher level methods of digital support

Finding more advanced prospective digital and technological support methods to handle new issues, opportunities, and the intended process improvement for the chosen area(s) is the second actual transformation step.

As demonstrated in the methodology in section 4.5 sample higher DT support techniques can be found by building on the previous technology mind maps, based on the chapters 2 and 4

The reference architecture is employed once more to focus on the chosen area and its relation to the other levels and components. The choice of a new higher-level DT support methods is made using the currently available data from any prior transformation iteration. Methods effectively applied in the past can now be expanded to improve the process further.

Here the middle management input is especially important to any identified methods, as higher levels of DT support methods are often more disruptive than lower-levels. A bottom-up approach can aid in limiting the disruption, guiding the research and implementation of the task team, and testing the potential relationship of and the impact of the implementation within the environment.

5.4.3 Visualising the transformed area

The DT task team should first attempt to comprehend the impact that the implementation(s) would produce, both within the selected area and within the general environment, before implementing the DT method(s) specified in the selected area(s). Additionally, charting the process' future state would help the task team adopt the DT support approach by enabling them to see the effect graphically.

This section examines the relationship effect and emphasises the relationship with human resources while listing the implementation and areas. Standard operating procedures are updated, or new ones are created if necessary to reflect changes to the relevant process flows. The reference architecture also incorporates the anticipated impact and implementation.

The possible cost-benefit proposition of the implementation should also be examined because it may decide if the DT implementation is financially feasible. The potential disturbance should again be investigated to judge the potential RST produced by the implementation.

5.4.4 Implementing higher level methods of digital support

After studying the DT support methods and their effects on the environment, the following step is to put the solution into practice. The task team can use various techniques to implement the solution, including prototyping these approaches. Higher-level DT support methods are more radical and disruptive than their lower equivalents. After getting the go-ahead from senior management, the task team can purchase the hardware and software required for the implementation (if required, based on the task team selection).

Similar to the previous phase, depending on the implementation, either the team implements the solution or a third-party company is hired to implement the hardware and software.

5.4.5 Evaluating the transformation to determine further steps

The high-level digital support phase of the roadmap ends with an evaluation of the current process. The outputs of the roadmap are used to determine whether the user organisation should continue with its roadmap-based approach to Digital Transformation or declare the transformation successful.

The new and improved process needs to be evaluated to determine whether the transformation was successful, much like step 5. The task team would, in this case, use both quantitative and qualitative approaches to identify how the process was improved. The middle manager or individual in charge of the transformed area is once more consulted to evaluate the transformation. Each user environment would result in different outcomes depending on their strategic objectives and specific area DT target.

As seen in the quantitative template in step 5, quantitative analysis for the break-even of implementations, energy savings, and efficiency difference may all be calculated. Once again, the transformation's disruption potential and cost-benefit proposition should be considered to evaluate if the implementation is successful.

Calculations and tools such as these can be used to determine the effectiveness of the transformation, along with other qualitative measures. Some examples are listed based on the example criteria listed in section 5.4.1:

1. Is the DT support method increasing the transparency of the labour-intensive process?
2. Is the higher-level implementation well received in the environment, both in the process and the labour workforce?
3. How disruptive was the implementation based on the feedback from middle management?
4. Is the task team satisfied that the DT support methods support a collaborative environment?
5. Does the new implementation address the challenges and opportunities played out by the previous low-level or high-level implementation?
6. Is the task team and top management satisfied with the environment's overall level of digitalisation?
7. Can the difference be measured quantitatively, and is it worth it?
8. Does the benefits of the implementation out-way the cost?

5.5 Conclusion

Throughout this chapter, the roadmap was developed based on the reference architecture developed in chapter 4 to serve as a practical and bottom-up approach to the Digital Transformation of labour-intensive organisations. In addition to providing the user environment with a straightforwards procedure on how to achieve their desired level of DT, the roadmap also makes of the reference architecture (or other assessment methods) to analyse the current state of the user environment and brainstorming ideas, such as the technology mind maps, which are developed in section 4.5, to visualise the desired state of their Digital Transformation.

Labour-intensive environments wanting a degree of Digital Transformation have the chance to immediately use the roadmap because of the principles and techniques featured in it. The roadmap can be used as an implementation tool. In addition, the roadmap can be used educationally to inform people at different levels in a labour-intensive organisation about Digital Transformation, as demonstrated in Chapter 6. Results from Chapter 6 have demonstrated the tool's instructional effectiveness in encouraging cooperation and adoption of Digital Transformation within such an organisation.

The reference architecture developed in the previous chapter is expanded upon in this chapter by developing a roadmap for Digital Transformation in a labour-intensive value-creation environment. The methodology and each step of the roadmap are explained, where-after the technology development, and mind maps used within the DT roadmap are explained. The roadmap, reference architecture, and mind maps are ready to be used in a labour-intensive environment. Research objective 1.5, where the different components of the roadmap is developed, and ROI 1.6, the actual development of the roadmap, were completed in this chapter.

Chapter 6 evaluates the research with expert verification. The chapter also tests the research on a repair facility in which operations have been physically simulated in the Stellenbosch Learning Factory (SLF) and where the input of middle managers is used for validation purposes.

CHAPTER 6

Evaluation of the DT roadmap and methodologies used.

The goal of this chapter is to present the Digital Transformation roadmap's verification and validation. The chapter begins with verification, which tests the output and usability of the roadmap. The participant selection, verification, and post-verification actions are all described. The roadmap is then validated with use cases in the Stellenbosch Learning Factory and survey validation input from middle management at a research partner. The validation process involved using the architecture on a replicated repair facility and testing various low-level and high-level DT support methods to validate the steps of the roadmap. Finally, the chapter is completed with a discussion of the validation results.

6.1 Evaluating the output and usability of the roadmap

The first stage of research evaluation is to verify the use and outcome of the roadmap, which includes using the reference architecture and the technology mind mapping methodology. Industry professionals were selected to advise on the usability and output of the roadmap (referred to as experts for the remainder of the research). The verification process, entailed email or MS Teams correspondence in which the roadmap document, as shown in Appendix C, was distributed to the experts. Depending on the nature of the correspondence, a brief explanation of the research rationale and approach was provided. Example uses of the reference architecture, as illustrated in section 4.1 and technology mind mapping methodology in section 6.4.1 were also distributed. The experts were asked to read through the document, assessing its logic, readability, and final usability to determine whether the document could be used in their environment or as consulting material in their client-type environment.

The verification inputs are shown in table 6.2, where the verification input from each expert correspondence is summarised with their rationale and usability input, along with any changes they would like to see or recommended in the architecture, mind map methodology or roadmap.

6.1.1 Selection of industry experts

Two types of industry experts were consulted to verify the roadmap's output: professionals with experience in labour-intensive environments and Digital Transformation, respectively. In total, five experts were consulted, two in the field of Digital Transformation, two in the field of labour-intensive value-creation and one with experience working in both a labour-intensive setting and as a DT consultant. To be selected, all experts had to have an engineering or operations management background with a minimum of five years of industry experience in their field and experience in working in a developing context.

Expert A is currently the global operations manager in charge of digitalization and Digital Transformation at a major German technology company with offices in more than 40 countries. They are based in South Africa but regularly travels for work to various area. Expert B works as a business analyst for a global multidisciplinary engineering firm, mainly focusing on Digital Transformation and change management in mining and manufacturing. In addition, the expert has worked as a digital project manager and consultant for one of the world's leading consulting firms. Expert C also works for the same organisation as expert B and has more than 13 years of experience working in labour-intensive organisations and as a digital consultant. They also have an MBA degree and first-hand experience as a superintendent in a labour-intensive environment.

The remaining experts currently own and operate labour-intensive environments in South Africa, expect D working in metal fabrication to fabricate steel products for use in construction. Finally, expert E is the owner and managing director of a leading rubber and silicone production company with more than 30 years of experience. Table 6.1 summarises the experts, subject-matter knowledge, experience, and other relevant information.

6.1.2 Rationale and research verification

All five experts agree that Digital Transformation is a challenge in their environments or client environments that use much labour. Similar to the challenges shown in section 2.2.2, experts A, D and E point out the cost risk involved with Digital Transformation. Additionally, all experts concur that there are issues with change management, with expert D emphasizing in particular that *"Culture eats strategy for breakfast"* when referring to resistance to change (RTC).

Additionally, Expert A, who regularly does similar projects in their professional capability, also uses observation and qualitative data collection in their consulting, where the emphasis is put on finding a practical problem to change digitally and not merely transforming for the sake of transforming. Finally, it should also be mentioned that expert D has stalled any digital endeavour due to its financial and staffing risks.

6.1.3 Architecture and mind map methodology discussion

The reference architecture and mind map methodology were discussed in detail. All experts, especially experts D and E, agree that the reference architecture captures all areas in the value-creation sector of their organisation, and that mapping the processes together can aid in selecting particular areas. Expert D mentioned that the reference architecture and mind mapping methodology could solve their desire to track products and spares in their environment's inventory.

Additionally, experts A and C agree with using the reference architecture. Expert A regularly develops and uses layered diagrams similar to the reference architecture, the automation pyramid and levels used in the discussion in section 2.12.

All experts also agree with the mind mapping methodology, especially when prototyping or testing areas in their or a client's environment for transformation. Expert E mentioned that in their last significant change - in automation and digitization, incrementally testing implementations in areas aided the adoption.

The consensus among experts was achieved on developing the mind mapping methodology to identify user-specific support methods rather than creating a complete set of mind maps. Each user environment is distinct and different DT support methods are appropriate to varied circumstances. In the verification correspondence, the experts generally support using the reference architecture and technology mind mapping process, and no significant adjustments were suggested. Experts agree that these techniques might be applied in practice rather than only as theoretical ideas.

6.1.4 Roadmap discussion

The roadmap approach developed in chapter 5 has continuously developed to its current state, and the input from industry experts has aided in refining the roadmap to be used, at least as a starting point, as an implementation model in either a labour-intensive user environment or a client environment.

In detail discussions with each expert were used to verify the roadmap approach, the summary of which can be seen in table 6.2. Experts A, B and C, who are all experienced in Digital Transformation, noted that the approach is not different from what is expected in specific industries, especially in their exposure to developing countries. Experts A and C concur that making digital changes solely for the sake of DT is not a good idea and that solutions should instead be found for real-world issues. Experts D and E also agree that, given the challenges in their environment, using the first phase of the roadmap is beneficial to find value-adding change and not merely implementing change for the sake of DT.

The use of low-level implementations to precede more complex, disruptive or high-cost Digital Transformation is accepted by all experts. Breaking down the transformation into two transformation phases is also good, especially with the continuous loop, giving user environments the opportunity to revisit areas and select new areas. Expert A, the head of digital operations at a large German technology company, agrees that the overall roadmap approach is a good way of tackling a labour-intensive environment and uses a similar approach to their clients in South Africa, Germany, the USA and China. Expert B used a similar approach in their DT projects in Namibia and Botswana in recent years and could not find any significant shortfalls in the roadmap.

The industry experts recommended that more emphasis should be placed on the cost-benefit proposition of Digital Transformation, and additional tools or methods could be used to counter RTC. Experts A and C also recommended reshuffling steps in the first phase of the roadmap to counter the notion of transforming for the sake of Digital Transformation. As senior management has the final say in all decisions, expert D recommended adding more connections with top levels of management to the roadmap for financial and goal-setting reasons. These recommendations are discussed in section 6.1.5 below.

According to expert verification, the collective use of the tools in the roadmap approach is suitable for practical and value-adding Digital Transformation. All experts concur that the roadmap may be applied practically in industry. However, for best results, a medium-sized organisation should use the roadmap, or a consulting company could use it as a consulting tool for smaller-sized businesses. The inability to launch such an endeavour on one's own due to lack of knowledge and resources are two reasons behind this. Nevertheless, according to the consensus of industry experts, the roadmap can be utilized as a practical instrument to accomplish beneficial levels of Digital Transformation in user companies or client environments.

6.1.5 Conclusion and post-verification adjustments

Even though a consensus on the output and usability of the roadmap was reached, the findings in the verification stage led to a minor adjustments in the roadmap document. Specifically, four areas that the first draft roadmap lacked are addressed below, where specific changes are indicated.

1. Cost-benefit proposition and strategic goal decision-making

Expert A pointed out that the lack of a cost-benefit proposition could threaten a user organisation's DT endeavour, as this is often the bottom line for any operational decisions. Expert E recommended using more input from upper management and further outlining in determining strategic goals. Additional sheets were added to the template, including various cost-benefit and goals-setting tools that can be incorporated into exsiting company cost-benefit and goal-setting procedures of user-environments.

2. Resistance to change

Even though the incremental approach to implementation design is intended to limit disruption and promote change management, experts D and E suggested adding RST tools and workshops that can be applied in specific steps of the roadmap. The addition of social dialogue, change management workshops, and RST evaluation tools in steps 8, 10, 13 and 15 were added to address these concerns.

3. The evaluating phase of the roadmap

Before verification, the first four steps of the roadmap were in a different order. The first edition of the roadmap started with defining the transformation drivers. After that, the DT task team step, followed by the DT goals, with step four being understanding the environment's operations. Experts A and C especially pointed out that to avoid change for the sake of Digital Transformation, the first thing that a user environment should do is understand its environment's operations and ensure that DT can solve practical problems and have concrete results without being a liability. After consultation, the first four steps of the roadmap were re-arranged to their existing order.

4. Roadmap user target group

The target group of the roadmap was adjusted to focus on medium-sized organizations with ample resources to perform DT. In addition, DT consulting companies can use the roadmap on smaller companies. As pointed out by expert D, the use of the roadmap as a consulting tool for smaller companies can potentially overcome challenges, such as the lack of internal DT knowledge.

TABLE 6.1: *Industry experts used in verification.*

Expert	Subject-matter area	Years experience	Other relevant information
A	Digital transformation, Operations & technology management	20+	• Global DT operations manager for a large German technology company. • Industry DT experience in Germany, the United States, South Africa, and China • Experience as a digital and operations manager • Uses DT resources (such as roadmaps, frameworks) in both internal and client processes.
B	Digital transformation, Manufacturing & mining management consulting	5+	• Previously worked as a DT consultant for a global consulting firm in management, and projects in South Africa, Botswana and Namibia. • Senior business analyst for a multidisciplinary consulting firm operating in South Africa and Kazakhstan, specialising in business practice • Experienced in change management and process optimization
C	Digital transformation Labour-intensive value-creation, Production management, Industrial management	13+	• Management consultant for a multidisciplinaryconsulting firm operating in South Africa, Brazil and Kazakhstan. • Experience in labour-intensive and digital industrial management • Qualified MBA with consulting experience in a wide variety of fields that regularly involves labour. • Worked previously as a superintendent in a labour-intensive environment.
D	Labour-intensive value-creation Project management, Metal fabrication	25+	• Owner and managing director of a steel factory in South Africa (Freestate) • Experience in labour-intensive job-shop and project-based manufacturing. • Factory has minimal DT and a new DT process is desired.
E	Labour-intensive value-creation Manufacturing, Labour management	30+	• Owner and Managing director of one of South Africa's leading rubber production facilities • In charge of more than 200 unionized employees for 30+ years. • Previous experience with major transformation and disruption in a labour-intensive setting (digitization and automation)

TABLE 6.2: *Expert verification correspondence summary*

Expert	Research rational	Usability and output in expert's or expert client context	Recommended changes
A	Agree	• Similar to models and approaches taken in expert client environments. • Supports using a qualitative approach to comprehend and map user environments. • Agrees with mind map methodology, and uses a similar prototyping approach in their industry.	• Additional focus on cost-benefit proposition. • Start with a problem to solve first. • Include an example of mind-mapping methodology.
B	Agree	• Usable, similar to approach used by expert in Namibia and Botswana. • Roadmap diagram easy to understand and interpret. • Acceptable use of level diagrams and mind mapping methodology.	• Additional focus on change management and costs.
C	Agree	• Would use the approach in the client context. • Believes the incremental approach can aid in adoption acceptance. • The model is appropriate if the intention is to illustrate the possibilities available today.	• Understand environment before defining digital drivers. • Leaving room for future technology could be beneficial.
D	Agree	• Reference architecture captures entire factory value-creation process • Incremental in-house use in the factory is possible. • Possible to use the roadmap on inventory. • Additional use might be limited at first due to a lack of knowledge and resources, would have to hire someone.	• Some concepts and terms might not be understood by a user environment. • Recommended for medium to large companies with available resources.
E	Agree	• The architecture, mind maps and roadmap are thorough and includes all aspects of labour-intensive value-creation. • Can see the factory using this approach in implementing various levels of DT. • Potential in connecting machines and using additional data. • Similar to the approach taken with widespread automation and digitisation.	• Additional links to senior management is preferred. • More emphasis on resistance to change (RTC). RTC tool inclusion. • Include a focus on company culture. • Inclusion of workshop as part of DT strategy.

6.2 Validating the use of the roadmap

To validate the use of the roadmap, the Stellenbosch Learning Factory was used, where various DT support methods were tested in the incremental roadmap approach. A repair process based on case study 1 was replicated in the SLF, and the roadmap was tested on this replicated process. In addition, the approach, and its experiments, presented from pages 203 to 240 of Appendix D, were summarised and presented to a group of middle managers from a labour-intensive partner institution.

6.2.1 The Stellenbosch Learning Factory

The Stellenbosch Learning Factory (SLF), established in 2015, is a hands-on facility where students of Stellenbosch University can practically understand and learn the principles of a typical manufacturing environment. Initially, the SLF was created to teach students to implement lean principles within the manufacturing environment of model trains. Specifically, the facility manufactures two variations of train models inspired by the South African Metrorail, a cabin train and a driver train. The SLF's model environment includes all processes and steps in a typical manufacturing environment, from the order placing, commissioning, assembly and quality inspection before finishing the order with shipping. The original facility layout can be seen in figure D.1 in Appendix D.

Over the years, the focal point of the learning factory has shifted to demonstrating more Industry 4.0 concepts, such as RFID systems, digital quality control and collaborative work, all of which will be used as demonstrative digital support methods in this chapter.

As the learning factory is an interactive environment where students perform the tasks at each workstation, it serves as a possible demonstrative labour-intensive environment. It provides the researcher with a representative environment to test individual methods of digital support in the roadmap approach and present these tests to middle management in labour-intensive environments.

Therefore, the focus of this section is not to digitally transform the Stellenbosch Learning Factory, as there are various previous ventures in this regard, but to demonstrate the use of digital support in a typical labour-intensive environment. The layout of the learning factory will be adapted, and newer, more aesthetic methods will be implemented and tested in this chapter, which combines and builds on previous work done in the learning factory.

6.2.2 Arduino and Raspberry Pi

DT support methods designed or adapted by the researcher in this validation section use Arduino or similar microcontrollers. Arduino is an Italian electronic company that designs and manufactures electronic devices and software. Arduino's open-source boards and software are low-cost and straightforward, allowing accessibility of their technology worldwide [7]. The chapter's DT support method implementations use Arduino boards, third-party NodeMCU boards, and the Arduino IDE, a programming interface that uses specialized Arduino code (adapted from C++) [7]. Arduino boards use both digital and analogue inputs and outputs to control electronics. In addition to Arduino, one of the concepts DT support implementations (see section 6.6.2) makes use of a Raspberry Pi, which is a small and low-cost computer with general-purpose inputs and outputs, allowing similar control to an Arduino board [102].

6.2.3 Validation presentation

Three increments of the roadmap were presented to the group, where each phase of the roadmap was validated and where the implementations focused on three areas: data collection, process improvement and quality improvements. The first two increments focused on the value-creation area of the architecture, specifically the labour-intensive manufacturing process. The first increment focused on data collection in the labour-intensive process to improve the transparency of the process and gather data that can be used to determine additional transformation steps in that sub-area. The second iteration demonstrated the potential use of the data collected by the first iteration to implement additional DT support methods. Finally, after two iterations an additional area, in product management, was selected from the reference architecture, to demonstrate shifting the focus of the roadmap from one area on the architecture to another.

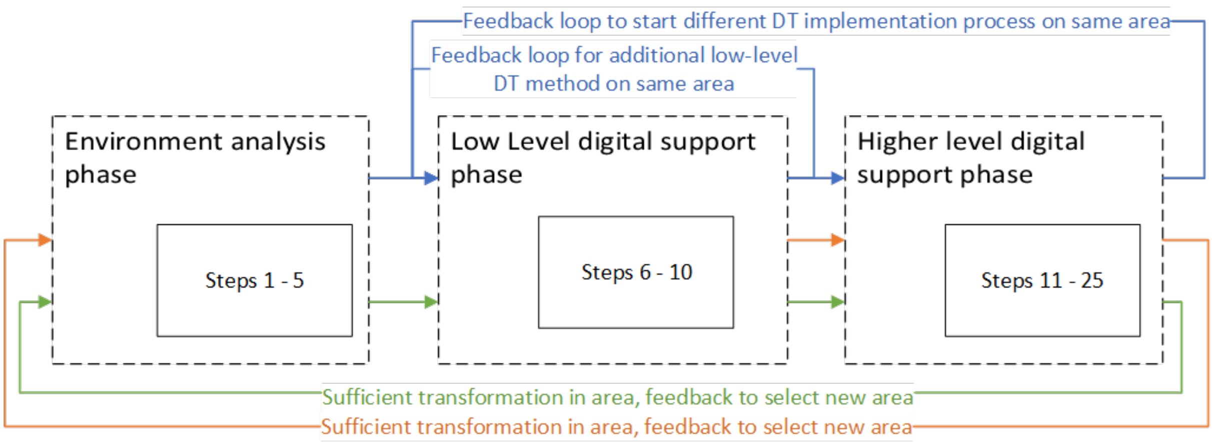


FIGURE 6.1: *Route taken through the roadmap for the SLF DT process*

First, a brief overview of the research was presented. After that, the roadmap, in figure 5.1, an adapted reference architecture (figure 4.4) for a repair process and its use, in table 6.3 along with developed mind maps (figure's 6.5 and 6.8) and developed roadmap used on the SLF repairs process was presented to the participants group in the following order, as shown in figure 6.1:

1. **Environment Analysis:** The research rationale and reference architecture development and use were briefly explained. After that, three transformation iterations were presented.

2. **Iteration 1 - Data collection and transparency:** The blue connectors show the first iteration in the roadmap in the value-creation area, with its return process for a further low-level implementation depicted in the feedback loop. In this DT iteration, the RFID tracking system was presented, followed by the PIR system and eventually the ultra-high frequency RFID system.

3. **Iteration 2 - DT collaboration:** The orange connectors show the second iteration, where the low-level lean methods were followed by the UR3 implementation in the same area as the previous iteration.

4. **Iteration 3 - Data collection and transparency:** The green connectors show the third iteration, an entirely new cycle, where a new area (product management) is selected from the architecture after analyzing the process and moving on to additional DT iteration, and new DT methods are selected using a new set of technology mind maps.

The approach is summarised below, after that the results from the validation survey are presented in section 6.7 .

6.3 Environment analysis phase

The reference architecture was used to map and evaluate the current repair process replicated SLF facility, with only the value-creation process being changed from a 6-station assembly line to a 3-station repair line. This replicated process is supposed to physically simulate one process in case study 1, similar to smaller units for repair in figure B.4 in Appendix B. Furthermore, an extensive process was not planned because the physical repair process is intended as an example of implementing the various DT support methods. Due to disruption concerns and time constraints, implementation with the research partner was not carried out. Instead, a demonstrative approach in the roadmap application was used to obtain validation opinions from the research partner's middle management.

This section tests the use of the reference architecture in phase one of the roadmap and briefly addresses the other courses of action in the first five steps. Furthermore, this evaluation validates the overall roadmap approach, reference architecture, and mind map methodology; as a result, specific steps including existing validated tools, models etc. are not focused detail but are briefly discussed, where more detail can be seen in Appendix D.

6.3.1 Replicating a repair facility on the SLF

SLF repairs adhere to a general repair workflow process, as depicted in page 206 of Appendix D, which was developed using case study 1, the supporting literature in section 3.3.1 and a SIPOC process by Duggan [30]. The SLF repair environment adapted to the process flow can be seen in figure 6.3. Currently, there is no working degree of DT implementation.

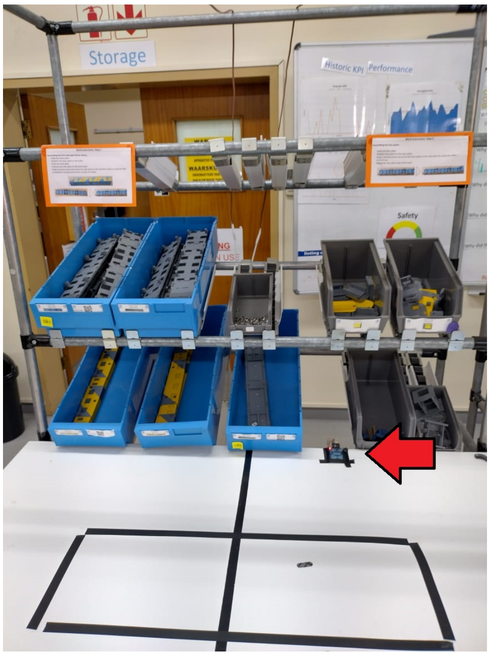


FIGURE 6.2: *RFID scanner attached to SLF workstation 1*

Train compartments that require repairs are sent from the depot or outlet to the unit storage area, where it is determined whether such a unit is in stock. If a unit is in stock, a replacement unit is sent to the depot, and a new works order is created, either for driver trains or cabin trains. If no spare units are available, a new job works order is generated, and the depot must wait until a new unit becomes available.

The defective unit is then delivered to the repair facility with three workstations and a cleaning bay. Each workstation has storage bins for recycling or spares, as shown in figure 6.2. Workstation 1, seen in figure 6.2, disassembles the unit and sends it to the cleaning bay for cleaning. After cleaning, an inspection and diagnosis are performed to order (via delivery note, similar to case study 1) any unique spare parts that are not included in the train repair kit. Each train has a repair kit, and all seats and internal items are replaced during each repair cycle.

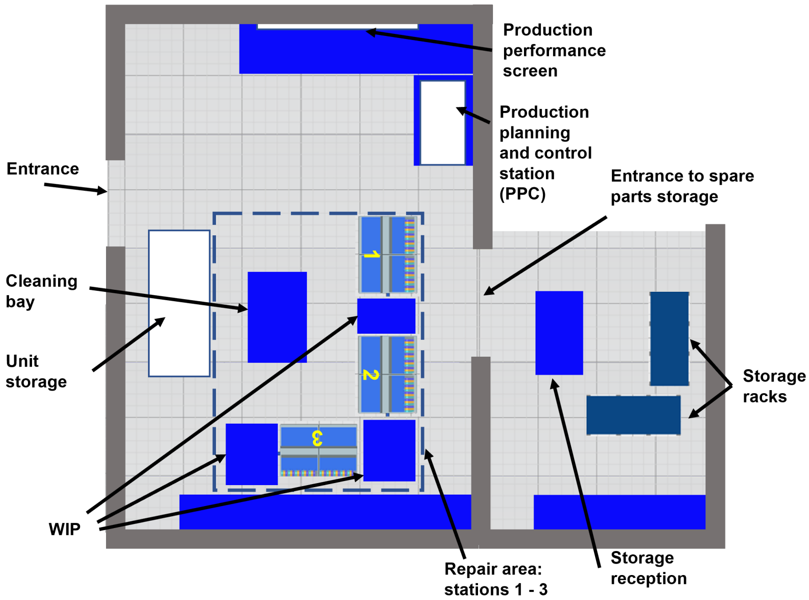


FIGURE 6.3: *Adapted SLF layout*

The unit is then transferred to workstation 2, where it is reassembled. The employee refurbishes the unit using the appropriate kit. After collecting any unique spares, such as new wheel compartments, side panels, or other specific spares, the final assembly takes place (without the train's roof), and the unit is sent to workstation 3. Workstation 3 is responsible for testing and quality control. The employee ensures that all components in the train compartment are included, performs quality checks on these items, and tests the wheel compartments to ensure usability. Finally, the roof is attached, and the completed unit is delivered to unit storage. The complete description with the SOPs for each station can be seen on pages 204 and 205 of Appendix D. The SOP for workstation 1 is described below.

Workstation 1 SOP:

1. Remove roof, wheel compartment and supplementary compartments 1 & 2.
2. Remove train compartment chairs and inner compartments and place them in the recycling/sub-storage area.
3. Move the remaining items to the cleaning bay.
4. Move cleaned items back to Workstation 1.

5. Inspect and diagnose units and compartments and remove faulty spares by placing them in the recycling/sub-storage area.

6. Move the unit with remaining spares to the work-in-progress (WIP) for workstation 2.

7. Order additional spares from storage.

6.3.2 Mapping the repair process on the reference architecture

The replicated repair process is briefly mapped on the reference architecture in table 6.3. Additionally, case study 1's process mapped on the reference architecture can be seen in figure 1 in Appendix 2. The repair process is mapped on the reference architecture, using the SOPs above and a SIPOC developed process flow in page 206 of Appendix D.

1. Data Level:

There is no online management system used in the SLF repair process. The facility uses traditional data collection methods, such as work sampling, time studies and observation, to collect the data used for line-balancing and other process modelling. Performance management is done using traditional lean calculations such as cycle time,takt time and OEE, all which are calculated manually. Traditional MS office is used with a projector for performance management.

2. Application level

The five application-level areas are mapped as follows:

1. **Value-creation:** The SLF repairs process uses manual labour in all three steps of the value-creation process. Storage orders for certain spare parts, such as the supplementary compartments and repair kits, are produced by the 3D printer (supporting manufacturing process) on an order basis and bath orders, respectively. This is similar to machining, drilling, folding and cutting orders in case study 1. Workstation employees are guided utilizing printed SOP cards at each station, where the SOPs, as described above, are used. The process is managed using a whiteboard and projector, where orders, where the process is managed and synchronized.

2. **Apparatus management:** Special tools required for unique repairs are controlled using a paper sign-in system at the storage reception. Employees are responsible for their own tool management and are provided with a precision bit set used on the trains. There are various old and unused equipment in the facility, used in previous units, similar to in both case studies.

3. **Inventory management:** The facility uses a delivery note system, where manual orders for repair kits and specialized parts are taken to repairs by assigned employees. Spares management is audited by manual counting, and units are tracked using paper tags with their assigned job numbers. Access to spare parts storage is limited to employees working in reception. Storage is locked with a coded door where only kits are ordered in batch orders, and unique spares are ordered on a requirements basis. No actual forecasting; kit bathes are ordered when out of stock.

4. **Product management:** Manual quality control is conducted by paper checklists to ensure that all required parts are present in the unit. The process is designed only to repair two types of trains. There is no product design due to it being a repair facility. 3D printed parts are done using CAD software. There are no digital methods used in product management.

3. Technology layer:

There is a 3D printer and UR3 robot in the facility, with the latter not used in the repair process. The UR3 robot is a demonstrative DT support method in section 6.5.2. These two assets only have a standalone connection, similar to case study 1, and there is no Wi-Fi used in the value-creation process in the facility. The only software used in the SLF repair process is CAD for 3D printing instructions, the UR3 robots interactive programming software and MS office for performance analysis. The UR3 robot is currently not used in the repair process.

6.3.3 Remainder of the environment analysis phase

The remainder of the environment analysis phase can be seen from pages 208 to 211. These steps were summarised and presented to the middle manager group. Briefly, in step 2, example drivers that necessitate Digital transformation in the environment include the reduction of paper waste and the desire for increased data collection (both are internal drivers listed by management in case study 1). For step 3, sample SMART goals of the environment are as follows:

1. **Specific:** Increase transparency with data collection capabilities and reduce paper usage.
2. **Measurable:** Quantify information from workstations and reduce paper by at least 50
3. **Attainable:** We can eventually reach these goals by incrementally using the roadmap.
4. **Relevant:** Increased data collection can help us determine waste and improve the various environmental processes
5. **Time-based:** Lower-level implementations: 2 weeks, higher level implementation, 1 year.

Step 4 created a task team, consisting of a company engineer, operation manager, quality controllers and a team of middle managers, also based on case study 1. After mapping the process on the reference architecture, the environment's task team can proceed with step 5, where root-cause analysis, 5 Whys and brainstorming can be used to qualitatively analyse the environment [18].

TABLE 6.3: *SLF repair process mapped on reference architecture*

Data Management	
1. Data collection - Traditional methods: sampling, time studies, observation - Printed paper: orders, parts, delivery 2. Data management system - No current system 3. Communication - No level of asset or resources connection (no online system) - No Wi-Fi connection 4. Analysis: - Manual data analysis using MS Excel or written calculations 5. Process modelling - Line balancing, lean methodologies (non-digital) 6. Performance management - Based on data analysis, manual calculations.	
Value Creation	**Labour Management**
1. Labour-intensive processes: - WS1: manual disassembly & cleaning - WS2: manual assembly - WS3: manual assembly & quality inspection 2. Supporting manufacturing processes: - 3D printer 3. Guidance: - SOP at each station 4. Process & synchronisation - Whiteboard and projector using MS office for process management system	1. Task allocation: -Subjective task assignment -Subjective RST allocation 2. Training: -Observation and interactive learning with employees 3. Safety: -UR3 smart emergency stop system -Designated safety areas with yellow floor lines -PPE required to enter the facility
Apparatus Management	**Inventory Management**
1. Asset control - Sign in the system for special tools (paper) 2. Asset security - Sign in the system for special tools (paper) 3. Relevancy - Various unused equipment.	1. Inventory control - Delivery note system (paper) - Manual stock count - Paper unit tags 2. Inventory security - Access limited to receptionist at spares storage - Code locked door 3. Forecasting -Out-of-stock ordering
Product Management	**Technology Management**
1. Quality: -Manual quality check 2. Product design: -N/A 3. Customer requirements: -N/A	1. Software infrastructure: - MS Office, CAD, UR3 IDE software 2. Hardware infrastructure: - 3D printer, UR3 robot, projector system.

6.4 First increment of the roadmap: DT support in data collection and transparency

The next phase in the roadmap use is the low-level digital support phase. The first increment of the roadmap starts with step 6, where a Pareto analysis is conducted on the SLF area, and where the value-creation area is deemed to be the area with the most recurring qualitative challenges, based on step 5. The figure of the Pareto can be seen in figure 6.4. The Pareto is done using the cause-and-effect diagrams in chapter 3 on the previous steps, with more detail on page 211. The value-creation process, i.e., the actual manufacturing or repair process, is the most affected in a labour-intensive environment. It has the most challenges in data collection and transformation hesitancy. From this, the actual labour-intensive repair process was selected as sub-area from the reference architecture.

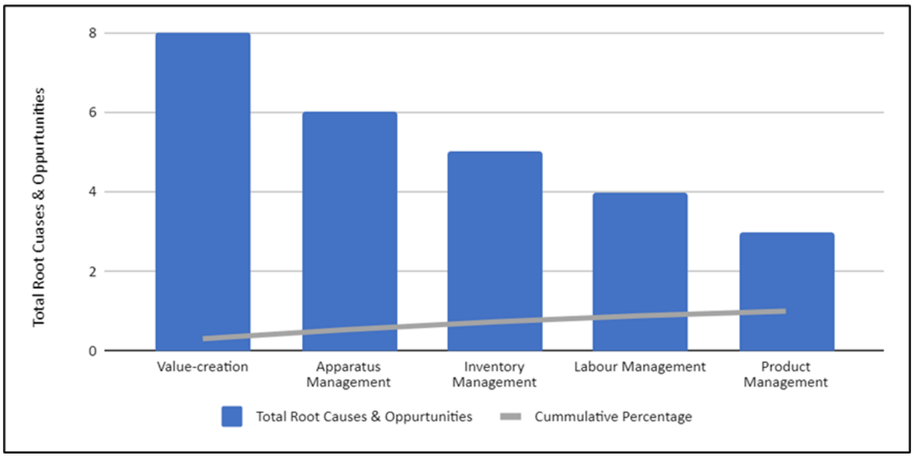


FIGURE 6.4: *Pareto analysis as conducted in step 6*

6.4.1 Using the technology low-level mind-map methodology on value-creation

The technology mind mapping methodology created in section 4.5 is utilized in step 7 to identify distinct DT support methods based on the areas of the reference architecture. The value-creation area was selected as the primary point for the set of mind maps, and this subsection demonstrates how to use the mind mapping methodology in this setting. 2.7.2 and chapter 3, respectively.

A low-level mind map, developed by the researcher from the reference architecture, illustrates the first three steps of the methodology on page 214 of Appendix D, with the final step shown in the extract mind map in figure 6.5, where the DT brainstorming process is visualized.

1. Data collection

Data collection is the first subbranch of the selected labour-intensive process using the mind mapping methodology. A common challenge in data collection of a labour-intensive process is the lack of transparency - due to the variation in the labour and supporting processes, as can be seen in case study 1 and discussed i n section 2.7.2. Additionally, product tracking was also an issue, and the implementation of a tracking system, and time, motion and location data, can be used to calculate efficiency in the process. Section 2.3.2 discusses RFID, which can potentially be used for product tracking. Additionally, the use of QR-code tracking can also be used. These technologies can determine cycle times and variations and increase overall

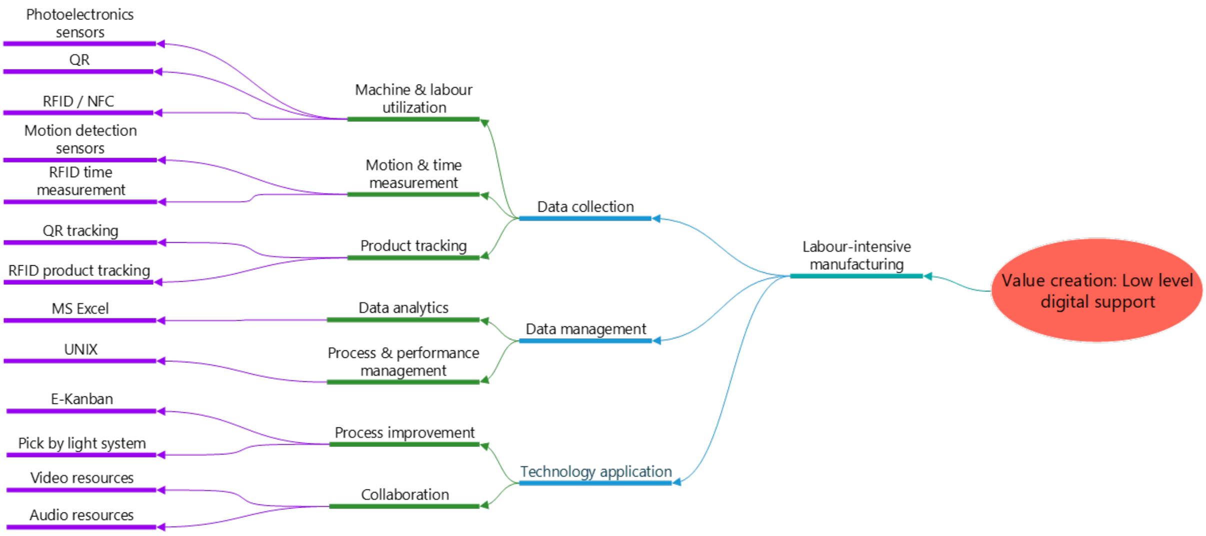


FIGURE 6.5: *Low-level technology mind map development on labour-intensive manufacturing in the value-creation application area*

transparency. Furthermore, section 2.7.2 mentions using photo-electronic sensors for material flow tracking and motion sensors to calculate productive times.

2. Data management

As there is currently no data management infrastructure in the SLF, tools such as MS Excel or MS Access, or other MS Office programs for analytical and database creation can be used to manage the data collected (both by a potential method above or manual data from a time-study for Excel analysis).

3. Technology application

Physical technology can improve various areas in the operations of the endowment. An example is using digital lean tools or achieving a level of human and CPS collaboration. Lean manufacturing is a broad range of methods that, when put together and developed, allow a company to reduce and ultimately eliminate its waste. By minimizing waste, the use of such a system improves a company's responsiveness [136]. Lean methods can be digitalized on a low-level using visual or audio aids. Video or audio guides can also aid in the training and standardization processes in the repair process, creating a low-level of human and cyber=physical systems collaboration.

The first roadmap increment aims to increase the labour-intensive process's data-collection potential. Given the demonstrative opportunity and low disruption level, a low-cost RFID tracking system was identified from the technology mind maps developed in section 6.4.1.

Low-level DT use case selection

From the low-level mind map extract developed in section 6.4.1, the first use case has been selected that would be implemented in the roadmap format - in steps 8 and 9 of the roadmap. A low-level RFID unit tracking system, described in section 6.4.2, is the first use case.

The actual DT support methods are only demonstrated. As a result, no concrete results in data collection or process improvement are anticipated. The implementation is intended to demonstrate DT support methods and the roadmap approach to obtain feedback in section 6.7 for validation. The evaluation after each section is briefly discussed in each iteration of steps 10 and 15 of the roadmap.

6.4.2 Roadmap iteration 1: RFID unit tracking system use case

The RFID system employs 125 kHz RFID tags, which may be an ideal use case replacement for the paper tags employed in Case Study 1. The researcher adapted an RFID attendance system developed by Ahmadlogs [4] that uses a NodeMCU microcontroller, RFID tag, and Arduino IDE to track and capture unit location data at each of the three workstations. Appendix D provides a comprehensive overview of the implementation, with steps 8 and 9 used in the roadmap's document format. Figure 6.2 shows the physical implementation of the RFID reader, which is the same at each workstation.

As shown in figure 6.6, the NodeMCU, RFID reader, and buzzers are connected; this is done for each station or three microcontroller installations. RFID tags are encoded using a microcontroller setup. The appropriate coding is utilized to categorize the tags as either cabin train or drive train and assign a job number to each tag. For new parts, the job numbers and tags are reused. The Google App Script file is published and ready for the microcontroller to establish an HTML connection. The Google Sheets are set up with columns for time, date, and work orders. For every configuration of microcontrollers, a different script is written. The appropriate packages are used to configure the microcontrollers. The microcontrollers are set up using the appropriate software, Arduino code, and a Wi-Fi connection. Upon contact with the tags, they extract the date and time, works order number, and compartment type. The microcontrollers are prepared and connected to Wi-Fi. The in-detail steps of this implementation are discussed on pages 215 to 217 in Appendix D.

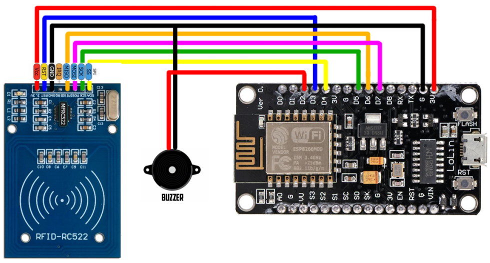


FIGURE 6.6: *RFID attendance system by Ahmad logs [4], adapted by the researcher and implemented at each workstation*

When a unit is assigned to a workstation, a Google spreadsheet receives the unit's time stamp, which includes the date, time, and unique job number. Step 10 of the roadmap calls to analyze the improved process. With a successful implementation, near real-time tracking (time delayed tracking of units - dependant on unit tag in times) is made possible so that anyone with access can know where a unit is in the value-creation process. The RFID tracking system also enables the recording of unit cycle times, facilitating variation analysis and standardization calculations. Additionally, the implementation enables a line manager to identify the stations that take the longest to create value. With additional study, line-balancing and waste management concepts can be developed to improve the efficiency of the repair line.

The use of the system is presented as the first DT support method for the middle management group. After the implementation, the researcher concluded that even with successful implementation, additional sources of digital data collection could be used to increase the transparency of the value-creation process. Rather than continuing to step 11, step 6 was revisited to select an additional DT support method.

6.4.3 Roadmap iteration 1b: PIR motion tracking system use case

A significant process improvement opportunity lies in collecting the correct data. Capturing motion data can aid management in increasing the transparency of a labour process by calculating labour efficiency and wastes in the process, as highlighted in section 2.7.2. To determine these efficiencies and wastes, the researcher developed a portable PIR motion sensor device that can be applied to individual workstations, motion tracking was also identified in the first mind map in figure 6.5. A non-permanent solution is preferred as it can serve as a stand-in for a work sampling analysis while not becoming a permanent burden on an employee. The Arduino code, combined from Arduino IDE examples, can be seen on page 200.

An RFID scanner and a passive infrared (PIR) sensor are connected to an Arduino UNO to provide DT support. In this case, the Arduino UNO is linked to a laptop running an Excel data streamer. Furthermore, the PIR sensor is mounted on the top of the workstation only to monitor the work area (the black line area of the workstation, as seen in figure 6.2).

The worker responsible for the workstation's value production is given a 125kHz tag encoded with a particular HEX ID. The system from the Arduino system links to Excel Data Streamer via a USB wire. An employee tags in, which generates a starting timestamp. The PIR sensor turns on when motion is sensed at the workstation and records a timestamp indicating the start of the station's active time. The PIR deactivates and sends a timestamp to the Excel data streamer when motion at the workstation stops. After the shift, the employee finally tags out. In order to further analyze workstations with a high downtime rate, quality controllers can use this to compute station downtime and non-value-adding time. The in-detail steps 8 and 9 of the PIR implementation can be seen from pages 219 to 221 in Appendix D

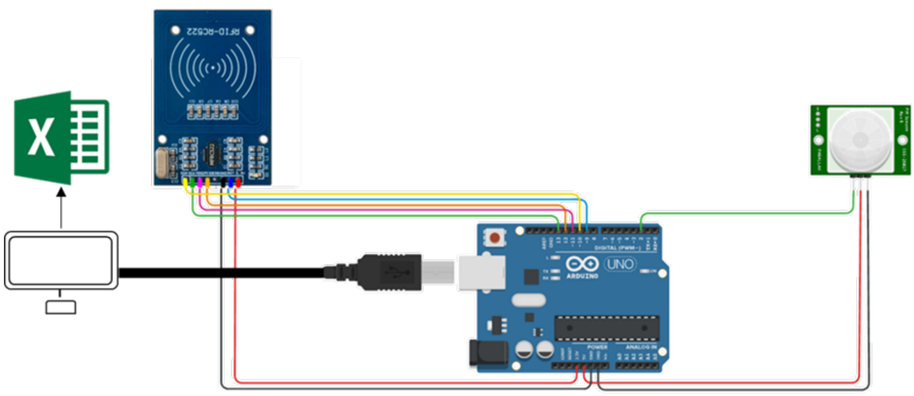


FIGURE 6.7: *PIR motion tracking system*

This solution enables line managers to further analyze and determine station downtime analysis and unsupervised productive time analysis and is more aimed at capturing time spent away from the workstation. This data collection method allows for more in-detail tracking and transparency and can be used to collect data that is to be used in additional implementations. With the increased transparency, and low-level implementation in place, the labour-intensive process can be advance in the roadmap, and a higher-level concept is presented to the group of middle managers.

6.4.4 Using the technology high-level mind-map methodology on value-creation

A successive high-level mind map, on page 224, shows the first four steps for the labour-intensive subbranch, and figure 6.8 again shows an extract from the mind-map ,with the addition of the final step. The in-detail identifying process is explained below.

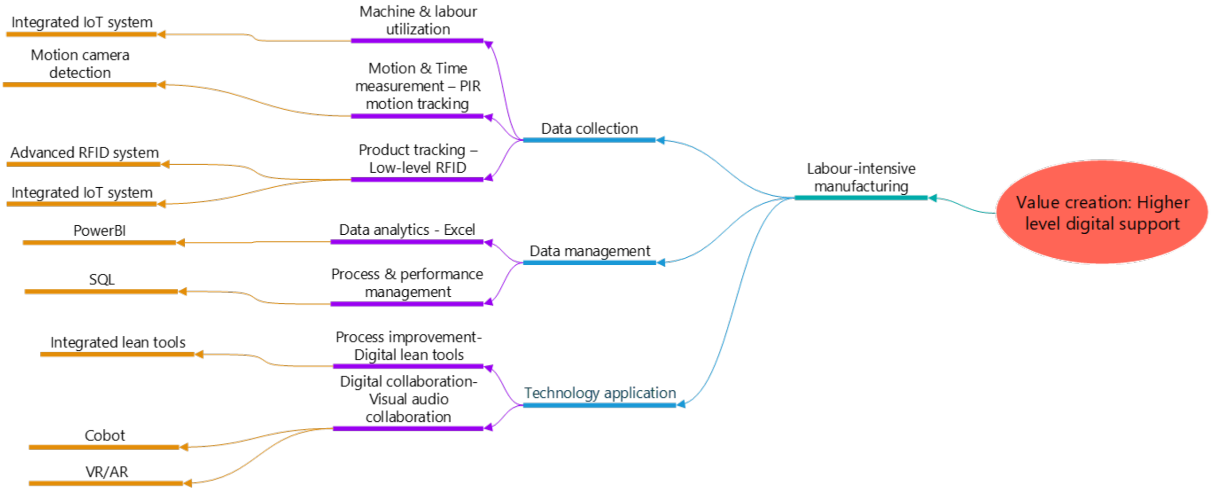


FIGURE 6.8: *Higher level technology mind map development on labour-intensive manufacturing in the value-creation application area*

The DT analysis phase of the high-level mind map methodology is done in step 10. If a low-level implementation is deemed successful, a higher level implementation that builds on the previous DT support methods is selected.

1. Data collection

By utilizing the capabilities of low-level DT support methods, higher-level methods can further enhance the ability to track and increase transparency. Advanced RFID systems can build on the previous infrastructure of a lower-level implementation. In addition, Section 2.3.2 explains the utilization of IoT, which can leverage RFID infrastructure to facilitate more comprehensive data gathering and enable real-time connectivity and communication between regions. It serves as an illustration of how the implementation in one specific region or sub-region can have a ripple effect and enhance digital capabilities in data management by implementing an IoT system.

2. Data management

Once a certain level of data management has been established and stakeholders have become familiar with using these technologies, the task team can implement more advanced systems such as Power-BI or SQL to expand their capabilities.

3. Technology application

The facility currently has a UR robot used in the roadmap sequence as an example to show the roadmap approach. For this reason, it is included in the higher-level potentials. Additionally, the eventual use of VR or AR, as described in section 2.3.7, can build on low-level visual and audio aids. Finally, a higher-level integrated digital lean system, with communication between all areas, can build on a low-level prototype after being tested and managed. Some of these potentials are selected, developed and implemented in the increments of the roadmap approach..

6.4.5 Roadmap iteration 1: Ultra high-frequency RFID solution use case

As RFID and PIR tracking has now been implemented in the environment, a more advanced solution can be implemented based on low-level implementations. Step 11 of iteration 1, on page 222 of Appendix D, concluded that a higher form of data collection and transparency in the environment could build on the previous implementations. More advanced forms of RFID or IoT systems were identified in the technology mind maps developed in 6.4.4.

A research collaborator designed a demonstration of an ultrahigh-frequency RFID (UHF RFID) solution for the repair facility. The solution aims to monitor every step of the process and enables real-time management of these parts with the use of digital touch screens. The readers have a long range and can track parts up to 9 meters away. The SLF repair process is digitalized in steps 12, and 13 (pages 225 - 226) of the roadmap with the following 11 steps explaining the high-level RFID system [121]:

1. **Step 1 - Labels:** RFID labels for all assembly parts are used in various sizes, depending on the part. Chair kits are packaged together with one tag.
2. **Step 2 - Association:** Parts are RFID enabled, and information, such as part numbers, are associated with the tags.
3. **Step 3 - Issue & return:** Parts are managed through a physical interface and fixed reader, where operators can issue and return parts.
4. **Step 4 - Track & trace from store:** The fixed reader allows for determining if items leave the store without being booked and indicates this to the system and operator.
5. **Step 5 - Assembly point 1:** Upon unit arrival, the system and dashboard are updated with a time and date stamp of arrival, indicating the exact number of items currently assembled. Artisans can then order by using the digital touch screen.
6. **Step 6 - Assembly point 2:** When parts arrive at this station, the system and dashboard are updated with an arrival time and date stamp, indicating the exact number of assembled items. Additional data can be gathered in the form of time laps from Assembly Point 1 to 2.
7. **Step 7 - Final assembly:** Similar to the previous two steps.
8. **Step 8 - Quality check:** Similar to steps 5-7, with additional information stamps regarding its quality test results. Redirection to other assembly points is possible.
9. **Step 9 - Master tag assignment:** All tags are associated with a master tag for the finished unit.

10. **Step 10 - Sale of item:** To ensure traceability, the final items sold can be scanned and assigned to a customer to complete the cycle. A change in status indicates that the item has been dispatched and allows for free movement, which is required for the final process.

11. **Step 11 - Dock door verification:** Similar to step 4, the fixed reader allows for complete tracking, alerting the system and operator with a buzzer and light if an unfinished item is indicated.

If implemented correctly, the system can facilitate complete real-time monitoring of labor-intensive value creation and provide an immediate view of parts, components, and final products. It also enhances security and control of inventory management in the environment. The reaction of the workforce will play a crucial role in the success of the deployment, including their attitude towards the implementation, willingness to utilize it, and any concerns raised by representatives as a result of the implementation.

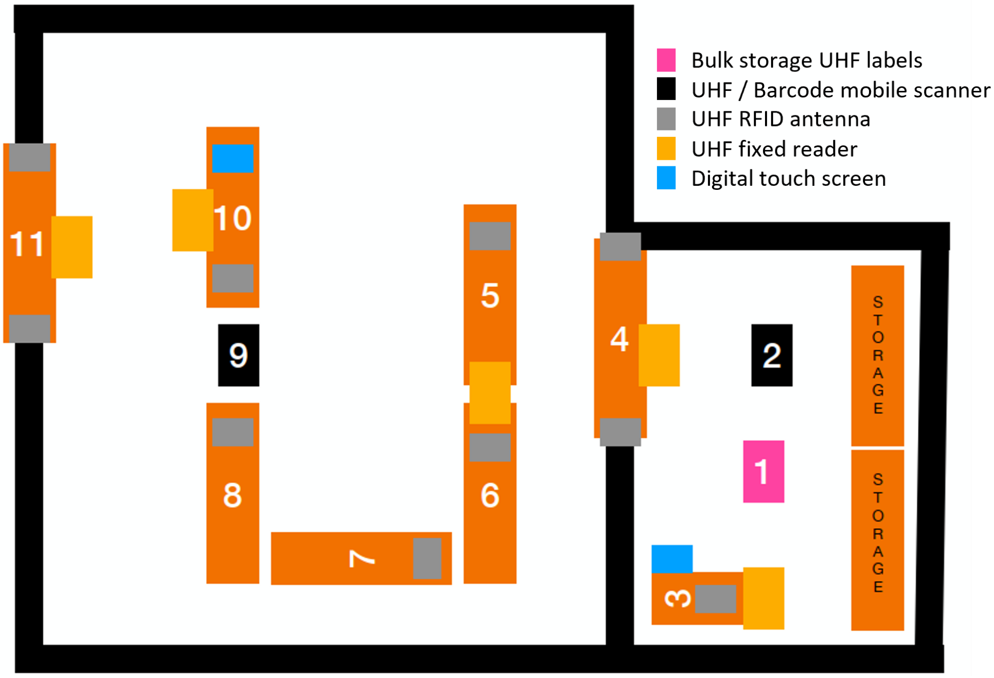


FIGURE 6.9: *Ultra-high frequency RFID system [121]*

Step 15 would take all of this into consideration. After a successful implementation, when the repair process's transparency and data collection have improved, the roadmap is restarted, and another area or subarea is considered for DT.

6.5 DT support use cases in process improvement, collaboration and supporting manufacturing of value-creation

Following the initial iteration, the roadmap was restarted, and the new DT support methods were included in the data-collecting reference architecture. After that, steps 2 through 4 remained the same. In step 5, it was now feasible to compute cycle time deviations in greater detail and allowed for station downtime analysis, which can also be employed due to the ability to analyze quantitative data. In order to choose DT for process improvement, steps 6 and 7 were again applied, where the same mind map was used to select the use cases.

The various data gathering and transparency DT support methods provide more understanding of the repair procedure. The DT task team can choose a workstation and area on the reference architecture and conduct a more in-depth analysis thanks to the PIR system and RFID system. Following the initial transformation iteration, a second iteration demonstration is carried out to enhance the process, foster collaboration, and showcase lower-level DT support techniques in preparation for the eventual implementation of higher levels, such as the UR3 robot. Due to the increased data collection ability, the task team can now determine at which station in the labour-intensive process additional DT support methods can be added. The labour-intensive process, process synchronization and collaboration are considered.

6.5.1 Roadmap iteration 2: Digital lean methods use case

Du Plessis [28] developed a previous e-kanban and pick-by-light system in the SLF, but the system has not been used for some time and is in disrepair. Both systems can improve the labour-intensive repair process by removing movement wastes and increasing standardization in a workstation. The researcher developed an updated server-client pick-by-light and kanban systems using two NodeMcu microcontroller-enabled boards and the remains of the previous implementation. The system is implemented at workstation 2 and the spare parts storage area. The system was developed to show how signals can be sent throughout the environment using ESP8266 (Wi-Fi modules) boards and are only demonstrative. Other implementations in most areas of the environment can be enhanced using a visual aid method as a low-level human-CPS collaboration technique (pages 228 to 230 show in-detail steps 8 and 9)

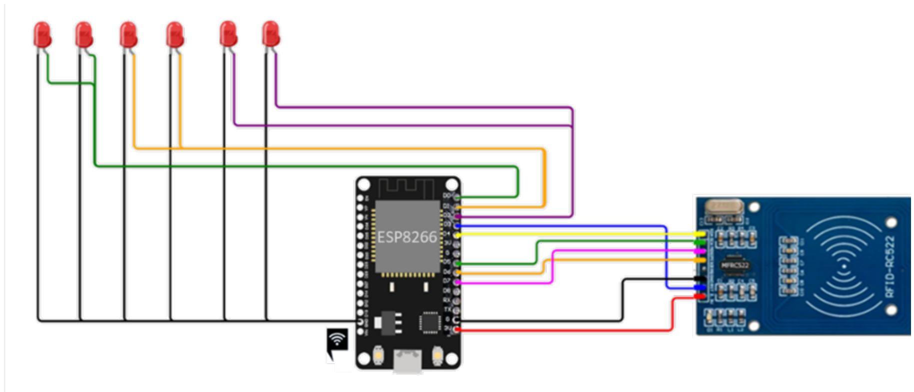


FIGURE 6.10: *Client pick by light system*

The pick-by-light system is installed at the assembly workstation, Workstation 2. The kind of compartment and the works order number are encoded on 125kHz tags attached to each train compartment scheduled for repair. The station has a NodeMCU microcontroller equipped with an RFID reader, various LED lights, various spare parts bins, and Wi-Fi generated from the server, as in figure 6.10. When a compartment tag is swiped over the reader, the reader sends the card information to the NodeMCU. The NodeMCU signals the appropriate parts to be employed in the selecting mechanism depending on the card type (different bins light up the kind of kit, and other required spares are needed for the associated train type). The Pick-by-light system's NodeMCU acts as a client micro-controller to the server micro-controller in the spare parts storage. The server NodeMCU installed at the spare parts, seen in figure 6.11, creates the

Wi-Fi signal and receives a signal with each swipe at workstation 2, where once again, the bins are light up, indicating which spares have to be resupplied by the spares reception, that is then delivered at the end of a shift to the workstation.

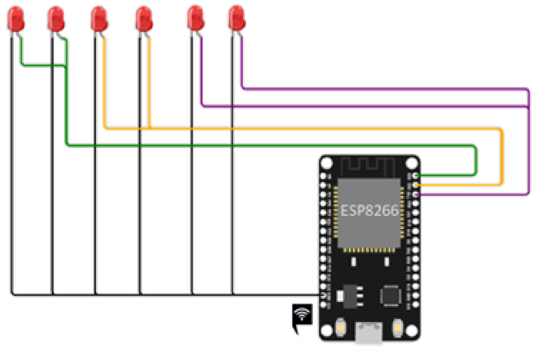


FIGURE 6.11: *Server E-Kanban system*

Microcontroller programmes are written using the Arduino IDE. A client-server communication between the two boards is set up using the steps by Siytek [113]. The client's lights are connected to bins at the workstation, and the server's lights are connected to bins for replenishing spare parts, as shown in the diagrams above. RFID tags are encoded using a microcontroller setup. The appropriate coding is utilized to categorize the tags as either cabin train or drive train and assign a works order number to each tag. The tags and job numbers are reused continuously.

This simple prototype system demonstrates the simplicity of a low-level implementation. In order to continuously improve the labour-intensive process and signal replenishment, it can be connected to other types of sensors, such as pressure plates for signal refurbishing, such as in Du Plessis [28], and other software, such as interacting with a Google spreadsheet, as shown in section 6.4.2. Visual lean techniques, such as this combined system, can reduce the likelihood of human error, increase the standardization approach in the labour-intensive process, and ease communication between areas on the reference architecture. Different areas on the RA can be connected incrementally using the roadmap approach and a similar DT method.

Based on the previous implementations, it was decided to investigate the use of higher-level DT support methods in the labour-intensive repair process for additional process improvement. The previous high-level mind map was revisited, and the UR robot was used for demonstrative purposes to show how it can integrate with the existing system and what a user environment can eventually progress to.

6.5.2 Roadmap iteration 2: Human-robot collaboration use case

The following use case in the roadmap demonstration is the demo implementation of a UR3 robot to establish a form of human-robot collaboration similar to those discussed in section 2.9.3. Due to the expenditures involved with such an implementation and the process redesign necessary to build such a system, moving quickly from the low-level implementations described above to a UR collaborative robot would be infeasible in practice (especially in the context of case study 1). This implementation is only included to serve as an example of a potential higher-level implementation and effectively illustrate the roadmap method in the SLF repair process. The use case builds on the previous methods, with the addition of a technological implementation in the supporting manufacturing sub-area.

The UR3 robot is installed at workstation three and is solely utilized to attach the chair kits in the implementation. The chair kit bins are transferred from workstation 2 to workstation 3, and workstation 2 is now used to install unit-specific repairs. The UR3 robot now attaches the chairs from a kit rack, where the individual chairs from the kits are housed. Additionally, the UR3 robot's implementation expands on workstation 3's RFID system, where the worker must set up the unit for assembly in the allocated space before scanning the RFID reader. A relay connected to the UR3's digital input reader and 24V source receives an electric signal from the reader in addition to the time stamp that is already present. The digital signal is read by the digital input reader as soon as the relay is activated, closing the circuit and initiating the assembly process. The assembly process is programmed using the build-in programming software. Due to the implementation being solely for display purposes, the implementation was only presented on cabin trains. The demo implementation can be seen in figure 6.12, with in-detail steps 13 and 14 on pages 232 to 233.

This implementation displays human-robot collaboration in synchronization, where the chair assembly is automated, and the employee can focus on other tasks.

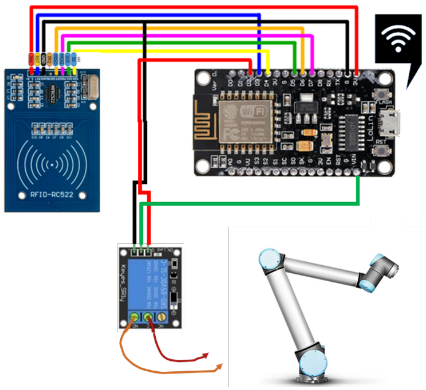


FIGURE 6.12: *UR3 human-robot collaboration system, building on the RFID system be AhmadLogs [4]*

The implementation serves as a demonstration of a higher-level implementation that such a repair environment might eventually implement. However, in actual use, it would be wise to move on to other areas of the reference architecture to implement other low-level DT support methods or incorporate these levels in a higher-level implementation that builds on a previous one.

After the second iteration, communication between areas and digital lean tools enable a more straightforward flow of information throughout the facility. Additionally, the high-level UR3 implementation demonstrates to the middle manager group what eventually can be reached.

After two iterations on the value-creation area of the reference architecture, it was decided to move on to an additional area, in product management, to implement DT support methods.

6.6 DT support methods use cases in quality control in product or service management

After the previous iteration, the roadmap is once again restarted, where the first 5 steps are discussed briefly, as no major changes in these steps have occurred. A new area on the reference architecture is chosen to continue the demonstration. To increase the quality process in the environment, the product management application area is where the DT support methods in this section are specifically identified. New methods are identified using a brief mind-map methodology on product management, with one set of DT support methods, a low-level digital quality checklist, and a high-level vision-based quality control system as a successor.

These implementations demonstrate DT support methods that can be used in the SLF and potentially in a partner institution's environment. Although the latter implementation was developed as a bachelor's thesis project for a previous student, it can be used as a DT support method in the environment, and a demonstration for the group of middle managers (Pages 234 to 240 briefly explain the final iteration in more detail).

6.6.1 Roadmap iteration 3: Digital quality checklist use case

The first use case of product quality is designing and implementing a digital quality checklist. Two interactive quality checklists are designed for both product types and are developed on google sheets, using a checklist template and populated with the SLF's parts list of both products. The checklists can be accessed by mobile phone, pc or internet-enabled Raspberry Pi at the final workstation.

As the focus in this iteration is more on showing the potential higher-level implementation to the management group, where this implementation could be used as a precursor implementation, a demo checklist was developed and, with further development, can be linked to the management system such as the OMS system in case study 1. Additionally, third-party applications are available with a similar digital checklist.

This low-level solution can help the environment rely less on paper by replacing paper-based checklists. Additionally, the checklists are kept online, eliminating the inventory and motion wastes produced by the paper-based approach. Finally, allowing employees to interact with a low-level implementation makes a higher-level implementation easier to accept and helps train staff members on the final workstation and other workstations.

6.6.2 Roadmap iteration 3: Machine vision-based quality control use case

The final demo DT support method suggests using a machine vision-based quality control prototype developed by Droomer [27] as a final-year project. The system, consisting of a microcontroller, camera and a data processing subsystem for data storage, can be implemented to improve the quality control process in workstation 3.

Several quality indicators, including the SLF parts list, were selected for the quality aspect based on prior quality checks in the SLF. Based on the stated quality indicators, the prototype takes an image, processes it, and then runs quality checks. Following the completion of each inspection, the data is entered into the database, and the train is either marked as correct or incomplete [27]. A train can be shipped to a customer once logged correctly.

Through a *PiCamera* package, a camera and a camera flash are connected. This package makes it possible for Python and the Raspberry Pi camera to communicate [27]. OpenCV is used for image detection. OpenCV is a computer vision, and machine learning software that provides open-source infrastructure for computer vision applications [87].

The Raspberry Pi Camera system can be implemented and used to detect whether parts are present, with the output shown on a complete and incomplete cabin train, in figures 6.13 and 6.14 as part of Droomer's [27] tests.

FIGURE 6.13: *System detects that one part is missing [27]*

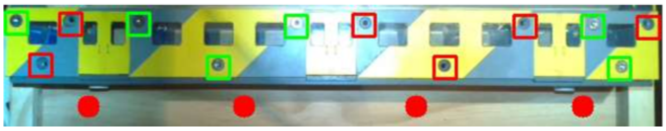


FIGURE 6.14: *System detects that certain parts are missing [27]*

If incorporated successfully, a quality check system such as this one can improve the quality of the value-creation output and reduce the extensive labour needed in the final workstation. This support method can reduce rework waste and over-processing and improve the standardization and efficiency of the value-creation. Employees can now be used in other parts of the value-creation cycle.

Evaluating the Digital Transformation

Finally, the opinions on the demo were collected from the middle manager group, and it was determined that the transformation is an adequate potential solution. After that, the roadmap can be restarted again, and additional areas can be selected from the roadmap in the continuous improvement cycle.

6.7 Demo presentation to middle management at a research partner

A validation survey, as seen on pages 241 and 242 in Appendix D, was presented to the middle managers to validate whether they agree with the roadmap use and approach taken in the SLF. The study surveyed participants to indicate their level of concurrence or disagreement with each statement, categorizing their responses as either strongly agree, agree, neutral, disagree, or strongly disagree, except for PV4 and RAV10, which were open ended questions and RAV7, where the participants answered either yes or no. The approach shown in figure 6.1 and described above was summarised and presented with physical and video demos of the DT support methods, and where the final iteration was briefly discussed.

6.7.1 Validation of the rationale behind the research

Figure 6.15 shows the responses to the three rationale questions, which highlight the difficulty of implementing Digital Transformation in labour-intensive environments, implementation hesitancy, and the requirement for a practical approach to implementing Digital Transformation in these environments, used as a rationale by the researcher for the study. The majority of the findings suggest that these difficulties indeed exist. Only one respondent disagreed with implementation hesitancy, but the majority agreed, and it can be inferred from section 2.2.2 that any transformation does experience implementation hesitancy. From this, the research's rationale is accepted as sound.

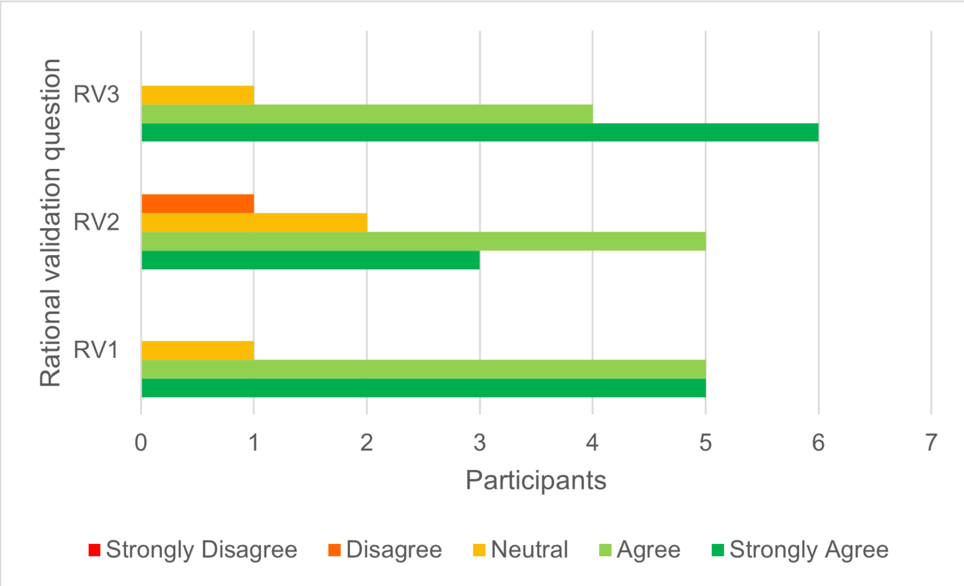


FIGURE 6.15: *Middle management rationale validation responses*

6.7.2 Practical validation on experiments in SLF

The brief practical validation examines the application of the actual DT support methods created or sourced, then applied or demonstrated in the replicated SLF repair process. The validation questionnaire tests whether these technologies can be extrapolated and implemented in the research partner environment. The DT implementation was presented as three roadmap increments, as shown in figure 6.1. The first increment, focusing on data collection and tracking, was as follows:

1. **RFID unit tracking system:** The RFID system was implemented and presented, along with the outcome in CSV form, where data is collected to be used to analyze the process further. After the implementation, it was decided that further low-level DT implementation should be used before moving on to a higher-level transformation.

2. **PIR motion tracking system:** The PIR system was implemented and meant to be used with interval line-manager supervision as a possible replacement for time studies on selected workstations. After that, it was decided to move on to a higher-level data collection and tracking system,

3. **Ultra high-frequency RFID solution:** The UHF RFID concept was presented as a demo solution to the participants as a subsequent high-level implementation. The solution presents thorough tracking throughout the SLF facility, where all units and parts can be tracked, and data can be collected.

After presenting the first iteration, the possible results were discussed with participants, where opinions on the use of such systems for data collection, tracking and additional analysis, as well as opinions on the incremental implementation of such systems, were discussed. The feedback on the first practical validation (PV1) is shown in figure 6.16

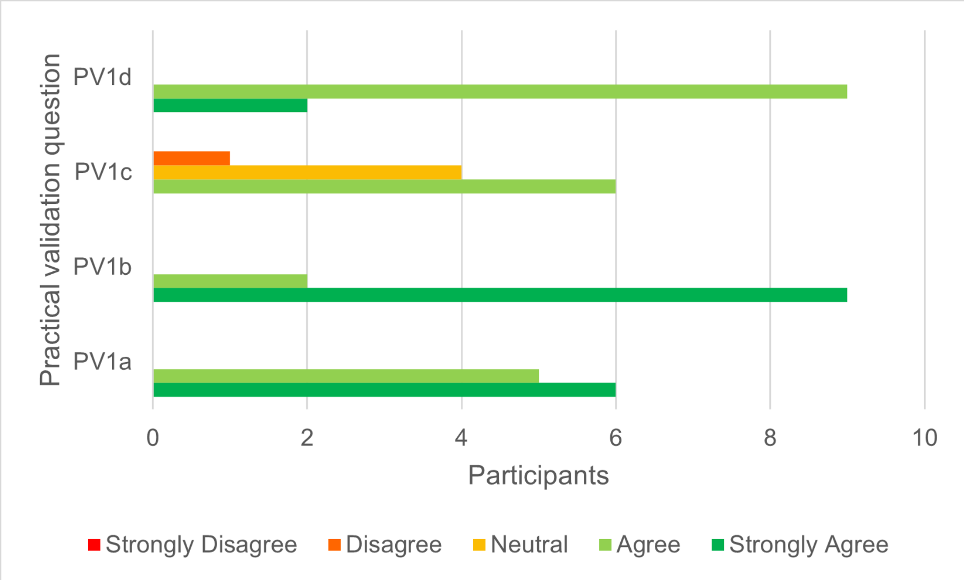


FIGURE 6.16: *Middle management practical validation responses on iteration 1 of SLF roadmap implementation*

The results from this section of the survey conclude that these implementations can aid in the data collection, transparency and even paper trail minimization of the SLF repair process. In addition, implementations can be extrapolated to the research partner's value-creation process (This is discussed in 6.7.4, where the discussion following the presentation is described). Additionally, the results conclude that using a low-level implementation in the RFID and PIR system as a test bed could aid in the transition to a higher DT implementation.

After that, the collaborative DT implementation in section 6.5 was presented. Middle management was presented with digital lean tools and low-cost, low-level digital communication between areas. The sample implementation can be used to explore additional areas to communicate with one another, and low-level collaboration between a cyber-physical system and the labour force could help future human-robot collaboration. Although it is now impractical for the partner institution to employ the UR robot, it was used to demonstrate a potential possibility (this is also covered in section 6.7.4). The level of transformation was regarded as sufficient demonstratively after the second increment, and a new location for transformation on the architecture was selected.

Increment three re-initiated the roadmap, where the area of product management was selected, and the mind mapping methodology was used to identify the two following DT support methods on the quality subarea of product management (as in section 6.6. Here the lower-level implementation was tested as a possible tool to proceed with the high-level machine vision-based system. The results of the second and third increments experiments are seen in figure 6.17

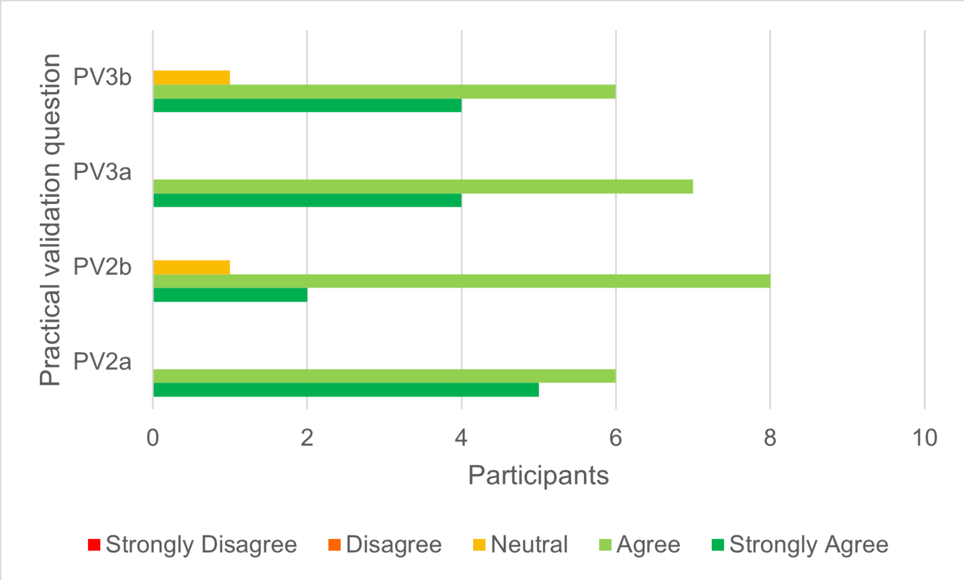


FIGURE 6.17: *Middle management practical validation responses on iterations 2 and 3 of SLF roadmap implementation*

Both implementations were deemed feasible implementations in the SLF, where the low-level collaborative implementation and quality control tools could be used in the partner facility. Once again, opinion results indicate that incremental implementation could be beneficial for performing Digital Transformation in these environments.

6.7.3 Roadmap approach validation

After demonstrating the use of the roadmap to the participants, the remainder of the validation survey was used to validate the roadmap approach and its usability, as seen in figure 6.18. RAV1 assessed the application of the incremental approach in the participant's departments. With two individuals being neutral and one disagreeing, most participants thought this approach would be helpful in their area. The majority (RAV2) also supported using the reference architecture to choose the areas for transformation, with two participants remaining indifferent and one disagreeing. RAV3 and RAV6 examined participants' perceptions of how the roadmap's incremental application would improve collaboration and implementation acceptance in these situations. Most participants in RAV3 (except for two neutral responses) concurred that this strategy would be advantageous in these settings. RAV5 investigated if a low-level test-bed or prototype implementation, as in the third increment, may facilitate the creation of a higher-level implementation. Once more, the majority of respondents agreed, while one provided a neutral response and one provided a "strongly disagree."

RAV4 and RAV7, in turn, looked at the disruption caused by the tests and the potential application of the roadmap approach for DT. According to RAV4 data, most participants agreed with this statement, except for two who disagreed and one who was indifferent. Nine of the eleven respondents agreed that the roadmap would be suitable for starting a DT endeavour.

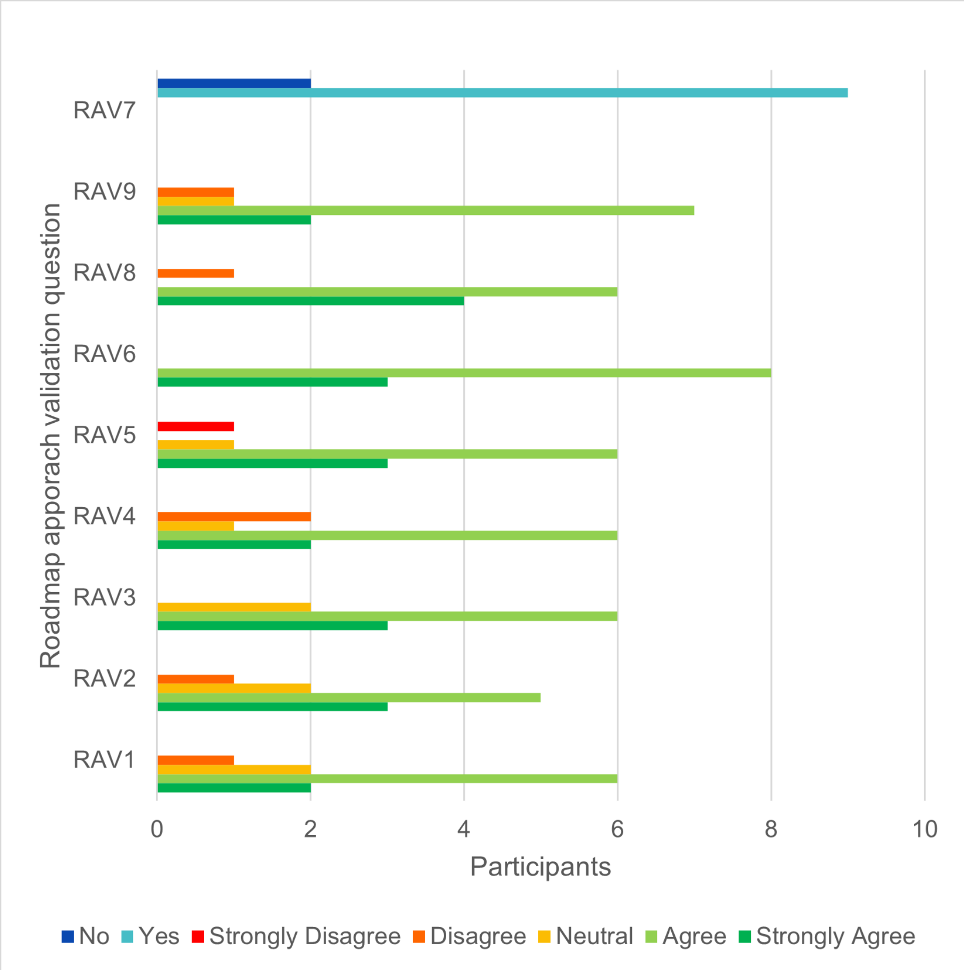


FIGURE 6.18: *Middle management roadmap approach validation responses*

Finally, RAV8-9 tests whether a learning factory environment could demonstrate the potential use of technology for industry and potentially be used for further cooperation between these types of industries and academic institutions.

6.7.4 Open-ended questions and discussion of findings

When discussing the extrapolation of the the experiments conducted to the research partner's environment, the majority agreed that at least a particular form of these experiments could be implemented. However, even lower-level implementations, such as a QR tracking system, could prove more cost-effective and easier to integrate with an exsiting system. The use of a UR3 robot is infeasible at this time, but it was agreed that a similar level of DT could eventually be reached by incrementally implementing specific DT methods.

Most of the open-ended feedback was positive, with critique focusing on how these environments are more fast-paced on a daily basis when compared with an academic environment. The incremental approach was deemed as a possible solution to the rationale behind the research, where more effort in continuous work with industry on these types of projects was recommended. Using technologies as a test bed can also be favourable, as some participants express that many employees are eager to use sophisticated technologies. However, integrating DT support methods, training and change management could be a potential hurdle when implementing this approach.

In general, the roadmap can be used in these environments, where additional focus on change management and integration should be added.

Finally, the use of the SLF was effective in the demonstration, but a desire for a more hands-on approach to industry was expressed, which is discussed in 7.3, where potential future projects in the partner facility is provided.

6.8 Conclusion

This chapter's objective was to present the Digital Transformation roadmap's validation and verification processes. Verification, which evaluates the output and usefulness of the roadmap, starts the chapter. The actions related to participant selection, verification, and post-verification were all explained. The verification addressed research objective 2.1, where the research were presented to industry experts to verify the research. The results of the verification was used partially satisfy ROI 2.4, and improvements were made to the roadmap, reference architecture and mind mapping methodology.

The roadmap was then validated using use cases in the SLF (satisfying ROI 2.2) with feedback from middle management (ROI 2.3) at a research partner. The validation process involved using the architecture on a replicated repair facility and testing various low-level and high-level DT support methods to validate the steps of the roadmap. Finally, the chapter was completed with a discussion of the validation results.

CHAPTER 7

Conclusion

7.1 Thesis summary

The thesis opened with an introductory chapter where the progression of Digital Transformation and the paradigm shift of the industrial revolution contextualised the current climate in the global industry. Chapter 1 contextualised the difficulty of DT in highly labour-intensive situations and underlined the need for a tool or method of DT within these circumstances. A formal problem statement with research questions was then presented. The two main research objectives, along with six and four sub-objectives, were developed using the problem statement and the questions. The gap, anticipated contributions, and the study's limitations were then discussed. The approach and techniques used for the research and data collection were then explained in the research methodology section. Finally, the research ethics, organisation of the thesis and project plan were discussed.

Two literature chapters followed. Chapter 2 was devoted to a mixed literature review. Chapter 3 investigated common labour-intensive environment by using observational case studies and supporting literature. The chapter also identified various areas and their challenges, opportunities and cause-and-effect relationships that occur frequently in labour-intensive environments. Chapter 4 provided the reader with the solution approach of the thesis. The literature and studies conducted in the previous three chapters and the areas and relationships identified in Chapter 3 were used to develop a reference architecture that labour-intensive environments can use to map their current digital and technological standing and be used to select areas to advance in their DT process in fulfilment of objective 1.3. Together with the reference architecture, objective 1.4 was addressed. A methodology to identify various digital or technological support methods was developed for user organisations to identify low-level and higher-level implementations in their transformation effort.

The roadmap approach was then developed in Chapter 5 by incorporating the reference architecture, mind mapping methodology, and other techniques and tools into various components of the roadmap. This achieved objectives 1.5 and 1.6 by providing user environments with an incremental roadmap for their Digital Transformation journey to get from their current standing to their desired future standing.

The roadmap, reference architecture, and mind mapping approach were presented to a panel of industry experts in the penultimate chapter of the research, where research objective 2.1 was achieved, and the study results were verified. The validation approach, which tested multiple DT support strategies on the replicated labour-intensive environment and included survey feedback and discussion from a group of middle managers of a labour-intensive partner institution, successfully achieved research objectives 2.2 and 2.3.

The final research objectives were also fulfilled in chapter 6, where amendments to the research were made after the verification and validation process. Finally, the current chapter concludes the thesis, where additional changes and suggestions on the research are summarised in the further conclusion of objective 2.4.

7.2 Research contribution and benefits

This thesis intended to provide organisations or manufacturing environments that are labour-intensive with a roadmap to incorporate Industry 4.0 and methods of digital support. The application of the architecture and roadmap may thus lead to successful Digital Transformation in such environments or at least aid such environments in starting the process of Digital Transformation by emphasising the implementation of various methods of digital support. The research outlines various technologies that can be used for various areas and aspects in such environments to aid in everyday operations. For countries such as South Africa, where both the demand for labour, and the necessary continuation of labour employment, are still evident, the roadmap and technologies may lead to operational and financial benefits. Furthermore, skill development and human-robot collaboration opportunities could benefit both the employer and the employee. Apart from the research conducted in Chapter's 2 and 3, three stand-out contributions are listed as follows:

Contribution I: *Application of the reference architecture to map the current digital standing of a labour-intensive user environment .*

The Digital Transformation reference architecture for labour-intensive value-creation enables user organisations to map the digital levels of their current operations - specifically all areas of operations that are centred around their value-creation, i.e. labour-intensive manufacturing, repair process and more. The reference architecture can be explicitly used to identify challenges and digital opportunities in their operations and understand the relationship between the cyber-physical connection, processes and actual technological implementations.

Contribution II: *Application of technology mind mapping methodology to identify potential digital or technological methods of support in the Digital Transformation effort of these firms .*

With the technology mind map methodology, user environments can find and create their own digital or technological support methods from the reference architecture for their DT endeavours. Any organisation can utilise the process to find technology pertinent to their environment. The mind maps do not necessarily have to be used in the roadmap method and can be used for low-level, high-level, and more integrated Digital Transformation.

Contribution III: *Application of the Digital Transformation roadmap for labour-intensive organisations .*

The principles and methodologies developed in this thesis give labour-intensive environments that desire some degree of Digital Transformation the opportunity to adopt the roadmap. The roadmap uses the reference architecture, technological mind maps, and other tools established in the thesis to assist a company in changing from its current state to its intended changed state. The roadmap can be used primarily as an implementation tool in these settings and as a teaching tool to explain Digital Transformation to individuals at various levels in a labour-intensive firm.

7.3 Recommendations for further studies

Following the contributions made in this thesis, several recommendations for prospective future studies have been made for this research's follow-up. These recommendations are primarily based on the research's verification and validation outputs.

Recommendations for further studies on the research

The first set of recommendations suggests additional research that can be used to expand the current roadmap and its accompanying architecture and methods. The research was limited to a developing context, where the focus was primarily on adding practical and value-adding DT to the operations of a labour-intensive user environment. Notable areas that are not covered in great detail are mostly concerned with the organizational, business and strategy components of these environments, and include cost-benefit proposition and change management.

Suggestion I: *Incorporate enterprise, business and supply chain into the research.*

The study's scope was restricted to how labour-intensive firms can transform their value-creation processes digitally. This is a result of the fact that these firms' predominant use of labour as compared to others sets them apart from others. The usage of finance and corporate culture can be built on at the enterprise and business levels of the architecture, which needs to be more in-depth. These businesses can also examine how they conduct business and how the process of Digital Transformation can enhance it. Finally, several aspects of operations management, including supply chain management, are briefly touched on. Most of these topics can be included in the investigation in greater detail.

Suggestion II: *Incorporate additional steps in the roadmap focusing specifically on change management and the cost-benefit proposition.*

The two major areas in which recommendations from the industry experts in the verification process were to focus more on change management and the cost-benefit proposition of implementing DT support methods. Although the incremental approach is designed in such a manner to limit the resistance to change in the user environment, additional research and approaches towards change management can be added. Post-verification changes added additional tools to specific steps of the roadmap to address these two areas. However, the roadmap can be expanded, and further research on effective change management and cost-benefit analysis can be added.

Suggestion III: *Development of DT support method database/list to use on the technology mind maps*

An individual DT endeavour may be challenging in a user environment with restricted resources. Utilising resources for DT research could be difficult for these firms to manage successfully. A list or database of prospective DT assistance methods that might be used with the technology mind maps could provide solutions to common problems in a labour-intensive setting.

Suggestion IV: *Additional research to broaden the scope to include other countries around the globe*

Post-verification conversations with experts A, B, and C revealed that related strategies have been or are being used in respective client situations globally. Expert A has specialised knowledge in DT and suggests that with more research, the project's scope can be expanded to cover other developed and emerging nations, including the USA, Germany and China. Based on their expertise in Brazil, expert B suggested that a similar approach could be applied. Finally, experts C suggested that firms in Kazakhstan, Botswana, Namibia and other nations can also use the roadmap. Therefore, more research on the settings and conditions in these nations may enable the architecture and roadmap to be expanded to incorporate more countries.

Recommendations for other studies

Alternatively, following the lengthy correspondence with the management from case study 1 and the desire for more practical implementation at the research partner, the researcher has also suggested two possible Bachelor level final year projects in suggestions V and VI. Finally, results from using the SLF and replicating processes from a partner institution proved promising (see RAV8 and RAV9 in section 6.7.3). Additional research on different academic levels could lead to increased use in a developing context of learning factories between industry and academia for educational and testing abilities, leading to the final suggestion VII.

Suggestion V: *Development of in-house prototype tracking system on the unit repair shop.*

The first use case presented to the case study participants proved to be one of the more relevant solutions that can be implemented at the partner institution. A similar system can be developed to increase the transparency and tracking ability of units in the electrical or transmission departments of the partner facility as a precursor for an eventual more extensive implementation. The use of low-cost QR codes and the linking of these QR codes to the UNIX or OMS system would be more relevant than RFID tags.

Suggestion VI: *Development of machine vision-based system for the quality control of paint for inner-city busses*

Droomer's [27] machine vision-based quality control prototype proved popular during the demonstration at the research partner. After the discussion, it was concluded that a working system quality system could be developed to test the painting and finishing steps of a busses' maintenance schedule. Using a similar approach as Droomer [27], a final year student can create a working system that assesses the quality of busses as they leave the painting shop, thus evaluating the quality of finishing and potentially determining if a washing machine is defective.

Suggestion VII: *Development of a learning factory implementation framework to increase cooperation of collaboration of academia and industry in South Africa*

The SLF is traditionally only used for educational purposes for students of Stellenbosch university. The use of the SLF to replicate the process and test possible solutions has led to two potential projects that can be completed by the undergraduate student as part of a final-year project. The development of a more in-depth framework to use a learning factory with industry support could aid in testing various technologies and process improvements in the South African industry, with another example being the use of IoT systems and RFID systems as in section 6.4.5 to digitalise business processes. Additionally, various previous implementations go into disrepair. A framework could aid in ensuring the facility's continued use, and a set of SOPs to ensure no research or demonstration is lost from one year to another.

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APPENDIX A

Project timeline

The expected timeline is given in Figure A.1 in Gantt-chart form.

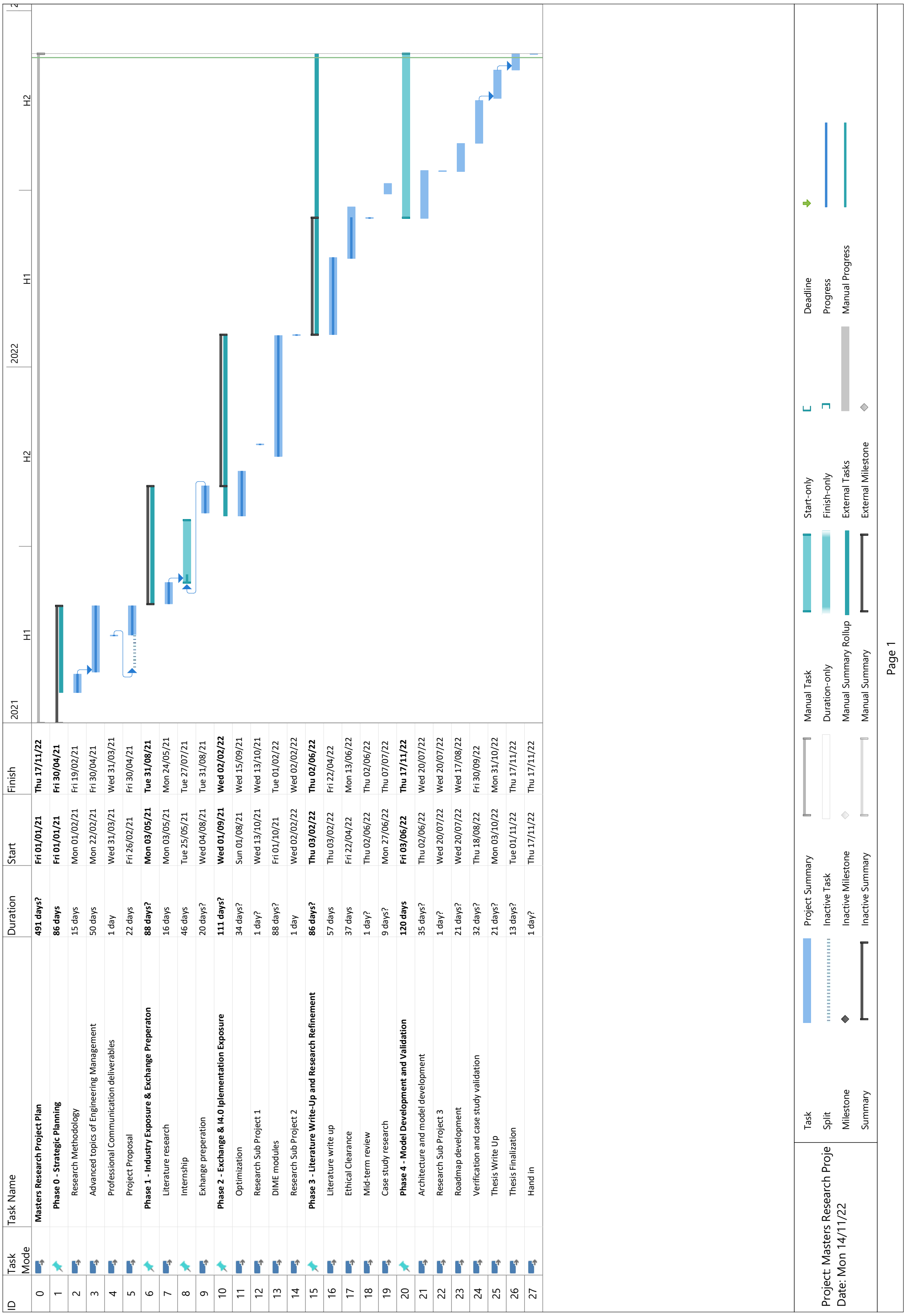


FIGURE A.1: *Expected timeline in Gannt-chart form.*

APPENDIX B

Literature and case studies supplementary figures

Appendix for all additional diagrams, figures and process flow maps used in the research and case studies on labour-intensive environments.

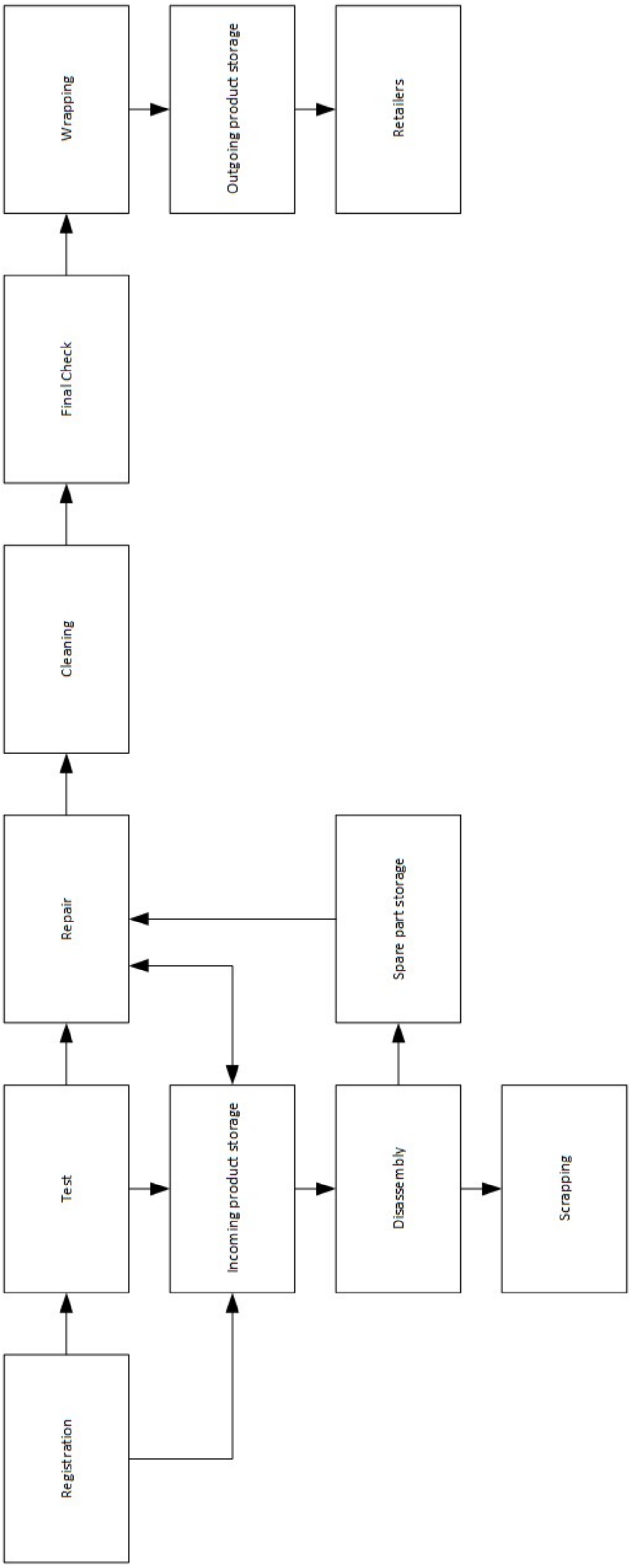


FIGURE B.1: *The re-manufacturing process showing the main material flows at the facility in Motala [120]*

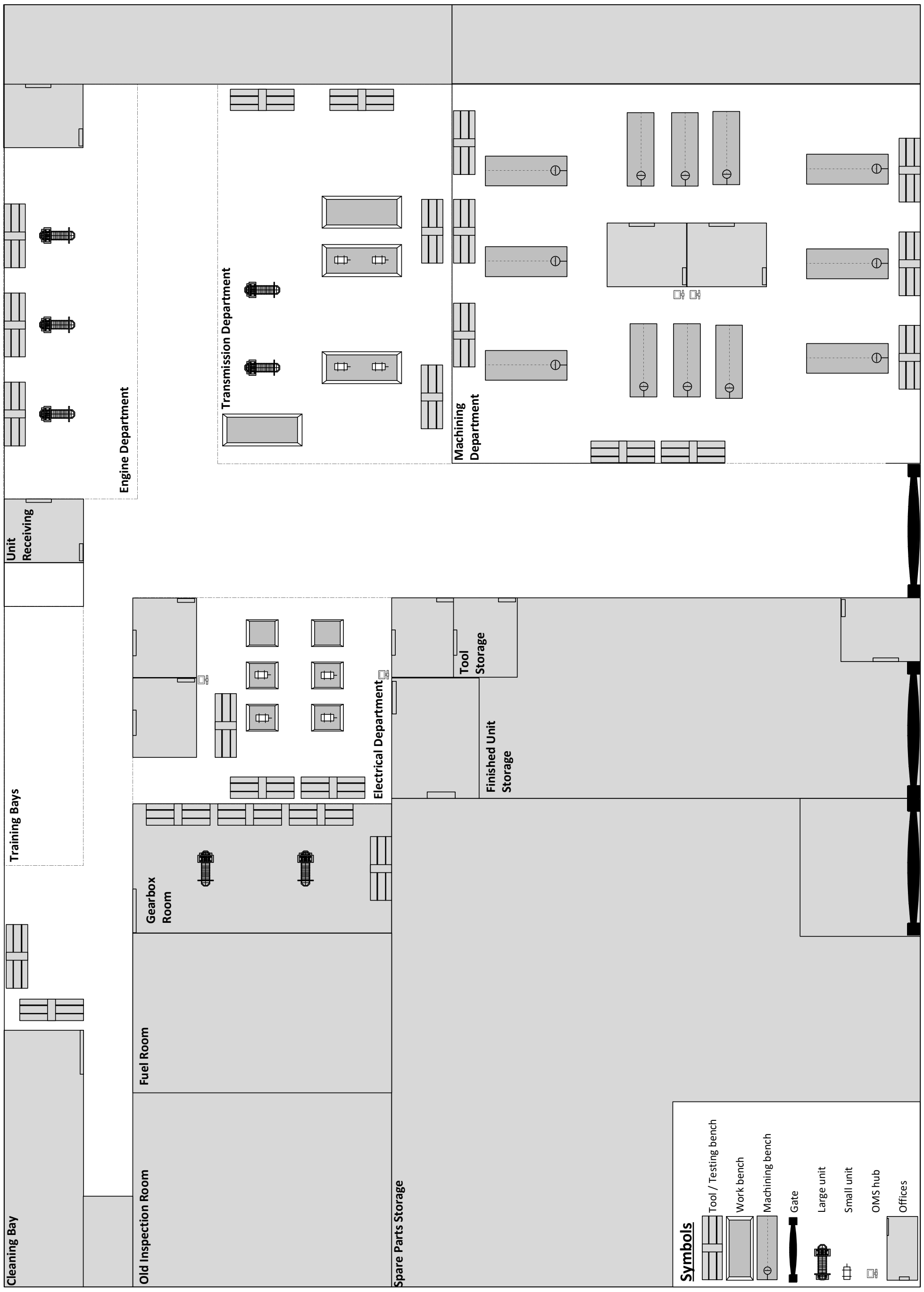


Figure B.2: *Case Study 1: Unit repair shop outline*

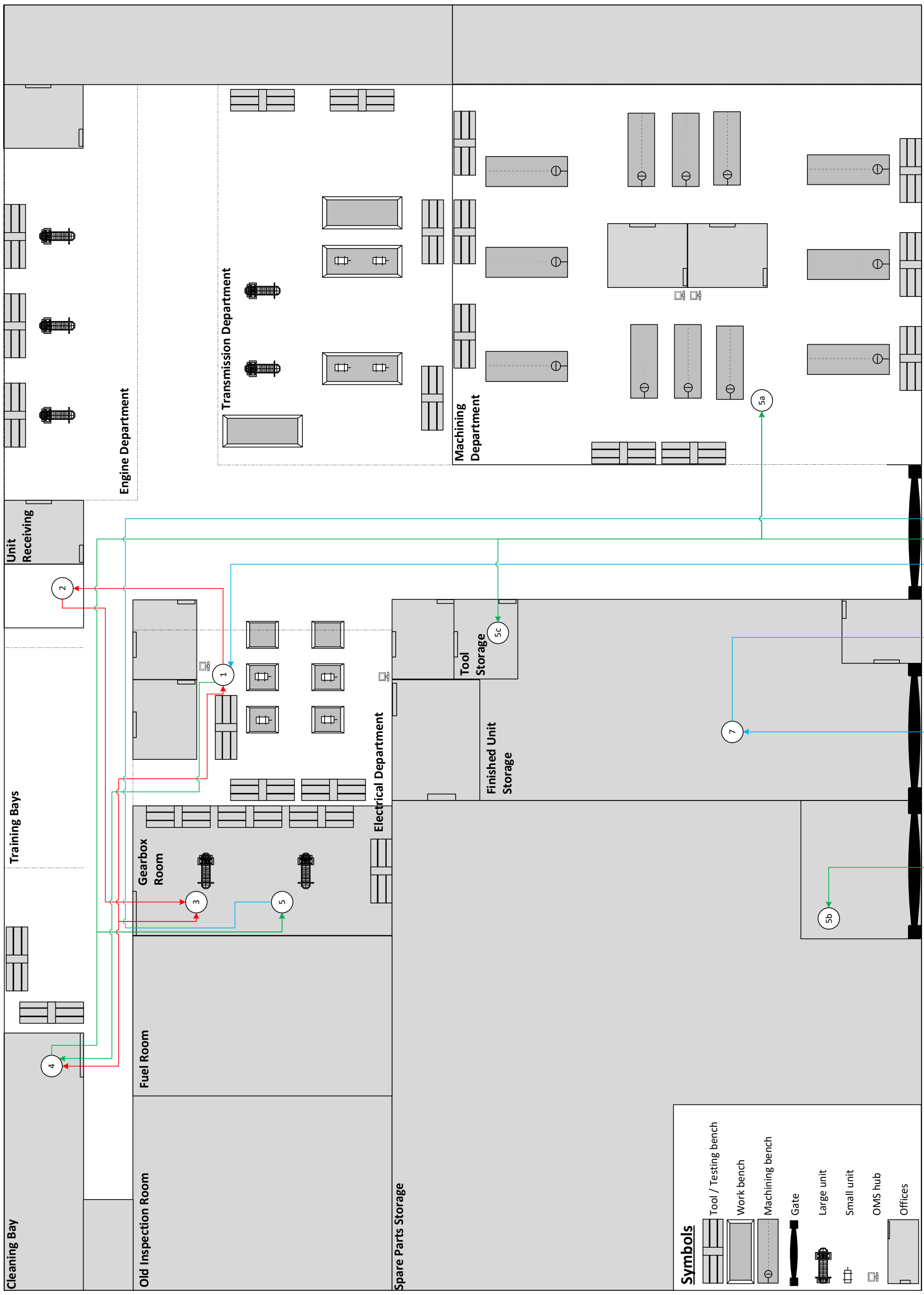


FIGURE B.3: *Case Study 1: Larger repair units*

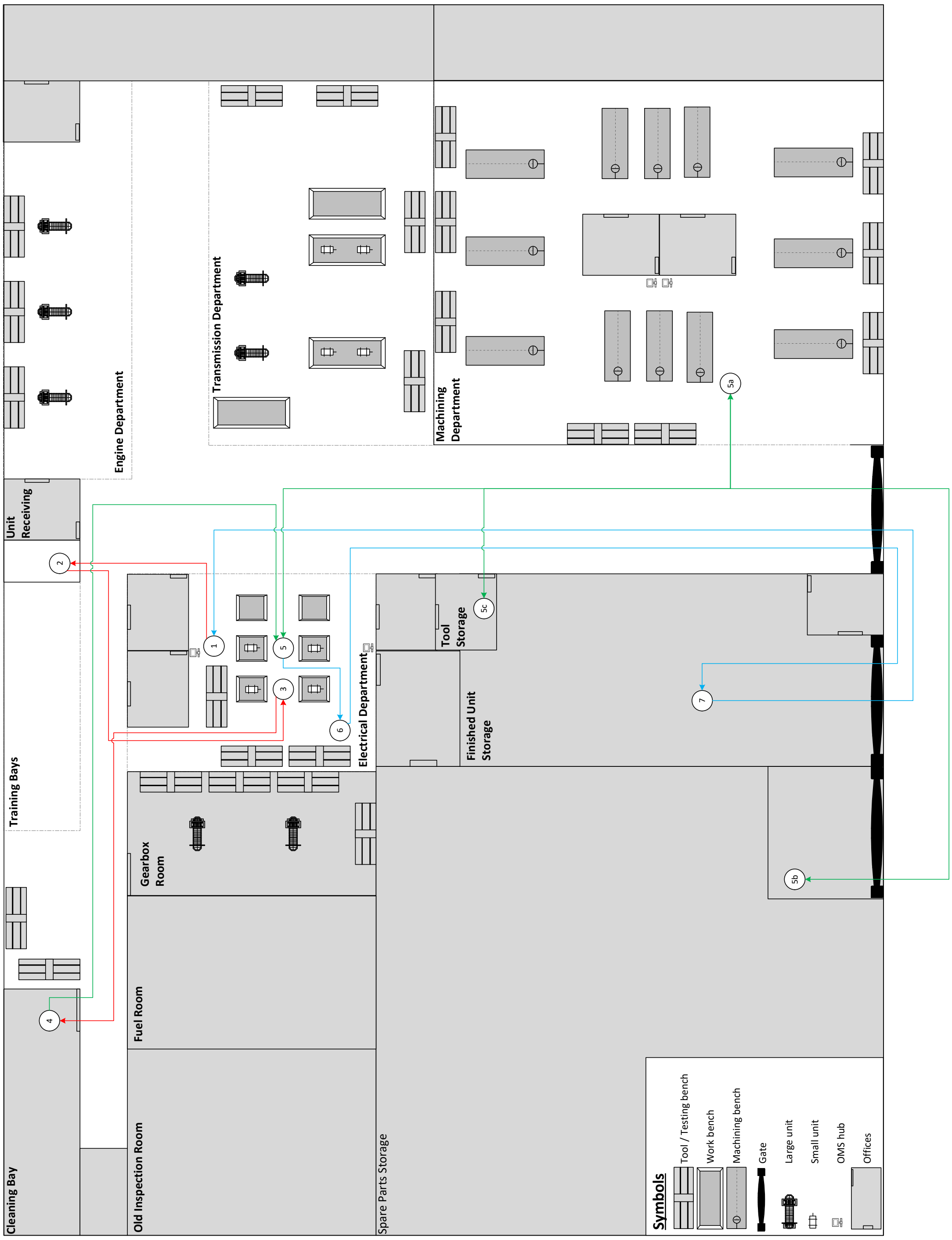


FIGURE B.4: *Case Study 1: Smaller repair units - electrical*

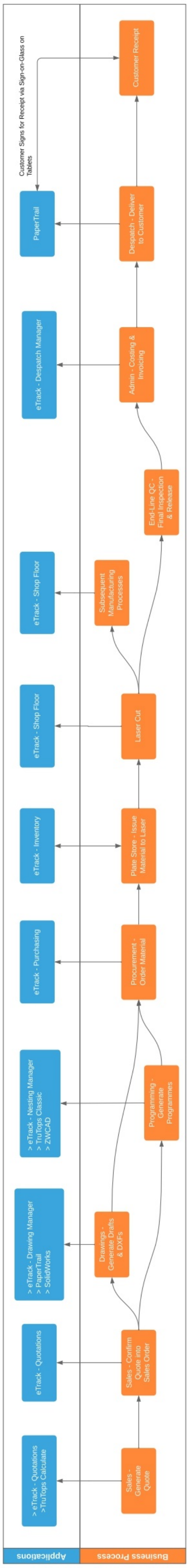


FIGURE B.5: *Case Study 2: Tailor made solution process flow [20]*

APPENDIX C

Final roadmap

Final version of the digital transformation roadmap for labour-intensive organisations.

A roadmap for the Digital Transformation of labour-intensive organisations

Introduction

This document aims to assist organisations that use labour-intensive environments for their value creation, or environments with a significant reliance on a labour workforce, in their Digital Transformation (DT) endeavour. The document can guide the DT process in these environments for in-house use or as a consulting tool. The document uses a roadmap approach, where an organisation can use an incremental approach in their DT to limit disruption. The roadmap focuses explicitly on practical implementations and relevant technologies to common issues in the labour-intensive process. Rather than a full-scale Digital Transformation, this document presents the user steps where digital or technological support methods are implemented incrementally in different areas in the organisation's value-creation environment.

User Instruction

The steps of the document and all accompanying information should be studied and adapted by the organisation or task team where necessary. The roadmap uses a reference architecture that categorises the different value-creation areas of a labour-intensive environment. The reference architecture is used to analyse the current and visualise the potential future state of the environment's operations. Additional sources, such as hype cycles, can be used to adapt by removing or adding digital or technological support methods in the technology mind-map development. The roadmap is constructed in such a way as to be used as a continuous improvement tool in the DT approach, where all implementations and DT goals are aimed to promote human-CPR and human-robot collaboration to limit any detrimental impact on the workforce by DT or Industry 4.0 implementation. For practical use, the user organisations should have access to Google sheets or MS Excel for the physical spreadsheet accompanying this document.

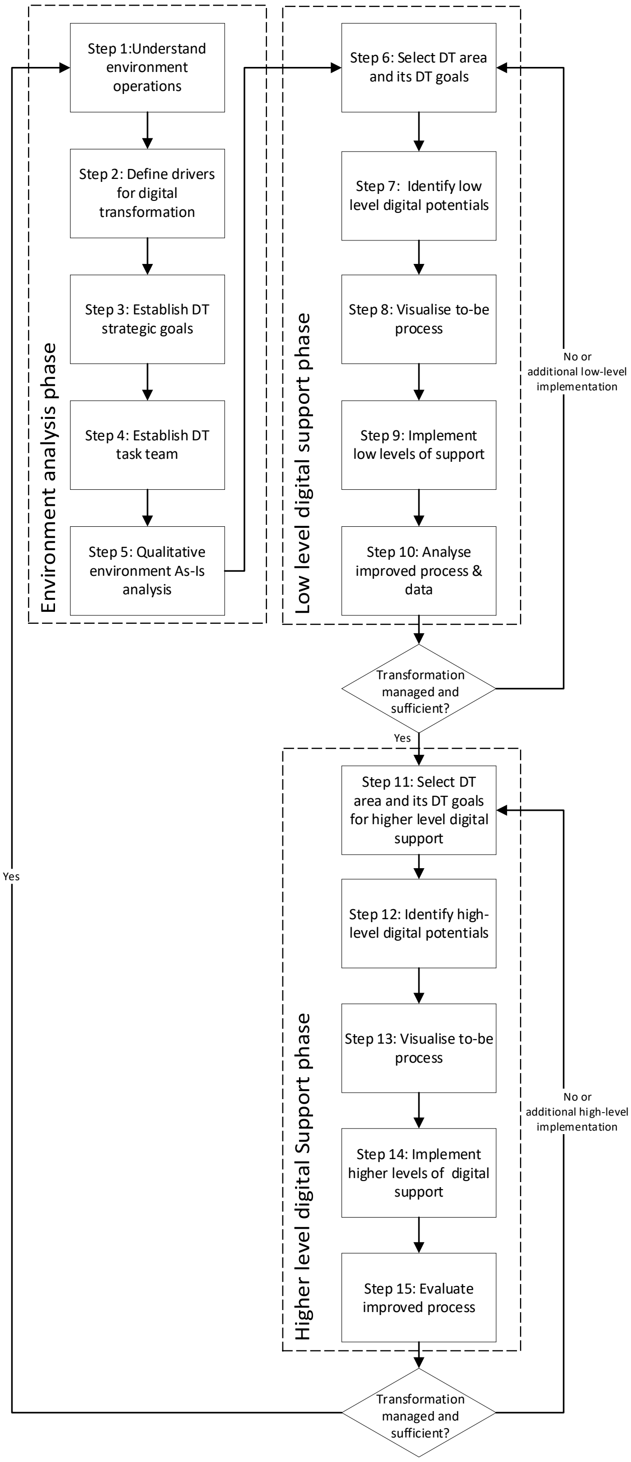


Figure C1: A roadmap for the digital transformation of labour-intensive organisations

Step 1: Understand environment operations

Element Aim:
Familiarise the DT task team with the manufacturing/value-creation within the environment to gain an overview of the organisation's operations, its current position and its objectives

Element Motivation
By using the reference architecture on the operations of the environment, an adequate understanding of the labour-intensive value-creation environment can be gained.

Element Template
https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=316093203

Element Guidance

This first step is to understand the operations, specifically the value-creation of the environment. Management needs to be familiarised with the value-creation process of the environment to complete this step. The DT reference architecture for labour-intensive value-creation was developed to help such an organisation visualise the value creation in their operations. The organisation's operations or process management employees can then combine a process flow or description of their work environment in the centre of the reference architecture.

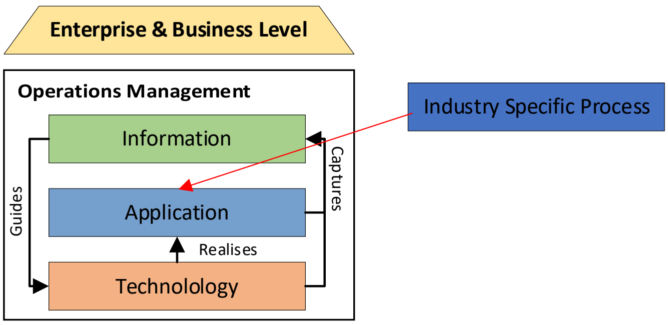


Figure C2: Categorising the user environment to the reference architecture

1. To understand the operations of the labour-intensive environment, the following information is required:
   a. Industry-specific process: A process flow or similar diagram is used to visualise the flow of work in the environment, involving each area of the environment and used to populate the different levels. If there are no such visual flow charts or tools, they can be developed using tools such as:
      i. MS Visio
      ii. MS Office alternatives
      iii. Additional third-party or online flow chart applications.
   b. Data level: How is data being collected, stored, managed, and applied in the environment, and is there a relationship to the application layer? For example: an online maintenance system for tag-in times.

c. Technology level: What are the current hardware and software technologies used in the operations of the environment, and how are they applied, i.e., UNIX data management system, 3D printers, PC service points?
d. Application layer: Understand the different areas of the labour-intensive environment:
    i. Value-creation: Which steps are required in the value-creation of the environment? This includes labour, machinery usage, and other manufacturing or service delivery forms. Furthermore, what are the current operating procedures and support methods in manufacturing or service delivery?
    ii. Human resource management: How is the current labour workforce managed? This is specifically towards their role in the value-creation, i.e., how are they assigned to tasks, how are they trained, and what forms of safety are used in the operations of the environment.
    iii. Apparatus management: How are resources, such as assets, consumables, tools, and machinery, controlled, stored, and managed in the value-creation environment? This includes the security measures or methods in the process and the relevancy of the resources in the environment, i.e., is a specific machine being used?
    iv. Inventory management: How are inventory inbound (spare parts) and outbound (finished units) managed? This includes controlling stock into and out of inventory, security measures and requirements forecasting for the demand and supply of inventory.
    v. Product/Service management: Understand the outcome of the value creation, i.e., the product or service delivered and how and why the product is produced based on the customer requirements or operations output requirements. Furthermore, what quality control methods does the environment employ to ensure top-quality products?

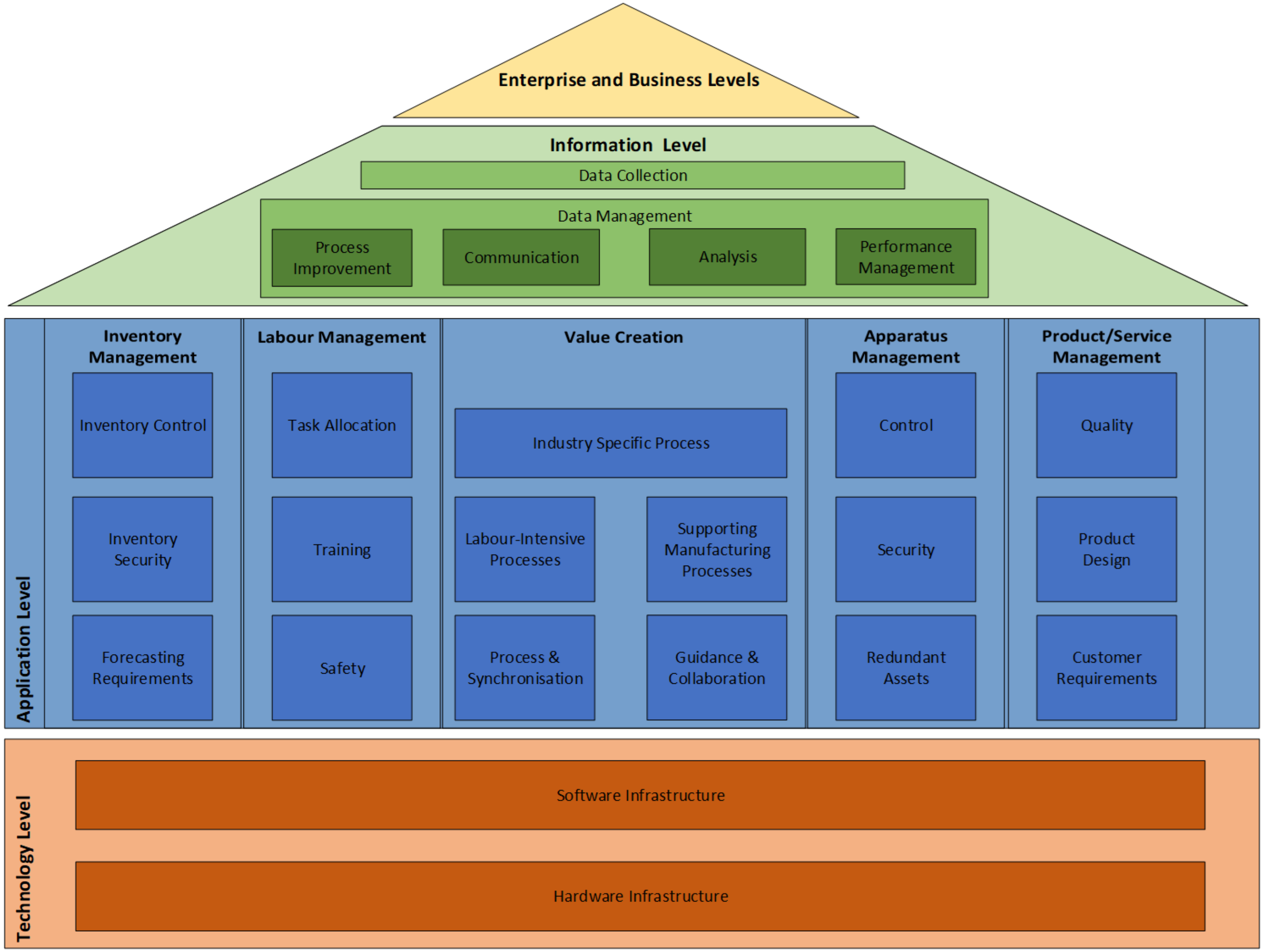


Figure C3: Digital Transformation reference architecture for labour-intensive value-creation

Step 2: Define drivers for Digital Transformation

Element Aim:
Establish the driver for Digital Transformation in the scope of the business/ operation.

Element Motivation
To truly understand Digital Transformation and its relevance to operation, it is important to understand what drives the need for Digital Transformation in the organisation. The first step in this roadmap is to establish the different drivers of the DT process.

Element Summary
Describing the drivers, needs or desires for the organisation to start the DT process.

Element Guideline

The need for Digital Transformation is not always driven internally. There are various reasons why an organisation desires or requires Digital Transformation. There are external drivers, such as competition, policy or industry innovation pushes, and internal drivers, such as the need for workplace and process improvement, cost reduction or integration.

The second step in the roadmap is to define the need for Digital Transformation by:

1. Establishing the external driver of transformation, such as:
    a. Market pressure from competition with innovative value delivery.
    b. Changing customer requirements.
    c. New laws, policies, or Industry commitments
2. Establishing the internal drivers of transformation, if any, based on the first step:
    a. Workplace improvement
    b. Waste management
    c. Data management and analysis

After defining the desire for Digital Transformation, the detailed roadmap can be continued, where all drivers are kept in mind as the transformation process continues.

Step 3: Establish DT strategic goals

Aim:
To establish the overall outcome of Digital Transformation within the environment and identify the desirable type of Digital Transformation.

Element Motivation
This element is to establish the overall outcome of the Digital Transformation project within the environment. Where does Digital Transformation fall within the organisation's vision, objectives, and mission statement?

Element Template
https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=584675680

Element Guideline

In this step, the organisation must find out where Digital Transformation fits into the core values of the organisation.

1. To do this, the organisation must define what the term Digital Transformation means within the context of the organisation and what areas are to be considered. The definition and approach to DT are then integrated into the core values of the environment. The following are examples of considerations within the broader strategic DT goals of the environment:
    a. What are the Digital Transformation and Industry 4.0 vision of the environment?
    b. How far is the organisation willing to take the transformation process?
    c. Limiting the negative effect of transformation on the worker.
    d. Limitations of the transformation.
    e. Environmental and societal impact.
    f. Human-centric, sustainable and resilience (Industry 5.0)

Essentially, this step is to determine what the organisation wants to achieve through the Digital Transformation process, what and who is considered in their approach, and how far they are willing to go in their DT process. The attached template outlines the core commitments of an organisation and gives two examples of transformation approaches, in the triple bottom line and Industry 5.0 and two examples of goal-setting methods (SMART and CLEAR). Given that goal setting is already a vital part of a business management, this step focuses only on integrating digital transformation within the existing goal-setting measures,

In a labour-intensive context, it is always essential to keep the value of the labourer in mind, and a human-centric approach, especially in a South African context, is recommended.

Step 4: Establish DT task team

Element Aim:
Establish a planning team that is responsible for Digital Transformation.

Element Motivation
The establishment of a task team enables shared responsibility, reduces stress, and enables group thinking. Furthermore, a diverse team is selected on knowledge, skills, communication and their fit into the environment operations.

Element Guideline

After understanding exactly why DT is relevant in the context of the labour-intensive organisation, creating a team responsible for the organisation's DT endeavour is essential.

The following roles are general roles that can add value to the DT process in such an environment. These roles can be combined or separated into different roles, depending on the requirements of the organisations using the roadmap.

1. Appoint individuals(s) who have the business authority to authorise any decisions and changes in the strategy and operations of the organisation (company engineer, operations manager, board member, higher management)
   a. Role conditions:
      i. Understand the organisation's structure, operations, activities, and customers.
      ii. Have adequate business management, human management, and communication skills.
      iii. Be aware of alternatives at each level of the company structure.
   b. Role responsibility:
      i. Serves as the link between the DT task team and business management.
      ii. Authorise significant changes, purchases, implementations and (sub)contractors.
      iii. Align any ideas or means of digital support within the operations and organisation.
      iv. Address resistance to change (RTC) concerns from all stakeholders. This includes organising workshops and other measures to ensure cohesion in the environment's culture
2. Appoint individuals(s) who have the authority to make decisions and changes in the operations management or value creation of the environment (operations manager, operations engineer, technical manager).
   a. Role conditions:
      i. Understand the environment's operations and all activities and areas required to deliver the output value of the operations.
      ii. Have adequate human management and communication skills.
      iii. Be aware of common sources of waste, inefficiencies etc., in the operations and be aware of alternative processes or options in the value-creation process.
   b. Role responsibilities:

i. Communication with upper management
ii. Managing people in operations
iii. Driving the cultural change
iv. Team leader, communicating, task assignment.
v. Align any ideas or means of digital support within the operations and organisation.
vi. Address RTC concerns on a ground level with staff and middle management.

3. Appoint individuals(s) to assist in the Digital Transformation / digital support project (quality controllers, assisting engineers etc.)
   a. Role conditions:
      i. Understand operations or value creation
      ii. Understand technologies, tools and methods of transformation.
      iii. Teamwork, communication
      iv. Commitment
   b. Role responsibilities:
      i. Research on Industry 4.0, DT, and methods of digital support.
      ii. Work and implement Industry 4.0, DT, and methods of digital support.
      iii. Communicate with leadership on progress
4. Appoint managers(s) from relevant departments(s)/area(s) (middle management, leading hands, foreman, task managers)
   a. Role conditions:
      i. Departmental (middle) management, managing human resources.
      ii. In charge of relevant DT area
   b. Role responsibility
      i. Teamwork with employees in the operations or value-creation process.
      ii. Direct communication with human resources and value-creation.
      iii. Drive cultural change from the bottom.

Step 5: As-is analysis

Aim:
Broadly analyse the current state of the environment qualitatively to support determining the DT goals of the environment.

Element Motivation
Before quantitatively investigating each separate area, a broad as-is analysis based on qualitative data is used to identify obvious challenges, risks and wastes in each area of the environment to rank the areas for Pareto analysis in the subsequent step.

Element Template
Qualitative Analysis: https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=780280619 Quantitative formula's: https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=659859365

Element Guideline

Various qualitative analysis techniques can be used to gather qualitative data on the process, analyse the environment and identify and understand the challenges such as bottlenecks, inefficiencies, and other wastes. The reasoning behind the qualitative step is to aid in the DT goal selection in the subsequent step and address apparent issues first. Furthermore, in a labour-intensive setting, the collection and use of quantitative data often need to be improved.

1. Various qualitative data collection methods can be used:
    a. Observational studies
    b. Process analysis
    c. Discussions with labourers and middle management
2. Qualitative data is used to identify root causes of challenges in the environment with methods such as:
    a. 5-Whys
    b. Ishikawa Fishbone Diagrams
    c. Pareto analysis

Additionally, users can use existing data (if available) to do various quantitative analyses to for further as-is analysis., such as:

a. Overall Equipment Effectiveness
b. Overall, Labour Effectiveness

Low-Level Digital Transformation

This roadmap approach to Digital Transformation uses an incremental approach, where various methods of digital or technological support are implemented step-by-step. Based on the environment analysis, the next phase in the roadmap is to identify, pick, and execute potential low-level digital or technological support methods. Before moving on to higher levels of digital or technological support, this roadmap phase chooses lower levels of support to evaluate the DT process, interaction, and cause-and-effect relationships from the implementation in the environment, particularly with the labour force. The motive behind the incremental implementation is to:

1. Minimise the disruption of the implementation.
2. Aid in the solution acceptance by the entire workforce.
3. Test solutions out before a full-scale Digital Transformation.
4. Reduce the cost requirements for the DT project.
5. Practically show all stakeholders in the organisation that certain DT solutions can work.
6. Collect data in the environment to improve the process or implement solutions based on data-driven decisions.

The first phase of Digital Transformation in this roadmap is to identify, select, test, use and analyse lower levels of digital or technological support in the labour-intensive environment considering all the statements.

Step 6: DT area selection & goals

Element Aim:
Selecting the first area(s) for the transformation process/methods of digital support implementation

Element Motivation
The roadmap is an incremental approach to DT, where an individual or a group of areas are transformed at a time using digital or technological support methods rather than transforming the entire process. Based on the research done in the thesis, an incremental approach can help ensure all parties' collaboration without causing overwhelming disruption.

Element Template
Pareto Analysis: https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=1891822636

Element Guideline
1. The first step in the incremental Digital Transformation is selecting the areas for transformation. Based on the analysis in the previous step, any areas on the reference architecture identified by the task team through means such as Pareto are selected. Depending on the previous analysis, the first areas that are selected by the task team can be as follows: a. Areas identified where a potential implementation or change would not be too disruptive to the value-creation process,

   b. Areas where the most root causes have been identified.
   c. Area with outdated practises, such as paper data collection.
2. Next, if possible, the selected area(s) can be analysed quantitively, where existing data can be used to calculate wastes, inefficiencies etc. The results from the quantitative analysis can then be used to refine the area selection. A lack of available and usable data is noticeable in a labour-intensive value-creation environment. The subsequent step presents a feedback loop to constitute a lack of data, where new data collected by the following steps can now be used to analyse the relevant areas. The next step in the roadmap presents low-level forms of digital or technological support, where new data collection methods are also presented to the user where qualitative analysis is not possible.
3. Thereafter, area-specific digital goals can be selected by the task team were potential technologies, shown in the subsequent steps, by taking the strategic DT goals into consideration, for example:
   a. The task team wants to place emphasis on human-CPS of human-robot collaboration, where a balance between both is found and where results are measurable in the forms of waste reduction, increased efficiency, or process optimization.
   b. The task team desired new forms of data collection to use in data-driven decisions in the value-creation process.

Step 7: Identify low level digital potentials

Element Aim:
Identifying low levels of digital or technological support for the DT of the previously selected and analysed area

Element Motivation
The first transformation step is where relevant technologies and methods of digital support are identified to address the challenges and reach the digital goals set out up to this point. The user makes use of the mind maps of digital support to select suitable solutions..

Element Template
Low-level DT selection methodology: https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=503694915

Element Guideline
Based on environment analysis, area analysis and area DT goals, various digital or technological support methods are identified as potential solutions in this step. In this incremental approach, lower levels of support are emphasized to result in minimal disruption. The architecture is used, where the area is sorted into each relevant section and technology mind maps are used to select these solutions. Based on the environment's available data and current data collection, the lower levels of data collection for each area are also emphasized in this section and mind maps.

1. A lack of data is addressed by firstly implementing methods of data collection such as, whereafter the process continues in the feedback loop.
    a. RFID timestamp tracking in stations
    b. RFID tracking and tracing data collection
    c. Motion sensor data collection
2. With data available and analysed, various methods of lower-level digital support can be implemented such as:
    a. Lean or Kaizen digital solutions, such as a pick-by-light system.
    b. RFID control & security
    c. Low-cost Wi-Fi connectivity & m2m systems.

The basic process for creating user-specified mind maps consists of three parts, including area selection (completed in step 6), sub branching and brainstorming, as shown below:

1. **Reference Architecture selection:**
   After environment analysis, each part of the application layer in the reference architecture is selected as the centre point for its two technology mind-maps, with its sub-areas serving as subbranches.
2. **Architecture relationship branches:**
   Each sub-branch is broken down into further branches of data collection, data management and technology application.
3. **Root-causes, challenges, and opportunities:**
   The various challenges, opportunities, or cause-and-effect relationships are listed for each relationship branch. These subbranches indicate specific processes where various digital or technological support methods can be added to collect data and/or improve the process.
4. **DT brainstorming:**
   Utilizing research and brainstorming techniques, solutions in the form of digital or technological support methods are found to address the challenges or opportunities in a form of Digital Transformation.

Step 7: Methodology Visualised:

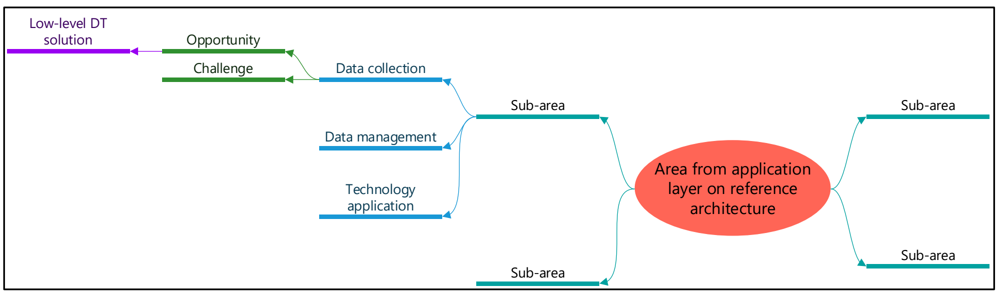


Figure C4: Low-level mind mapping methodology

Step 8: Visualise and examine to-be process

Element Aim:

Visualise the to-be process after identifying and selecting one or more areas for DT and the appropriate low-level method of digital or technological support to understand the practical and financial impact of the DT support method.

Element Motivation

Mapping the future state of the process allows the task team to visually understand and implement the new process. Furthermore, investigating the potential effects, both practical and financial, could aid in deciding whether to implement the DT support method.

Element Template

Cost-benefit proposition:
https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=846657725
Qualitative analysis:
https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=780280619
Link back to reference architecture:
https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=316093203
Quantitative analysis:
https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=659859365
RTC template:
https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=704147376

Element Guideline

Procedure:

1. Identify and list all low-level improvements in the selected area(s)
2. Determine all cause-and-effect relationships that are affected by the improvements, such as:
    a. Which resources are affected?
    b. Which other areas are affected?
    c. The relationship between human resources and the implementation
3. Map out or describe the implementation in the selected area(s) to visualise the actual implementation:
    a. Mapping the process flow in the area
    b. Noting the implementation(s) in any SOP or instructions in the use of the area
4. Update the entire workflow chart if the impact of the implementation(s) warrants it.
5. Update the area(s) and relationships on the reference architecture
6. Determine the financial feasibility and potential of the DT support method using:
    a. Investment ranking
    b. Cost-benefit analysis
    c. Break-even analysis

Three templates containing the cost-benefit analysis, qualitative analysis and qualitative analyses are linked to this step, where the impact of any potential implementation can be assessed to determine if the DT support method is an adequate improvement. In addition, the user environment can also move back to the templates used in the reference architecture mapping, where the impact can be added.

Additionally, an implementation's potential resistance to change should be analysed. There are various methods to address RTC, and the RTC template briefly outlines measures that user organisations can take. Social dialogue is an example.

Step 9: Implement low levels of digital support

Element Aim:
Implementing the identified method of digital or technological support in the selected area.

Element Motivation
With the incremental approach, most low-level solutions are not as disruptive and can be implemented with minimal cost, thus warranting the actual implementation(s) of the support method.

Element Summary
Implementing the digital or technological method(s) of support.

Element Guideline

Procedure:

1. Select the desired DT support method.
2. Ensure that all relevant areas and impact of the implementation has been considered.
3. Acquire the selected method of support.
4. Implement the method of support by:
    a. Prototyping the solution if necessary.
    b. Changing the process where required.
    c. Practically implementing the technologies

Step 10: Analysing the improved process

Aim:
Analyse the area(s) after the low-level implementation.

Element Motivation
Before moving on to more low-level solutions or possibly higher levels, the impact of the solutions must first be analysed. The implementation's disruption, workforce acceptance, practicality and data collection potential must be analysed to decide if the transformation was adequate and to determine the logical next steps.

Element Template
Qualitative analysis: https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=780280619
Quantitative analysis: https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=659859365
Cost-benefit proposition: https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=846657725
RTC template: https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=704147376

Element Guideline

Procedure:

1. Analyse the transformation in detail, using similar methods as in step 5, to determine the success of the implementation and to determine if potential higher levels of digital support can be approached in these areas.
2. Analyse the cost-benefit proposition of the implementation, and if the improvement is worth the cost.
3. Analyse the RST caused by the implementation.
4. The following are a set of output questions that can be used to test the sustainability and management of the implemented solutions:
    a. How disruptive is the task?
    b. Is the solution accepted by the workforce?
    c. If applicable, is the solution gathering adequate data?
    d. What are the cost benefits for the company?

The three analysis templates are once again linked to this step, where the impact of the implementation can be assessed to determine if the DT support method was adequate.

Additionally, the disruptive nature of the task is assessed to evaluate the RTC caused by the implementation, where the user organisation can use the RTC template once again.

Thereafter the task team can move on to higher levels of digital support or can revisit other areas to implement similar or completely different low levels of digital or technological support.

High-Level Digital Transformation

The following phase of the incremental roadmap relies on the findings, analysis, and knowledge obtained by the user environment from the lower levels of digital support methods to deploy higher, more extreme, and disruptive levels of digital or technological support methods.
This phase builds on the previous implementation / mind-maps. It provides a methodology to find additional high-level methods of DT support. Similar steps are used in the second phase of the roadmap, where the only difference is in identifying and analysing the impact of potential higher-level DT support measures

Step 11: Defining higher-level goals

Element Aim:
Selecting the area(s) for the transformation process/higher level methods of digital support implementation

Element Motivation
If previous implementations have been found to work successfully, the task team can now move on to higher levels of digital support, where more complex systems can be used, and the eventual horizontal and vertical integration of all areas can be done in a full-scale Digital Transformation.

Element Template
Pareto Analysis: https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=1891822636

Element Guideline

1. The next incremental step is to move on to higher-level solutions. New goals can be determined based on analysis of the areas after lower levels of digital support. Like steps 5-7, methods such as Pareto analysis can be used to select the relevant areas. Similar considerations can be made:
    a. Areas identified where a potential implementation or change would not be too disruptive to the value-creation process,
    b. Areas where the most root causes have been identified.
    c. Area with outdated practises, such as paper data collection.
2. Thereafter, area-specific digital goals can be selected by the task team, where potential technologies, shown in the subsequent steps, by considering the strategic DT goals, for example:
    a. The task team wants to emphasise human-CPS of human-robot collaboration, where a balance between both is found, and results are measurable in the forms of waste reduction, increased efficiency, or process optimisation.

The task team desired new forms of data collection to use in data-driven decisions in the value-creation process.

Step 12: Identify higher level digital potentials

Element Aim:

Identifying higher levels of digital or technological support for the DT of the previously selected and analysed area.

Element Motivation

The next transformation step is where relevant higher-level technologies and methods of digital support are identified to address the challenges and reach the digital goals set up to this point. The user uses the mind maps of digital support to select suitable solutions.

Element Template

High-level DT selection methodology:
https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=624517702

Element Guideline

Based on environment analysis, area analysis and area DT goals, various digital or technological support methods are identified as potential solutions in this step. In this incremental approach, higher levels of support are emphasised to result in minimal disruption. The architecture is used, where the area is sorted into each relevant section and technology mind maps are used to select these solutions. Based on the environment's available data and current data collection, the lower levels of data collection for each area are also emphasised in this section and mind maps.

1. With data available and analysed, various methods of higher-level digital support can be implemented such as:
    a. Cobots
    b. Integrated processes
    c. IoT systems.

The basic process for creating user-specified mind maps consists of three parts, including area selection (completed in step 6), sub branching and brainstorming, as shown below:

1. **Reference Architecture selection:**
   After environment analysis, each part of the application layer in the reference architecture is selected as the centre point for its two technology mind-maps, with its sub-areas serving as subbranches.
2. **Architecture relationship branches:**
   Each subbranch is broken down into further branches of data collection, data management and technology application.
3. **Root-causes, challenges, and opportunities:**
   The various challenges, opportunities, or cause-and-effect relationships are listed for each relationship branch. These subbranches indicate specific processes where multiple digital or technological support methods can be added to collect data and/or improve the process.

4. **DT brainstorming:**
   Utilizing research and brainstorming techniques, solutions in the form of digital or technological methods of support are found to address the challenges or opportunities in a form of Digital Transformation.

This methodology is repeated for both the low-level technology mind map development, and the high-level mind map, with the only difference being:

5. **Advanced DT solution brainstorming**
   More advanced support methods are identified after analysing a previous implementation, either based on the previous set of solutions or the root causes and outcomes of step 3. In this step, a tool such as the Gartner cycle can eventually be used to select tools that have evolved enough to be used in the user's environment.

Step 12: Methodology Visualised:

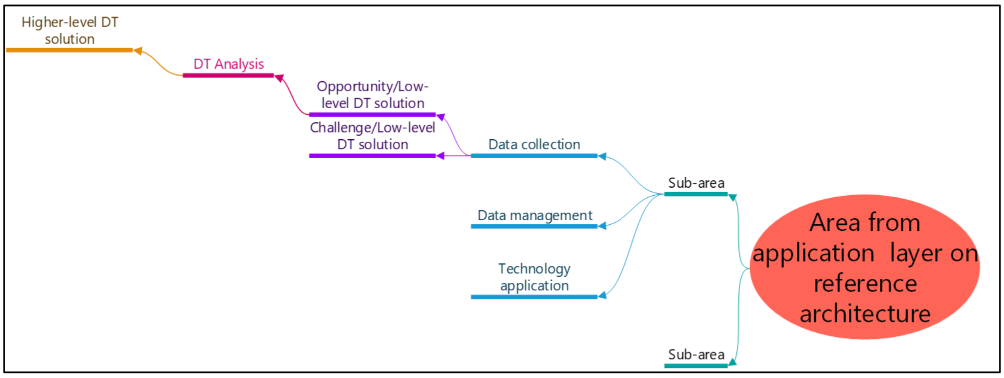


Figure C5: High-level mind mapping methodology

Step 13: Visualise and examine to-be process

Element Aim:
Visualise the to-be process after identifying and selecting area(s) for DT and the relevant higher-level digital or technological support method to understand both the practical and financial impact of the DT support method.

Element Motivation
Mapping the future state of the process allows the task team to understand the new process visually. The visual model is also used to implement the methods of digital or technological support. Furthermore, investigating the potential effects, both practical and financial, could aid in deciding whether to implement the DT support method.

Element Summary
Cost-benefit proposition: https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=846657725 Qualitative analysis: https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=780280619 Link back to reference architecture: https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=316093203 Quantitative analysis: https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=659859365 RTC template: https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=704147376

Element Guideline

Procedure:

1. Identify and list all low-level improvements in the selected area(s)
2. Determine all cause-and-effect relationships that are affected by the improvements, such as:
    a. Which resources are affected?
    b. Which other areas are affected?
    c. The relationship between human resources and the implementation
3. Map out or describe the implementation in the selected area(s) to visualise the actual implementation:
    a. Mapping the process flow in the area
    b. Noting the implementation(s) in any SOP or instructions in the use of the area
4. Update the entire workflow chart if the impact of the implementation(s) warrants it.
5. Update the area(s) and relationships on the reference architecture
6. Determine the financial feasibility and potential of the DT support method, using:
    a. Investment ranking
    b. Cost-benefit analysis

c. Break-even analysis

Once again, the linked templates can be used to identify the potential impact of implementation. The templates include methods to address RST, qualitative and quantitative improvement and various cost-benefit approaches.

Step 14: Implement higher levels of digital support

Element Aim:
Implementing the identified method of digital or technological support in the selected area.

Element Motivation
Higher-level methods can be more disruptive to the environment; thus, an incremental implementation is desirable. Prototyping or incremental implementation of a higher-level solution can aid in the transformation.

Element Summary
Implementing the digital or technological method(s) of support.

Element Guideline

Procedure:

1. Select the most suitable DT support method.
2. Ensure that all relevant areas and the impact of the implementation have been considered.
3. Acquire the selected method of support.
4. Implement the method of support by:
    a. Prototyping the solution if necessary.
    b. Changing the process where required.
    c. Practically implementing the technologies

Step 15: Evaluating the transformation

Aim:
Analyse the area(s) after the low-level implementation.

Element Motivation
The entire transformation process must be evaluated to see the impact of the implementations and move on to new and other types of solutions or transformations. The feedback loop is used to emphasise the continuous improvement of higher-level solutions. The disruption, workforce acceptance, practicality and data collection potential must be analysed to decide if the transformation was adequate and if to continue.

Element Template
Qualitative Analysis: https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=780280619 Quantitative Analysis: https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=659859365 Cost-benefit proposition: https://docs.google.com/spreadsheets/d/1y06CKf6iU3g6kAVSrsAsu_roWCz1r8kOTsVdLmxn9kQ/edit#gid=846657725

Element Guideline

Procedure:

1. Analyse the transformation in detail, using similar methods as in steps 5 and 6, to determine the success of the implementation and to determine if other higher levels of digital support can be approached in these areas or if a new approach needs to be initiated.
2. The following are a set of output questions that can be used to test the sustainability and management of the implemented solutions:
   a. How disruptive is the task?
   b. Is the solution accepted by the workforce?
   c. If applicable, is the solution gathering adequate data?

The three analysis templates are once again linked to this step, where the impact of the implementation can be assessed to determine if the DT support method was adequate.

Suppose the environment's drivers, strategic goals, and TD goals have been met, and the task team believes they are done with their transformation process. In that case, the entire process should restart where new drivers and goals are defined, and a new transformational direction is chosen.

APPENDIX D

Roadmap validation

All figures, code and additional resources used in the validation section of this thesis.

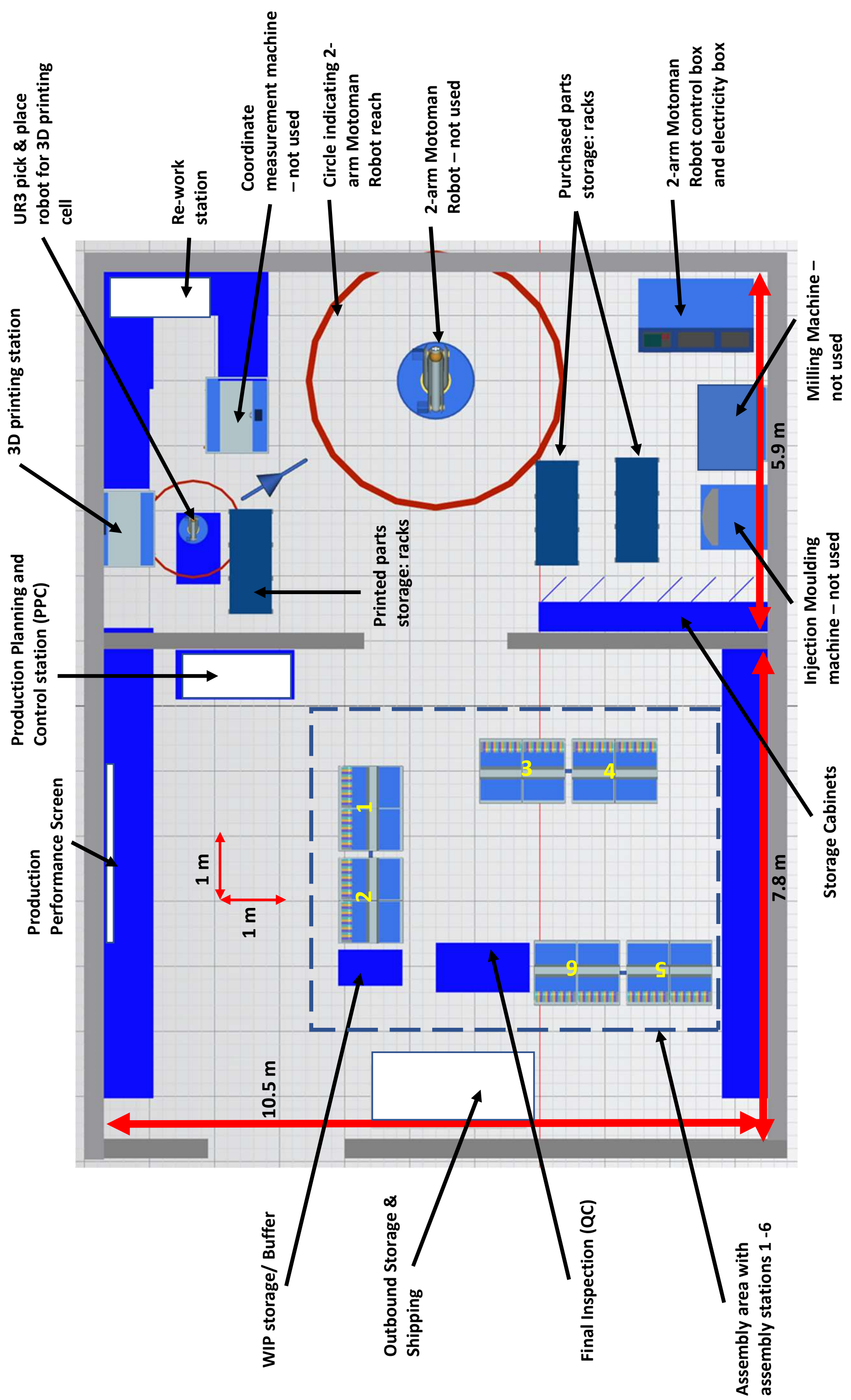


FIGURE D.1: *Current layout of the Stellenbosch Learning Factory*

Arduino code for PIR and RFID system

Below is an example of Arduino code used in this case for the PIR and RFID motion sensor system. This specific code was adapted and combined by the researcher from Arduino Project Hub's [25] basic PIR sensor and the RFID reading example from the MFRC522 library [73]. The two sources were used to create the code for the RFID PIR system. When connected to a PC with a data streamer enabled, the system can capture motion data at a workstation.

```
 /* ----------------------------------------------
  *  Configure MFRC522, PIR and UNO:
  *  ---------------------------------------------
 *             MFRC522      Arduino       PIR
 *             Reader/PCD   Uno/101       Motion
 * Signal      Pin          Pin           Sensor
 * -----------------------------------------------
 * RST/Reset   RST          9
 * SPI SS      SDA(SS)      10
 * SPI MOSI    MOSI         11 / ICSP-4
 * SPI MISO    MISO         12 / ICSP-1
 * SPI SCK     SCK          13 / ICSP-3
 * Digital                  2              OUT
 * ------------------------------------------------

 */
#include <SPI.h>
#include <MFRC522.h>
#define SS_PIN 10
#define RST_PIN 9

MFRC522 mfrc522(SS_PIN, RST_PIN);

// for a led
int lock = 6;
int serrure = 3;
int led = 8;                // the pin that the LED is attached to
int sensor = 2;             // the pin that the sensor is attached to
int state = LOW;            // by default, no motion detected
int val = 0;                // variable to store the sensor status
int x = 0;
char st[20];

void setup()
{
  pinMode(led, OUTPUT);    // initialize LED as an output
  pinMode(sensor, INPUT)   // initialize sensor as an input
  pinMode(lock, OUTPUT);
  pinMode (serrure, OUTPUT);
  Serial.begin(9600);
  SPI.begin();
```

```
  mfrc522.PCD_Init();


  /*Serial.println("Access test via RFID tag");*/
  /*Serial.println();*/
}

void loop() {
  rfid();
  detection(sensor);

}
void rfid(){
  if ( ! mfrc522.PICC_IsNewCardPresent())
  {
    return;
  }
  if ( ! mfrc522.PICC_ReadCardSerial())
  {
    return;
  }
  /*Serial.print("Tag :");*/
  String tag= "";
  byte caractere;
  for (byte i = 0; i < mfrc522.uid.size; i++)
  {
      /*Serial.print(mfrc522.uid.uidByte[i] < 0x10 ? " 0" : " ");
      Serial.print(mfrc522.uid.uidByte[i], HEX); */
      tag.concat(String(mfrc522.uid.uidByte[i] < 0x10 ? "␣0" : "␣"));
      tag.concat(String(mfrc522.uid.uidByte[i], HEX));
  }
  /*Serial.println();*/
 /* Serial.print("Message : "); */
  tag.toUpperCase();

  if (tag.substring(1) == "8F␣79␣D2␣1E")
  {
    digitalWrite(lock, HIGH);
    Serial.println("Artisan␣Check␣In/Out!");
    x = 1;
   /* Serial.println(); */
    delay(3000);
   // if you want to set a led
    digitalWrite(lock, LOW);
    digitalWrite(serrure, LOW);
    }
 else if (tag.substring(1) == "FA␣E0␣B8␣79")
  {
    digitalWrite(lock, HIGH);
    Serial.println("Artisan␣Check␣In/Out!!");
```

```
    delay(3000);
    digitalWrite(lock, LOW);
    digitalWrite(serrure, LOW);

    }
  else
  {
    Serial.println("Unknown␣tag␣-␣Access␣refused␣!!!");
    Serial.println();
    for (int i= 1; i<5 ; i++)
    {
      digitalWrite(lock, HIGH);
      delay(200);
      digitalWrite(lock, LOW);
      delay(200);
    }
  }
  delay(1000);
}

void detection(int sensor){
  val = digitalRead(sensor);    // read sensor value
  if (val == HIGH) {            // check if the sensor is HIGH
    digitalWrite(led, HIGH);    // turn LED ON
    delay(100);                 // delay 100 milliseconds
    if (state == LOW) {
      Serial.println("Motion␣detected!");
      state = HIGH;         // update variable state to HIGH
    }
  }
  else {
      digitalWrite(led, LOW); // turn LED OFF
      delay(200);             // delay 200 milliseconds
      if (state == HIGH){
        Serial.println("Motion␣stopped!");
        state = LOW;        // update variable state to LOW
    }
  }
}
```

Roadmap use on replicated repair process in SLF with middle manager input

Introduction

As part of validating the roadmap, the Stellenbosch Learning Factory (SLF) was used to replicate a repair process similar to the one in case study 1 of the thesis. First, the repair process was replicated, and the SLF was rearranged to simulate a repair process. After that, the reference architecture is used to map the repair process. Together with the mind-maps and other tools outlined in the roadmap document, the roadmap is tested on the process with opinion validation input from a group of middle managers from case study 1. This material was condensed and presented to the group who participated in a survey. These results were used for an opinion poll on the actual experiments and roadmap. This also included the use of the reference architecture and technology mind-mapping methodology. After a brief presentation on Digital Transformation, the first phase was presented. After that, three iterations of the roadmap, implementing various DT support methods and demo DT support methods, were presented to the group to validate the use of the roadmap. The implementation is summarised in figure 1 below:

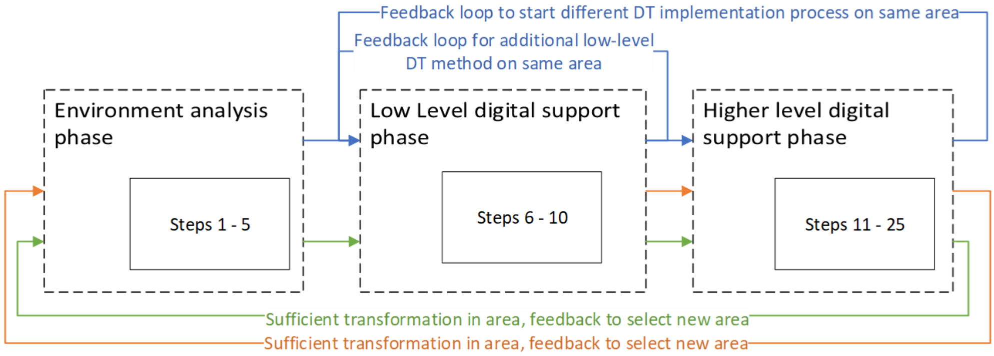


Figure D2: Route taken through the roadmap for the SLF DT process

This document outlines the various steps taken in the roadmap approach, where each step's aim and output are described to demo the roadmap user to the reader. Before using the roadmap, challenges in the Digital Transformation in labour-intensive environments and the research rationale questions were presented to the group of middle managers.

Step 1: Understand environment operations

Element Aim:
Familiarise the DT task team about the manufacturing/value-creation within the environment to gain an overview of the organization's operations, its current position, and its objectives

Element Output

1. **Operations Summary:**

SLF repairs follow a general repair workflow process, shown in figure 2, which was developed using case study 1 and the supporting literature of a repair shop.
Train compartments requiring repairs are sent to the repair facility from the depot or outlet to the unit storage area, where it is checked if such a unit is in stock. If a unit is in stock, a replacement unit is sent to the depot, and a new works order is created, either for driver trains or cabin trains. If no spare units are in stock, a new job works order is created, and the depot would have to wait until such a time that a new unit is available for them.
The defective unit is then sent to the repair facility, which consists of 3 workstations and a cleaning bay. Workstation 1 disassembles the unit and sends the unit for cleaning to the cleaning bay. After cleaning, inspection and diagnosis are conducted to order any unique spare parts not included in the train's repair kit. Each train has a repair kit, where all seats and internal items are replaced in each repair cycle. The unit is then sent to workstation 2, where the re-assembly occurs. The employee uses the relevant kit to refurbish the unit. Upon collection of any unique spares, such as new wheel compartments, side panels or any other specific spares, the final assembly takes place (without the train's roof). The unit is sent to workstation 3. Workstation 3 is the testing and quality control. The employee quality checks that all components are included in the train compartment does quality checks on these items and tests the wheel compartments to ensure usability. Finally, the roof is attached, and the finished unit is sent to unit storage for delivery.
The existing layout of the SLF was adapted for the SLF repairs case studies, seen in figure 1.

SOP for each workstation:
Workstation 1:

1. Remove roof, wheel compartment and supplementary compartments 1 & 2.
2. Remove train compartment chairs and inner compartments and place them in the recycling/sub-storage area.
3. Move the remaining items to the cleaning bay.
4. Move cleaned items back to Workstation 1.
5. Inspect and diagnose units and compartments and remove faulty spares by placing them in the recycling/sub-storage area.
6. Move the unit with remaining spares to the work-in-progress (WIP) for workstation 2.
7. Order additional spares from storage.

Workstation 2:

1. Move unit items from WIP to workstation.
2. Fetch ordered spares from storage reception.
3. Re-attach compartments and ordered spares.
4. Attach chairs from unit-specific kit to the inside of a train.
5. Move to WIP for workstation 2.

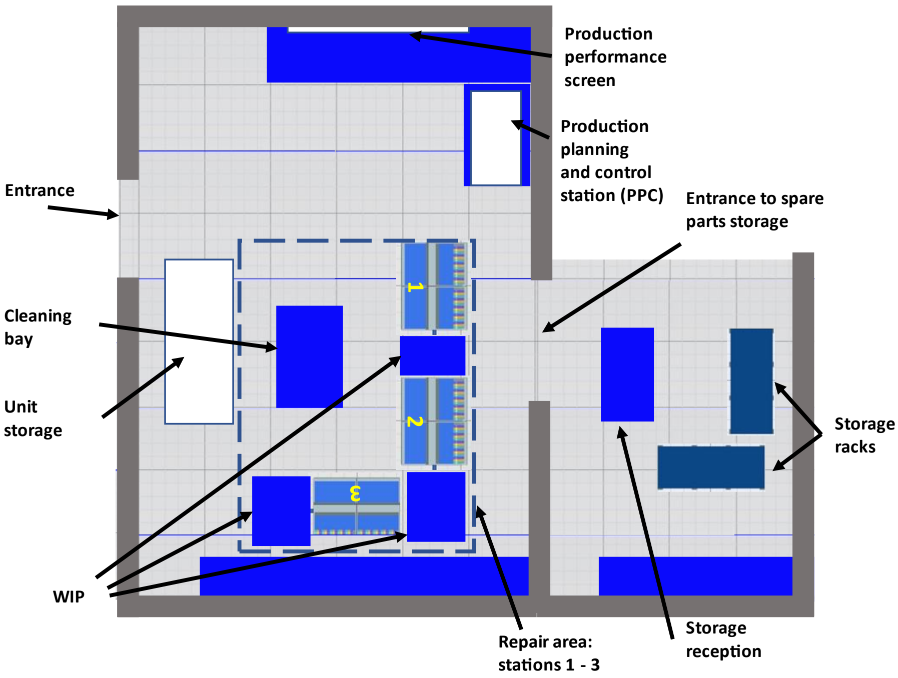


Figure D3: SLF Repair Layout Schematic

Workstation 3:

1. Move unit from WIP to workstation.
2. Visually inspect outside of the train as per checklist requirement.
3. Sample quality check of screws, walls and compartments.
4. Visually inspect inside of train as per checklist requirement.
5. Sample quality chairs and walls.
6. Attach roof.
7. Move to WIP for collection from unit storage.

2. Using reference architecture on repair process:

The operations description, and process flow, figure 2, are then used on the reference architecture of digital and technological support methods for a labour-intensive environment, figure 3. The process flow is central to the reference architecture, and the environment is categorised

1. Business processes are identified from the process flow and SOPs.
2. All sub-processes, resources, apparatus, and digital/technological connection are listed from the business processes.
3. The primary business processes and all accompanying business processes are categorised into the different areas of the reference architecture

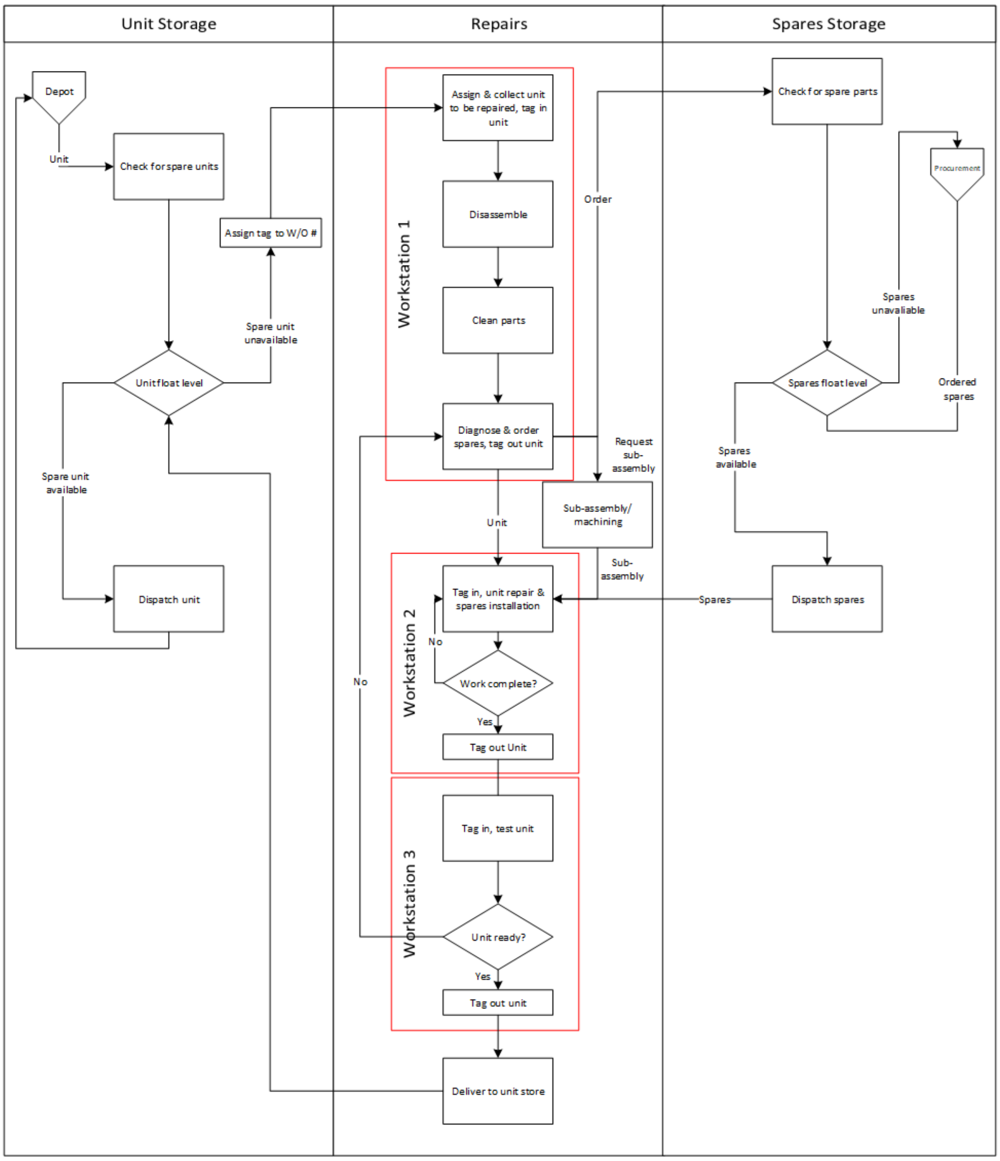


Figure D4: Process flow of general repair workshop used in SLF repairs

Table D1: SLF repair process mapped on reference architecture

<table>
<tr><th colspan="2">Data Management</th></tr>
<tr><td colspan="2">1. Data collection
- Traditional methods: sampling, time studies, observation
- Printed paper: orders, parts, delivery
2. Data management system
- No current system
3. Communication
- No level of asset or resources connection (no online system)
- No Wi-Fi connection
4. Analysis:
- Manual data analysis using MS Excel or written calculations
5. Process modelling
- Line balancing, lean methodologies (non-digital)
6. Performance management
- Based on data analysis, manual calculations.</td></tr>
<tr><th>Value Creation</th><th>Labour Management</th></tr>
<tr><td>1. Labour-intensive processes:
- WS1: manual disassembly & cleaning
- WS2: manual assembly
- WS3: manual assembly & quality inspection
2. Supporting manufacturing processes:
- 3D printer
3. Guidance:
- SOP at each station
4. Process & synchronisation
- Whiteboard and projector using MS office for process management system</td><td>1. Task allocation:
-Subjective task assignment
-Subjective RST allocation
2. Training:
-Observation and interactive learning with employees
3. Safety:
-UR3 smart emergency stop system
-Designated safety areas with yellow floor lines
-PPE required to enter the facility</td></tr>
<tr><th>Apparatus Management</th><th>Inventory Management</th></tr>
<tr><td>1. Asset control
- Sign in the system for special tools (paper)
2. Asset security
- Sign in the system for special tools (paper)
3. Relevancy
- Various unused equipment.</td><td>1. Inventory control
- Delivery note system (paper)
- Manual stock count
- Paper unit tags
2. Inventory security
- Access limited to receptionist at spares storage
- Code locked door
3. Forecasting
-Out-of-stock ordering</td></tr>
<tr><th>Product Management</th><th>Technology Management</th></tr>
<tr><td>1. Quality:
-Manual quality check
2. Product design:
-N/A
3. Customer requirements:
-N/A</td><td>1. Software infrastructure:
- MS Office, CAD, UR3 IDE software
2. Hardware infrastructure:
- 3D printer, UR3 robot, projector system.</td></tr>
</table>

Step 2: Define drivers for Digital Transformation

Element Aim:
Establish the driver for Digital Transformation in the scope of the business/ operation.

Element Output

Sample drivers for Digital transformation

1. External drivers of transformation, such as:
    a. Market pressure from competition with innovative value delivery.
    b. Changing customer requirements.
2. Based on the output of step 1:
    a. Management wishes to increase its digital capability and reduce unnecessary expenses such as paper consumption.
    b. Data collection for increased transparency and further decision-making
    c. The need for a compromising solution without endangering jobs.

Step 3: Establish DT strategic goals

Aim:
To establish the overall outcome of Digital Transformation within the environment and identify the desirable type of Digital Transformation.

Element Output

With an eye on increasing the digital capability of the environment, human-centric and suitable approaches were used to define the following goals; below is an example using SMART goal setting for the first DT increment:

1. Specific: Increase transparency with increased data collection capabilities and reduce our paper output.
2. Measurable: Quantify information from workstations and reduce paper by at least 50%.
3. Attainable: We can eventually reach these goals by incrementally using the roadmap.
4. Relevant: Increased data collection can help us determine waste and improve the various environmental processes
5. Time-based: Lower-level implementations: 2 weeks, higher level implementation, 1 year.

Additional goals in the increments are optimizing the labour process and fostering human-CPS or human-robot collaboration in iteration 2 and quality improvement for iteration 3.

In a labour-intensive context, it is always important to keep the value of the labourer in mind, and a human-centric approach is recommended, especially in a South African context.

Step 4: Establish DT task team

Element Aim:
Establish a planning team that is responsible for Digital Transformation.

Element Output

Table D2: DT task team selection

Role	Role Description	Role Requirements
Upper Management Person(s): Company Engineer	The company engineer is the highest position in the organisation's operations and has the business authority to authorise any decisions and changes in the strategy and operations of the organization. In this case, they link the DT task team and business management. The company engineer has authority to implement major changes, authorise purchases, implementations and any contractors.	Understand the organization's structure, operations, activities, and customers. Have adequate business management, human management, and communication skills. Be aware of alternatives in each layer of the company structure. Align any ideas or means of digital support within the operations and organization.

Role	Role Description	Role Requirements
Operations Management Person(s): Technical Manager	The technical manager is the operations manager of the repair facility and has the authority to make decisions and changes in the operations management or value creation of the environment. In the DT task team, they communicate directly with upper management, manage people in the operations, are a team leader and drive the cultural change in the operations environment.	Understand the environment operations, and all activities and areas required to deliver the output value of the operations Align any ideas or means of digital support within the operations and organization. Are aware of common sources of wastes, inefficiencies etc. in the operations and be aware of alternative processes or options in the value-creation process. Have adequate management and communication skills

Role	Role Description	Role Requirements
DT process Person(s): Quality controllers Process Engineers	The quality controllers and process engineers design the process flow of the enviroment and ensure adequate quality control measures in the value creation. In the DT team they assist in the DT by doing research on digital or technological support methods, acquiring the actual technologies for approval, implement prototypes and actual solutions and communicate the progress of the tasks to management. They are the "ground crew" in this DT apporach, finding and implementing solutions were possible.	Understand operations or value creation Understand technologies, tools and methods of transformation Teamwork, communication and commitment to digital transformation

Role	Role Description	Role Requirements
Middle management: DT & Area support Person(s): Foremen Department leading hand	All relevant middle managers from all areas in the value-creation process are part of the DT team for supportive measures. They work with both the actual labour staff, and the DT team, where they form the communciation link between value creation in a specefic area, human resources and upper management.	Leading hand from a department in the value-creation process Manager of human resources, assets and any additional value-creation elements.

1. SLF repairs are based on case study 1, where the following leadership roles are relevant in the repair environment.
2. Process engineers and quality controls are the “ground workers” in process improvement and quality control in case study 1, where research and implement new process

improvements and quality measures. In SLF repairs, the researcher represents the DT process role, where the researcher does all research and implementations.

3. Finally, middle management are the supervisors (leading hands) and foremen responsible for overall day-to-day operations in case study 1 and serve as direct communication between the DT task team and the labour workforce. SLF repairs only has one repair line, thus the middle management of case study 1 will be consulted with the outcomes of this case study to investigate the feasibility of both the DT approach in a labour-intensive environment, and the cyber-physical systems or methods of digital and technological support used in SLF repairs.

Step 5: As-Is analysis

Aim:

Broadly analyse the current state of the environment qualitatively to support determining the DT goals of the environment.

Element Output

1. Various qualitative data collection methods are used:
   a. Observational studies
   b. Process analysis
   c. Discussions with labourers and middle management
2. Qualitative data is used to identify root causes of challenges using:
   a. Ishikawa Fishbone Diagrams

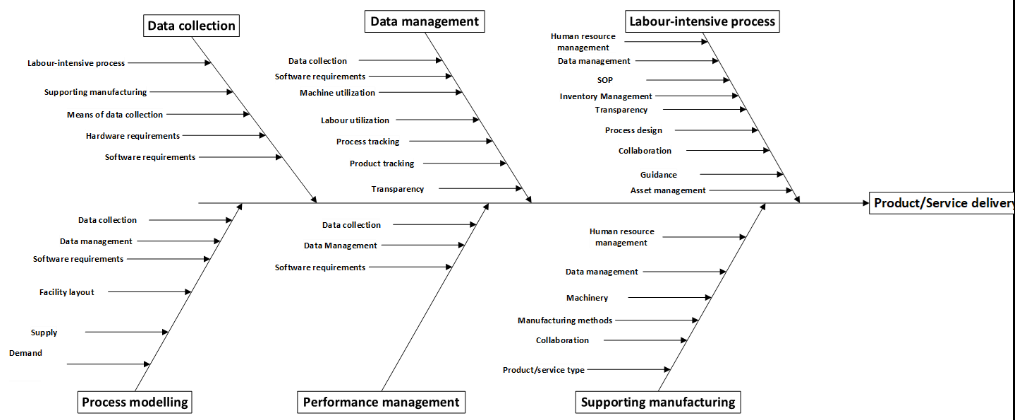


Figure D5: Value-creation Ishikawa diagram

Step 6: DT Area selection & goals

Element Aim:

Selecting the first area(s) for the transformation process/methods of digital support implementation

Element Output

Pareto analysis:

Table D3: Pareto scoring table

Area	Total Root Causes & Opportunities	Total Percentage	Cumulative Percentage
Value-creation	8	30.77%	30.77%
Apparatus Management	6	23.08%	53.85%
Inventory Management	5	19.23%	73.08%
Labour Management	4	15.38%	88.46%
Product Management	3	11.54%	100.00%

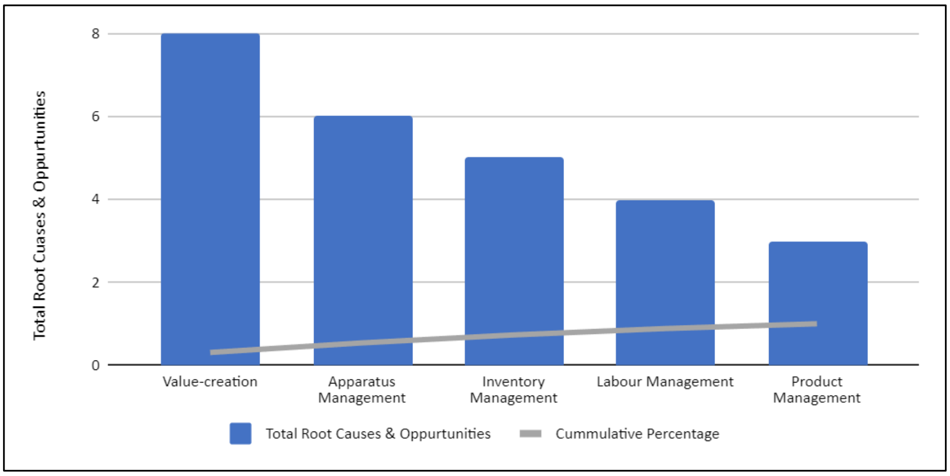


Figure D6: Pareto analysis on RA areas

Based on the Pareto results, value creation is selected as the first area of analysis, with the goal of increasing transparency and enabling increased data collection.

Step 7: Identify low level digital potentials

Element Aim:
Identifying low levels of digital or technological support for the DT of the previously selected and analysed area

Element output:

The basic process for creating user-specified mind maps is used:

1. **Reference Architecture selection:**
   After environment analysis, each part of the application layer in the reference architecture is selected as the centre point for its two technology mind maps, with its sub-areas serving as subbranches.
2. **Architecture relationship branches:**
   Each sub-branch is broken down into further branches of data collection, management, and technology application.
3. **Root causes, challenges, and opportunities:**
   The various challenges, opportunities, or cause-and-effect relationships are listed for each relationship branch. These subbranches indicate specific processes where various digital or technological support methods can be added to collect data and/or improve the process.
4. **DT brainstorming:**
   Utilizing research and brainstorming techniques, solutions in the form of digital or technological support methods are found to address the challenges or opportunities in the form of Digital Transformation.

A sample mind map for low-level identification can be seen in figure 6 on the next page, where the first three steps are outlined. An extracted mind map for labour-intensive manufacturing with step 4 is shown:

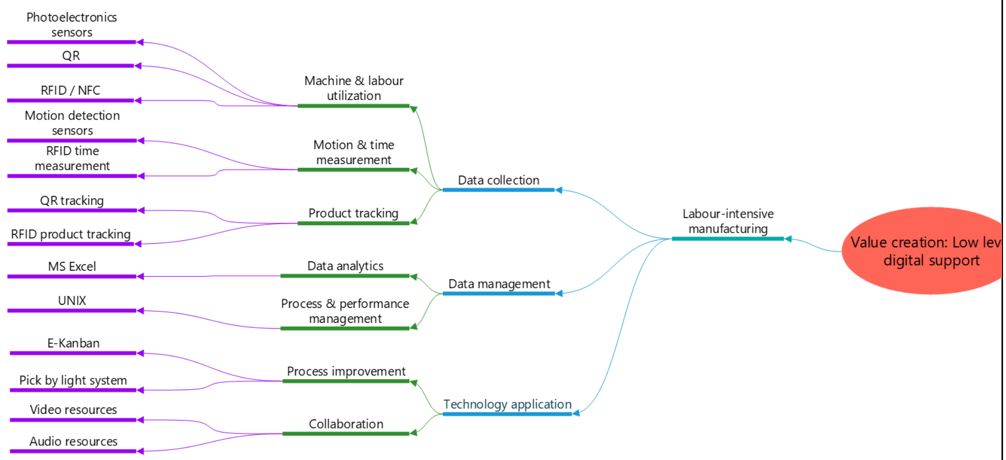


Figure D7: Extract from low-level mind map for labour-intensive manufacturing in the SLF repair process

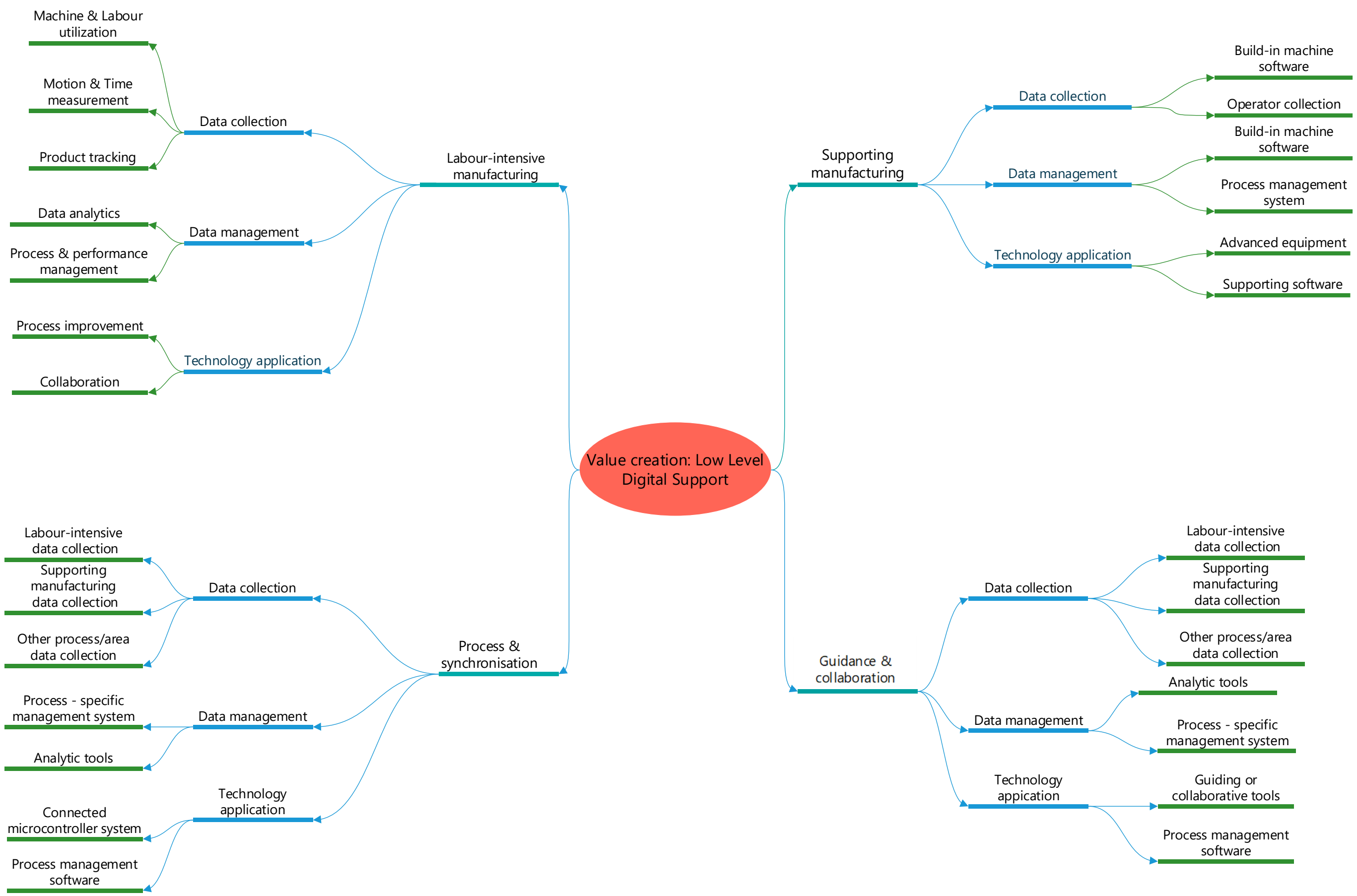


Figure D8: Low-level mind map for value creation of SLF repair process - steps 1-3

Iteration 1a: Step 8 - Visualise to-be process

Element Output

Procedure:

1. Selected improvement:

Table 4: 1. Selected Improvement – RFID

Area	Potential Implementation	Implementation purpose	Implementation requirements
Value Creation Sub-area: Labour-intensive manufacturinng Physical location: Workstation's 1 - 3	**Low cost RFID tracking system**	RFID tracking system to record cycle times and detect any variances. Results can be used to assign practical reasonable standard times and collect data to make other process improvement decisions, both digital and non-digital solutions. Finally, increases transparency of value-creation process.	1. Hardware requirements: a. Microcontroller and cables for each desired station (preferably wireless) b. RFID Reader modules for each desired station c. RFID tag for each unit d. Internet connection (preferably Wireless) e. Desktop for programming 2. Software requirements: a. Integrated development environment (IDE), such as Arduino IDE b. Access to google scripts c. Access to google sheets

2. Cause-and-effect:

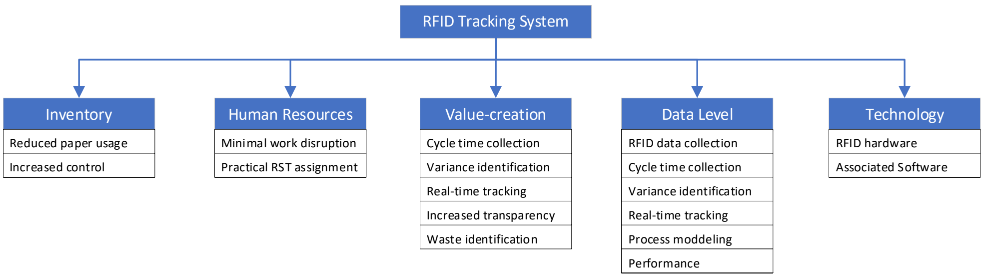


Figure D9: Potential RFID cause-and-effect

3. Map:

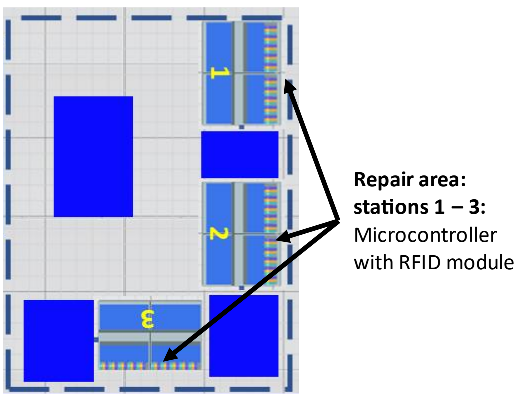


Figure D10: Physical location of DT support method

SOP change: Employee tags in unit in beginning and end of each SOP

4. See adapted process flow, figure 5.
5. RA update:

Value creation:

- Process, collaboration & synchronization: Semi-RT tracking, cycle time analysis, variance, analysis,

Human-Resources:

- Allocation: Practical RST allocation

Data Management

- Collection: Semi-RT tracking, cycle time, variance collection
- Connection: Unit connection via RFID tags
- Process modelling & Performance monitoring: new data leads to new analysis, calculation, and new process improvement design.

Inventory:

- Control: reduced paper usage, increased transparency

Technology:

- RFID system hardware & software.

Iteration 1a: Step 9 - Implement low levels of digital support

Element Guideline

Implementation Overview:

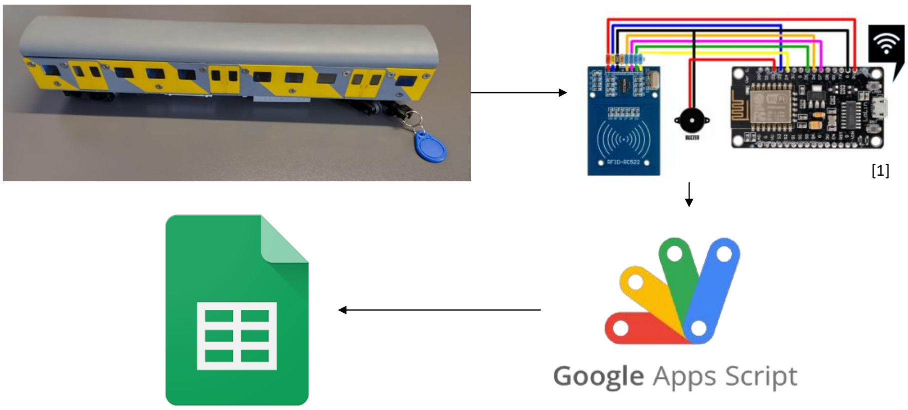


Figure D11: RFID system simplified

Each train compartment scheduled for repair is tagged with a 125kHz tag, where the compartment type and works order number are encoded. A NodeMcu microcontroller fitted with an RFID reader and buzzer and connected to Wi-Fi is implemented in each station. As a compartment tag is swiped on the reader, the reader sends the card information via Wi-Fi to a Google Apps Script. The script writes the date, time and job number variables from the tag on the Google sheet. The system enables Semi-RT tracking, where work order progress can be viewed remotely. Furthermore, data is collected on cycle times and variances in cycle times for a works order and the interpretation of data and decision-making, such as new RST standards.

Implementation Procedure:

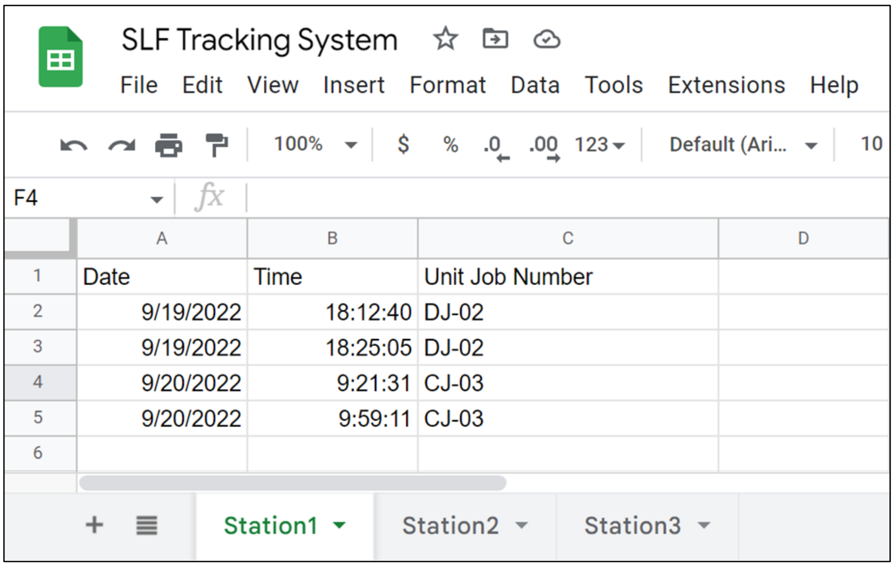
All microcontroller programming is done via the Arduino IDE, and Google Apps Script programming is used to program the GS file. The code and implementation were adapted from Ahmadlogs to suit the needs of the SLF repair system:

1. The NodeMcu, RFID reader and buzzer are connected as in the diagram above; this is done for each station i.e., 3 microcontroller setups.
2. RFID tags are encoded using a microcontroller setup. The relevant code is used to assign a work order number to each tag and extract the HEX ID from the tag to categorise the tag as either cabin train or driver train. The tags and job-numbers are re-used continuously.
3. The Google Sheets are set up with date, time and works order columns
4. The Google App Script file is published and awaits an HTML connection from the microcontroller. A different script is created for each microcontroller setup.
5. The micro-controllers are setup using relevant packages, Arduino Code and Wi-Fi connection, where a date and time stamps, works order number and compartment type is extracted from the tags upon contact.
6. The microcontrollers are connected to Wi-Fi awaiting and ready to use.

Implementation Operation:

1. Employee assigns relevant encoded tag to receiving unit at unit reception, as seen in the figure above.
2. Unit is scanned before and after SOP at each workstation.
3. The works order time stamps at each station are sent to Google Sheets via the Wi-Fi and Google Apps Script.
4. Employee removes tag after repair process for re-use.

Implementation Output:



	A	B	C	D
1	Date	Time	Unit Job Number	
2	9/19/2022	18:12:40	DJ-02	
3	9/19/2022	18:25:05	DJ-02	
4	9/20/2022	9:21:31	CJ-03	
5	9/20/2022	9:59:11	CJ-03	
6				

Figure D12: Low cost RFID spreadsheet output

The entry and exit date and time stamp for each work order at each station are now available for analysis, management and data-driven decision-making. DJ refers to a driver train job, CJ to a cabin train job.

Iteration 1a: Step 10 - Analysing the improved process

Aim:
Analyse the area(s) after the low-level implementation.

Element Output
The SLF tracking system allows for semi-RT tracking of units in the repair processes. The RFID tracking system also enables the recording of unit cycle times, facilitating variation analysis and standardisation calculations. Additionally, the implementation allows for a line manager to identify the stations that take the longest to create value. With additional study, line-balancing and waste management concepts can be developed to improve the efficiency of the repair line. Based on the brief analysis, it was decided to return to step 6 and perform a second low-level iteration to capture more data in the labour-intensive repair process.

Iteration 1b: Steps 6-7

Aim:
Analyse the area(s) after the low-level implementation.

Element Output
The previous mind-maps that were developed were used, and it was decided to attempt to capture motion data to increase transparency and implement a PIR motion tracking system. It was determined that further transparency and a more integrated tracking system in the environment can now be tested.

Iteration 1b: Step 8 - Visualise to-be process

Element Output

Procedure:

6. Selected improvement:

Table D5: Selected improvement - PIR system

Area	Potential Implementation	Implementation purpose	Implementation requirements
Value Creation Sub-area: Labour-intensive manufacturinng Physical location: Rotational	**Low cost PIR motion tracking system**	PIR motion sensor system, moveavle between station's one and three to calculating wastes quanattivtley by determining station downtime, and value-added station time. Increases transparency in the labour-intensive process. Substitute for conventional time study, and doesn't require additional employees. The system is designed to be a rotating tool that may be utilised in a variety of labour-intensive value-creation processes rather than a permanent installation.	1. Hardware requirements: a. Microcontroller and cables b. RFID Reader module c. RFID tag for each artisans e. Desktop for programming and data-collection 2. Software requirements: a. Integrated development environment (IDE), such as Arduino IDE b. Access to MS Excel c. Access to MS Excel data streamer

7. Cause-and-effect:

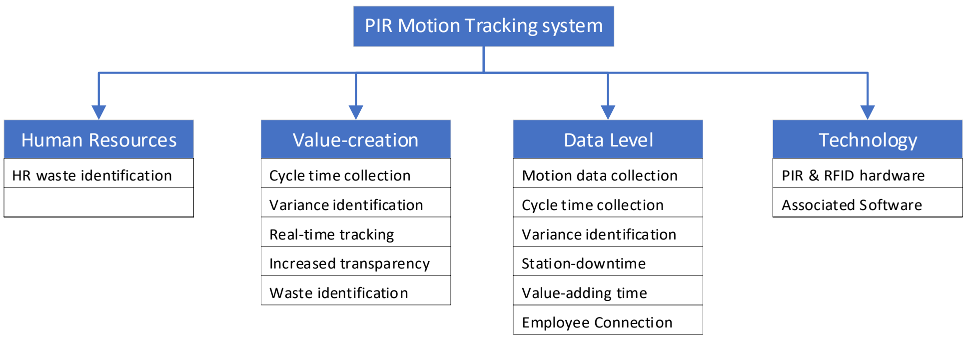


Figure D13: Potential PIR cause-and-effect

8. Map:

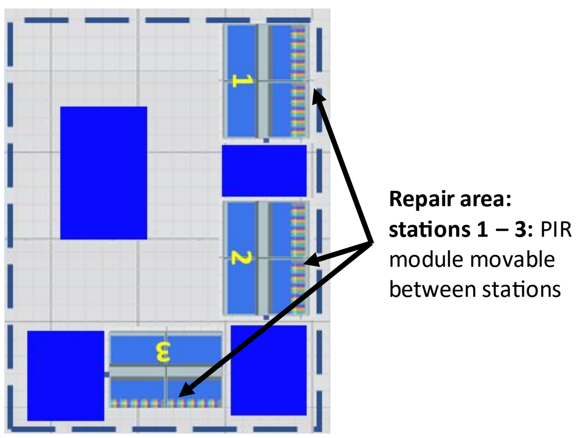


Figure D14: Physical location of DT support method

SOP change: Employee tags in at each station in beginning and end of each shift.

9. RA update:

Value creation:

- Process, collaboration & synchronization: Value-creation tracking, station down time analysis, variance analysis.

Human-Resources:

- Allocation: Practical RST allocation, transportation and moving waste management.

Data Management

- Collection: motion tracking, variance collection
- Connection: Employee connection with tags
- Process modelling & Performance monitoring: new data leads to new analysis, calculation, and new process improvement design.

Technology:

- PIR & RFID system hardware & software.

Iteration 1b: Step 9 - Implement low levels of digital support

Element Guideline

Implementation Overview:

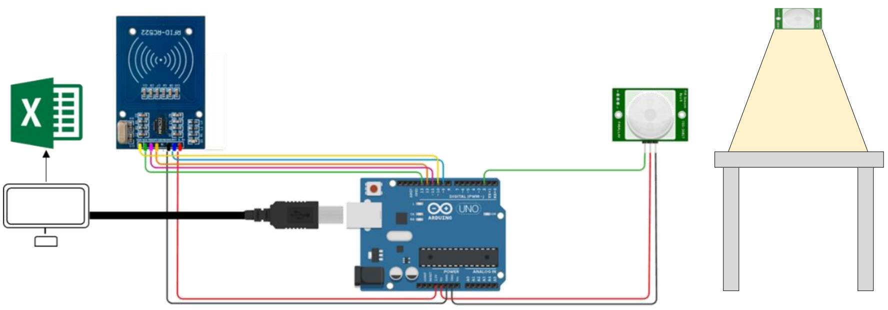


Figure D15: PIR system wire diagram and motion capture area visualised

A workstation selected for further analysis is equipped with the PIR & RFID system. The employee responsible for the value-creation of the workstation is equipped with a 125kHz tag encoded with a unique HEX ID. The system is connected to Excel Data Streamer from the Arduino system via a USB cable. As an employee tags in, a starting timestamp is generated. As motion is detected at the workstation, the PIR sensor activates and enters a timestamp stating station uptime as started. If motion stops at the workstation, the PIR inactivates and sends a timestamp to the Excel data streamer. This allows the quality controllers to calculate station downtime and non-value-adding time, where further analysis can be done for workstations with high downtime rates to determine waste.

Implementation Procedure:

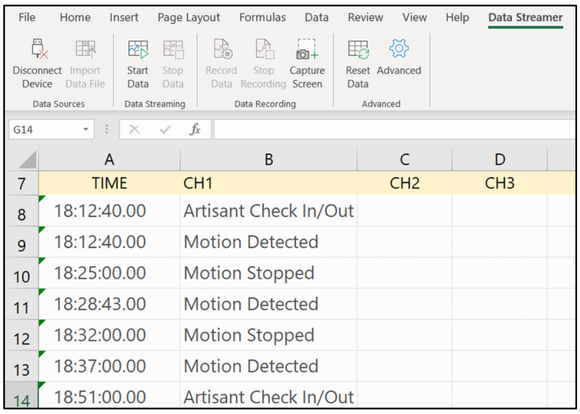
All microcontroller programming is done via Arduino. The code and implementation were created by combining a simple PIR detection code and RFID detection code examples on Arduino IDE.

1. The Arduino Uno, RFID reader and PIR are connected as in the diagram above.
2. The PIR sensor is attached in a downward position capturing only the production area of the workstation.
3. The system is connected to a laptop or PC and excel data streamer is activated.
4. The micro-controllers are setup using relevant packages and Arduino Code

Implementation Operation:

5. Employee tags into station
6. PIR is activated if infrared motion is detected.
7. PIR inactivated if no infrared motion is detected.
8. Employee tags out of station.
9. Data is captured from the system on excel streamer.

Implementation Output:



	A	B	C	D
7	TIME	CH1	CH2	CH3
8	18:12:40.00	Artisant Check In/Out		
9	18:12:40.00	Motion Detected		
10	18:25:00.00	Motion Stopped		
11	18:28:43.00	Motion Detected		
12	18:32:00.00	Motion Stopped		
13	18:37:00.00	Motion Detected		
14	18:51:00.00	Artisant Check In/Out		

Figure D16: PIR system excel output

The check-in, check-out, and detection timestamps can now be used to determine the station-downtime of each station and determine which station the task team should focus on for additional support methods.

Iteration 1b: Step 10 - Analysing the improved process

Aim:
Analyse the area(s) after the low-level implementation.

Element Output
This solution enables line managers to analyse further and determine station downtime and unsupervised productive time analysis and is more aimed at capturing time spent away from the workstation. This data collection method allows for more in-detail tracking and transparency. It can be used to collect data that is to be used in additional implementations. With the increased transparency, and low-level implementation in place, the labour-intensive process can be advanced in the roadmap, and a higher-level concept can be identified.

Iteration 1: Step 11 - Defining higher-level goals

Aim:
Selecting the first area(s) for the transformation process/higher level methods of digital support implementation

Element Output
Based on the previous two implementations, it was decided to investigate higher-level DT support methods in the labour-intensive repair process.

Iteration 1: Step 12: Identify high-level digital potentials

Element Aim:
Identifying high-level DT support methods for the DT of the previously selected and analysed area

Element output:

The basic process for creating user-specified mind maps is used:

1. **Reference Architecture selection:**
   After environment analysis, each part of the application layer in the reference architecture is selected as the centre point for its two technology mind maps, with its sub-areas serving as subbranches.
2. **Architecture relationship branches:**
   Each sub-branch is broken down into further branches of data collection, management, and technology application.
3. **Root causes, challenges, and opportunities:**
   The various challenges, opportunities, or cause-and-effect relationships are listed for each relationship branch. These subbranches indicate specific processes where various digital or technological support methods can be added to collect data and/or improve the process.
4. **DT brainstorming:**
   Utilizing research and brainstorming techniques, solutions in the form of digital or technological support methods are found to address the challenges or opportunities in the form of Digital Transformation.

This methodology is repeated for both the low-level technology mind map development and the high-level mind map, with the only difference being:

1. **Advanced DT solution brainstorming**
   More advanced support methods are identified after analysing a previous implementation, either based on the previous set of solution or on the root causes and outcomes of step 3 and 4.

A sample mind map for high-level identification can be seen in figure 8 on the next page. The first three steps are outlined and where the 4th step is shown in purple in the labour-intensive sub-area. An extracted mind map for labour-intensive manufacturing with step 4 is:

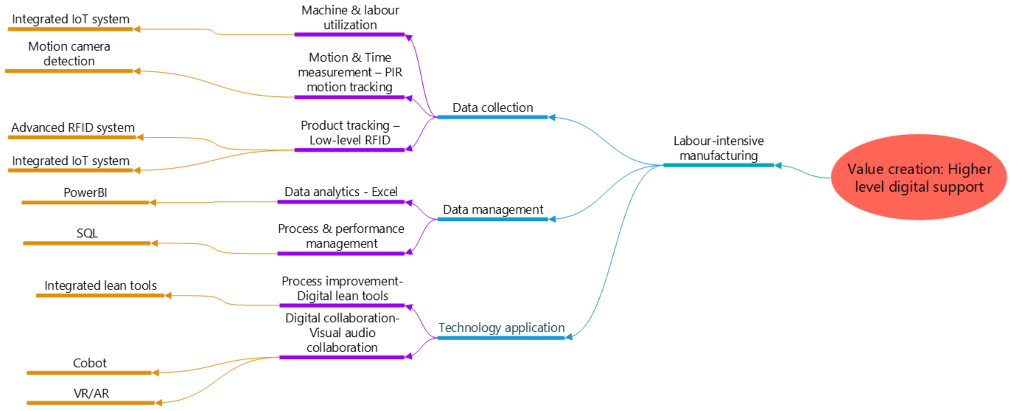


Figure D17: Extract from low-level mind map for labour-intensive manufacturing in the SLF repair process

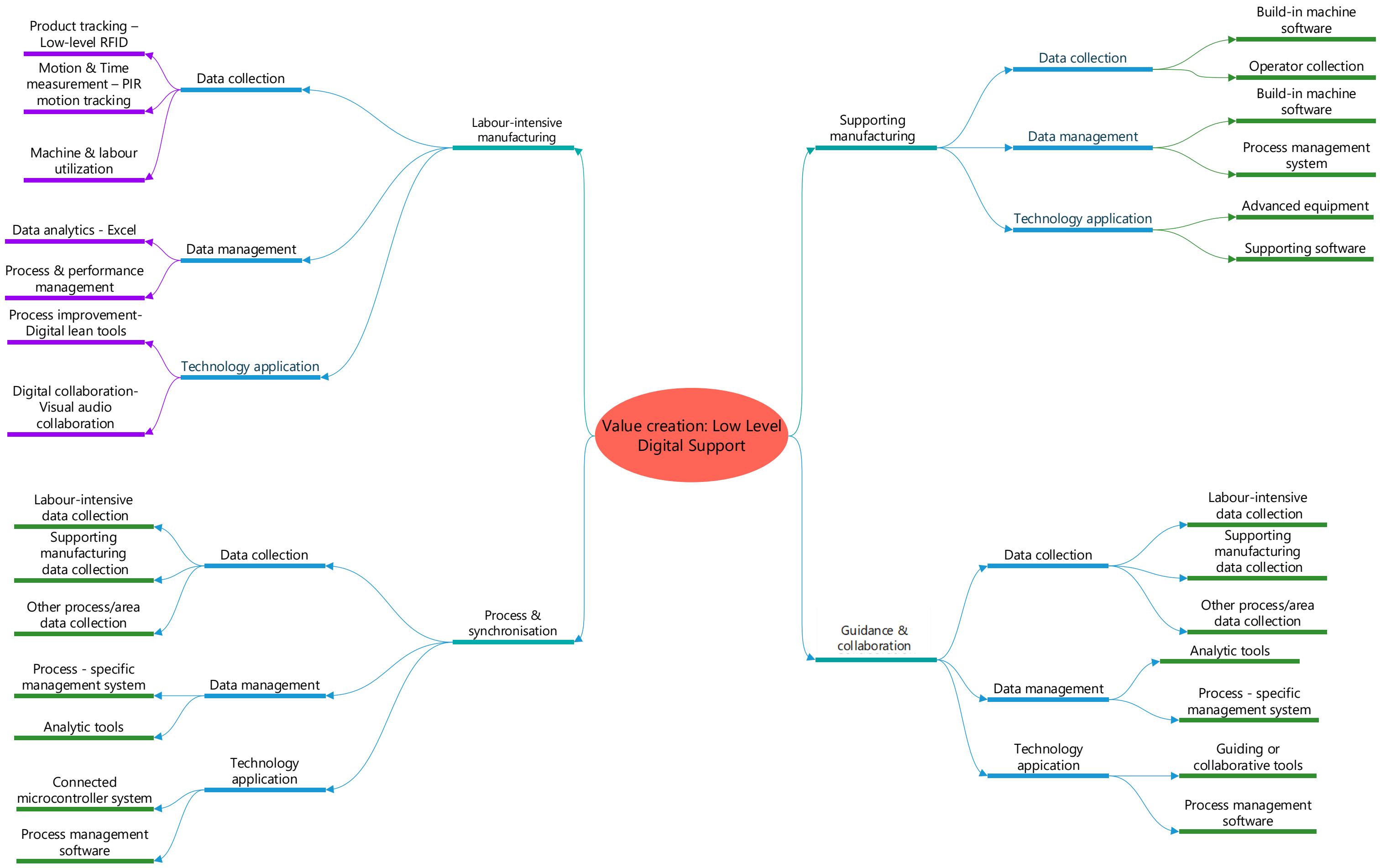


Figure D18: High-level mind map for value creation of SLF repair process - steps 1-3, and step 4 for labour-intensive process

Iteration 1: Steps 13 - 14 - Visualise to-be process

Element Output

Procedure:

10. Selected improvement – demo UHF RFID:

Table D6: Selected improvement - demo UHF RFID

Area	Potential Implementation	Implementation purpose	Implementation requirements
Value Creation	**UHF RFID system**	UHF RFID tracking system to record cycle times and detect any variances. Results can be used to assign practical reasonable standard times and collect data in all parts and spares in the enviromentcisions. Finally, increases transparency of value-creation process and allows for real-time tracking.	1. Hardware requirements: a. Third part hardware 2. Software requirements: a. Third part sofwarel
Sub-area:			
Labour-intensive manufacturinng			
Physical location:			
Entire SLF repair process			

11. Cause-and-effect:

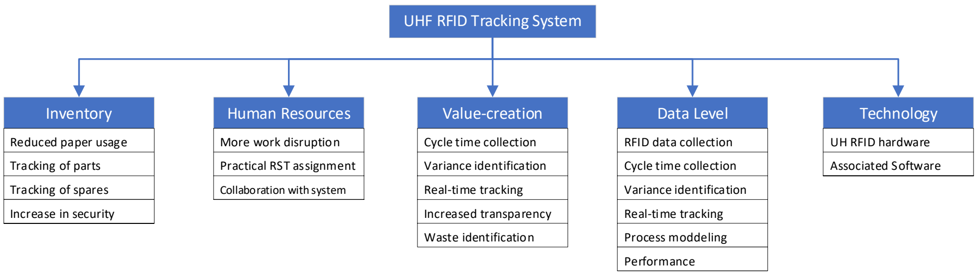


Figure D19: UHF RFID potential cause-and-effect

12. Map:

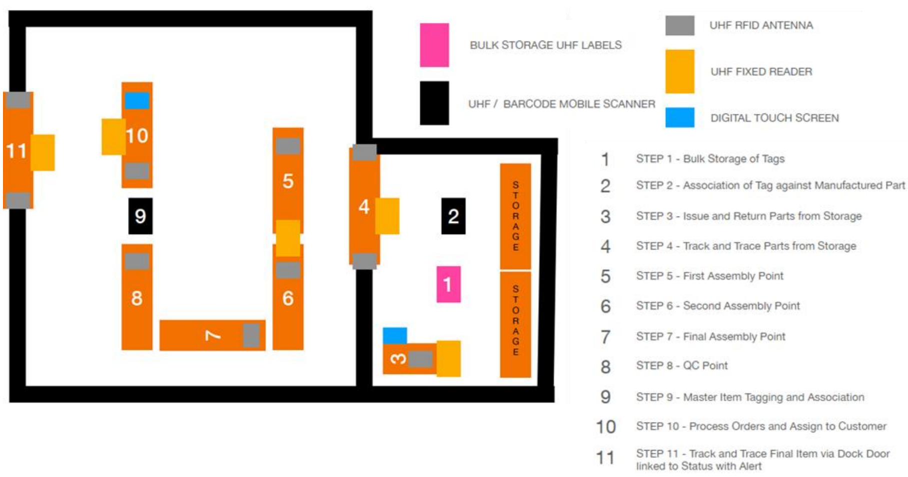


Figure D20: Physical location of DT support method

SOP change: Employee tags in at each station in beginning and end of each shift.

13. RA update:

Value creation:

- Process, collaboration & synchronization: Value-creation tracking, station down time analysis, variance analysis.

Human-Resources:

- Allocation: Practical RST allocation, transportation and moving waste management.
- More resistance to change expected.

Data Management

- Collection: motion tracking, variance collection
- Connection: All parts connected with RFID labels
- Process modelling & Performance monitoring: new data leads to new analysis, calculation, and new process improvement design.

Technology:

- UHF RFID system hardware & software.

Cost-benefit:

- Increased cost expectation

Implementation:

1. **Step 1 - Labels:** RFID labels for all parts of the assembly are used in a wide variety of sizes, depending on the part. Chair kits are packaged together with one tag.
2. **Association:** Parts are RFID enabled and information, such as part numbers, are associated with the tags.
3. **Issue & return:** Parts are managed through a physical interface and fixed reader, where operators can issue and return parts.
4. **Track & Trace from store:** The fixed reader allows for determining if items leave the store without being booked and indicated this to the system and operator.
5. **Assembly point 1:** Upon unit arrival, the system and dashboard are updated with a time and date stamp of arrival, indicating the exact number of items currently assembled. Artisans can then order by using the digital touch screen.
6. **Assembly point 2:** When parts arrive at this station, the system and dashboard are updated with an arrival time and date stamp, indicating the exact number of items currently assembled. Additional data can be gathered in the form of time laps from Assembly Point 1 to 2.
7. **Final assembly:** Similar to the previous two steps.
8. **Quality check:** Similar to steps 5-7, with additional information stamps regarding its quality test results. Redirection to other assembly points is possible.
9. **Master tag assignment:** All tags are associated with a master tag for the finished unit.
10. **Sale of item:** To ensure traceability, the final items sold can now be scanned and assigned to a customer to complete the cycle. A change in status indicates that the item has been dispatched and allows for free movement, which is required for the final process.
11. **Dock door verification**: Similar to step 4, the fixed reader allows for complete tracking, alerting the system and operator with a buzzer and light if an unfinished item is indicated.

Iteration 1: Step 15 - Analysing the improved process

Aim:
Analyse the area(s) after the low-level implementation.

Element Output
After the first iteration, full-scale tracking of parts and units is now available in the SFL. In addition, real-time monitoring and additional data collection are now possible, enabling further decision-making. The first set of practical validation questions was presented to the middle managers, whereafter, it the presentation moved on to other subareas of value-creation to improve efficiency.

Iteration 2: Step 1 - 7

Aim:
Analyse the area(s) after the low-level implementation.

Element Output
After the first iteration, the roadmap was restarted, where the new DT support methods were added to the reference architecture – in data collection. After that, steps 2 – 3 remained unchanged. Based on the ability to analyse quantitative data, quantitative analysis can also be used in step 5, where it is now possible to calculate more detailed variances in cycle times and allows for station downtime analysis. Steps 6 and 7 were used to select DT in process improvement, where digital lean tools in the form of a hybrid e-Kanban and pick-by-light system were chosen as the first implementation.

Iteration 2: Step 8 - Visualise to-be process

Element Output

Procedure:

14. Selected improvement:

Table D7: Selected improvement - digital lean systems

Area	Potential Implementation	Implementation purpose	Implementation requirements
Value Creation & Inventory Management Sub-area: Labour-intensive manufacturinng, inventtory control & forecasting Physical location: Workstation 2 & Spare parts stroage	**Pick by Light & E-Kanban System**	Client Pick by light system fixed to workstation 2 to guide the employee on which parts to use in the assembly process for each train, determined by train's RFID tag. Server E-kanban system that receives signals from workstation 2 indicating the parts usage of workstation 2 and guiding the spare parts storage employee which parts to replenish.	1. Hardware requirements: a. 2 Microcontrollers with Wi-Fi Modules b. RFID Reader module c. Existing RFID tracking system e. Desktop for programming and data-collection 2. Software requirements: a. Integrated development environment (IDE), such as Arduino IDE

15. Cause-and-effect:

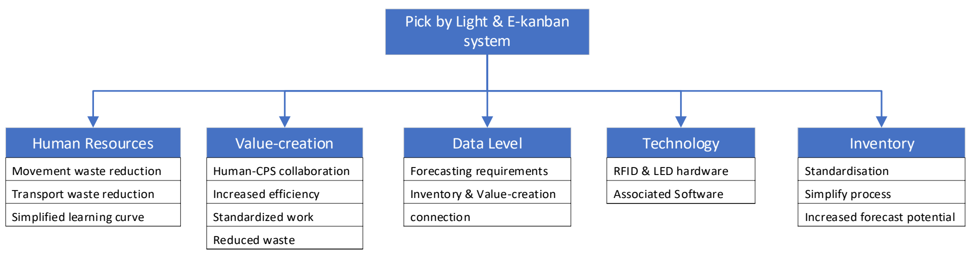


Figure D21: Potential digital lean cause-and-effect

16. Map:

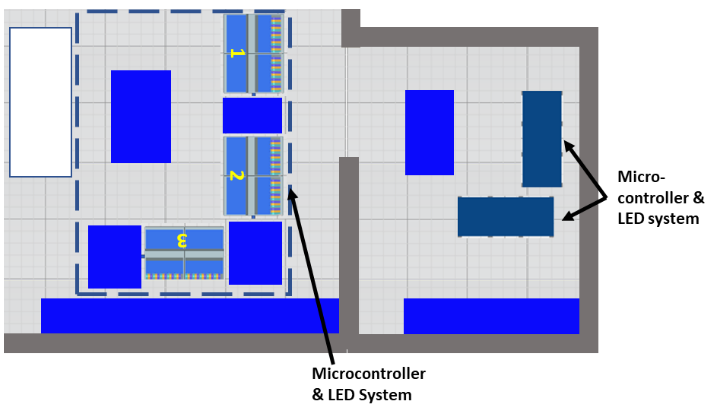


Figure D22: Physical location of DT support method

SOP change:
Value-creation: Builds on RFID tracking, works order tagged in. Employee only picks parts indicated by LED.
Inventory: Employee moves items to outbound delivery as indicated by LED.

17. RA update:
Inventory:
- Increased forecasting capacity
- Standardisation & Process simplification

Value creation:
- Process, collaboration & synchronization: Value-creation tracking, Increased station utilization.

Human-Resources:
- Allocation: Transportation and moving waste management.

Data Management
- Collection: Forecasting requirements
- Connection: Value-creation and Inventory communicates with each other directly.
- Process modelling & Performance monitoring: new data leads to new analysis, calculation, and new process improvement design.

Technology:
- E-Kanban & Pick-by light hardware

Iteration 2: Step 9 - Implement low levels of digital support

Element Guideline

Implementation Overview:

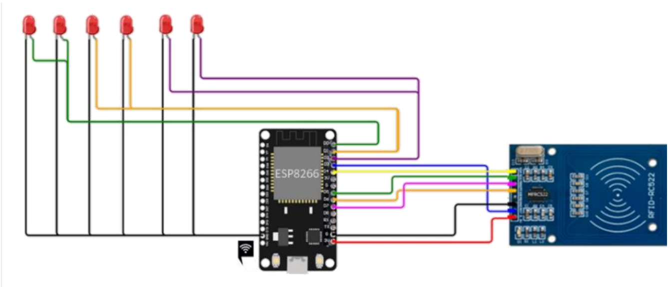


Figure 23: Client digital lean system

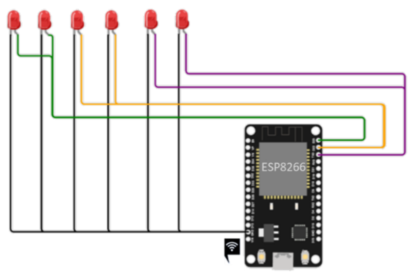


Figure D24: Server digital lean system

Workstation 2, the assembly workstation, is implemented with a pick-by-light system. Each train compartment scheduled for repair is tagged with a 125kHz tag, where the compartment type and works order number are encoded. A NodeMCU microcontroller is implemented in each station with an RFID reader and different LED lights connected to different spare parts bins and connected to Wi-Fi generated from the server NodeMCU. As a compartment tag is swiped on the reader, the reader sends the card information to the NodeMCU and, based on the card type, signals the respective parts used in the picking system. The Pick-by-light system's NodeMCU acts as a client microcontroller to the server microcontroller in the spare parts storage. The same tag information is sent to the server via the Wi-Fi signal. The server system's LED lights indicate the replenishment parts.

Implementation Procedure:

All microcontroller programming is done via the Arduino. The code and implementation were created by combining a simple PIR detection code and RFID detection code examples on Arduino IDE

1. The Two systems are connected as in the diagrams above, with the server connected to replenishment spare part bins and the client connected to bins at the workstation.
2. RFID tags are encoded using a microcontroller setup, where the relevant code is used to assign a works order number to each tag and extract the HEX ID from the tag to categorise the tag as either cabin train or driver train. The tags and job-numbers are re-used continuously.
3. The micro-controllers are setup using relevant packages, Arduino Code and Wi-Fi connection, where a date and time stamps, works order number and compartment type is extracted from the tags upon contact.
4. The server is encoded with its own output W-Fi capability
5. The client is connected to the Wi-Fi of the server.
6. The microcontrollers are ready to use.

Implementation Operation:

1. Employee assigns relevant encoded tag to receiving unit at unit reception.
2. Unit is scanned before and after SOP at each workstation.
3. The client server indicates the SOP action of the labourer and sent signal to the server, indicating replenishment bins.

Implementation Output:

The value-creation and inventory process is now simplified by means of digital light support. Employee reception on low-level DT support methods can now be accessed.

Iteration 2: Step 10 - Analysing the improved process

Aim:
Analyse the area(s) after the low-level implementation.

Element Output
Visual lean techniques, such as this combined system, can reduce the likelihood of human error, increase the standardisation approach in the labour-intensive process, and ease communication between areas on the reference architecture where different areas can be connected incrementally. This system allows for a low-level human-CPS collaboration, and it was decided to move on to a higher-level implementation.

Iteration 2: Step 11 - 12

Aim:
Selecting the first area(s) for the transformation process/higher level methods of digital support implementation

Element Output
Based on the previous implementations, it was decided to investigate the use of higher-level DT support methods in the labour-intensive repair process for additional process improvement. The previous mind map was revisited, and the UR robot was used for demonstrative purposes to show how it can integrate with the existing system and what a user environment can eventually progress to.

Iteration 2: Step 13 - Visualise to-be process

Element Guideline

Procedure:

1. Selected improvement:

Table D8: Selected improvement - UR3

Area	Potential Implementation	Implementation purpose	Implementation requirements
Value Creation Sub-area: Process, Collaboration & Synchroniztion Physical location: Workstation 3	**UR3 Robot**	UR3 robot is implemented to test the use of human-robot collaboration in the environment. Seat assembly is done by the UR robot to reduce the workload of the employee, as to increase their productivity on other sections.	1. Hardware requirements: a. Exciting RFID tracking system b. UR3 Robot 1. Software requirements: a. Arduino IDE b. UR3 Programming Software

2. Cause and Effect:

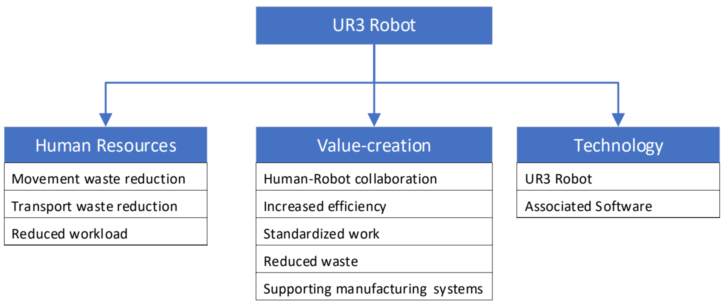


Figure D25: Potential UR3 cause-and-effect

3. Map:

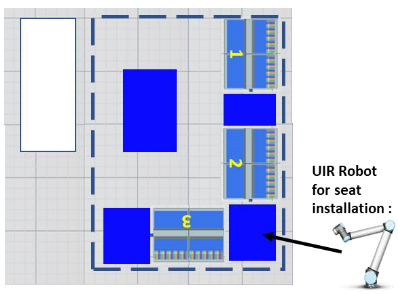


Figure D26: Physical location of DT support method

SOP change:

Value-creation: Builds on RFID tracking, worker places unit in designated area, and activates robot through RFID tracking system.

4. RA update:

Human-Resources:

- Human-robot collaborating

Value-creation

- Synchronized with labour-intensive process
- Supporting manufacturing systems – additional equipment (UR3 robot)

Technology:

- UR3 robot and software

Iteration 2: Step 14 - Implement method of digital support

Element Guideline

Implementation Overview:

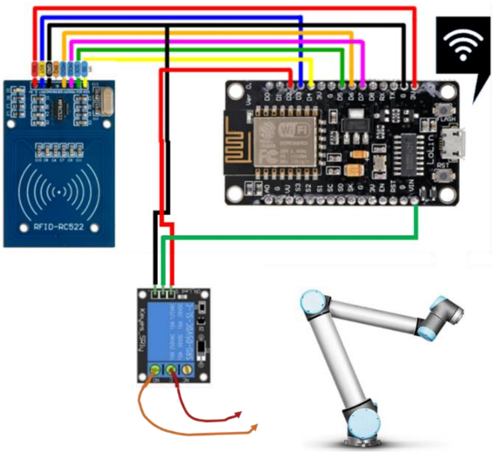


Figure D27: UR3 system visualised

Chair assembly is removed from workstation 2 and automated, where the UR3 robot would place the seats in each train at workstation 3, the quality control at workstation 3 continues as usual after the UR3's operation. The UR3 is connected via a relay to the NodeMCU of workstation 3, where the buzzer is removed, and the signal cable is attached to the relay. Upon workstation activation, the signal activates the relay, which activates the UR3 robot that places the seats in a sequence in the desired spots.

Implementation Procedure:

No additional programming is done via Arduino.

7. The UR3 is connected via the relay.
8. The UR3 robot is programmed using waypoints and actions in the desired sequence for cabin trains.
9. The previous RFID encoded tags activate the microcontroller as in iteration 1.

Implementation Operation:

4. Unit is scanned before and after SOP at each workstation.
5. Employee waits for UR3 sequence to finish.

Implementation Output:

The chair assembly is automated, and the employee can focus their attention on other tasks at hand. A level of human-robot collaboration in synchronisation is achieved.

Iteration 2: Step 15 - Analysing the improved process

Aim:
Analyse the digital transformation.

Element Output
After the second iteration, communication between areas and digital lean tools enable a more straightforward flow of information throughout the facility. Additionally, the high-level UR3 implementation demonstrates to the middle manager group what eventually can be reached. . The second set of practical validation questions was presented to the middle managers, whereafter, it was decided to move on to other subareas of value-creation to improve efficiency.

Iteration 3: Steps 1-7

Aim:
As the roadmap is restarted, the first 6 steps are revisited before implementing a new DT support method.

Element Output
After the first two iterations, all relevant areas were updated, and in steps 2 and 3, it was decided to move the goals towards product management, where increased quality in the repair facility could improve other areas. Briefly, a new potential low-level DT method was identified in digital checklists, where the same methodology was used as follows: Product management -> quality -> final inspection -> digital checklist. The third iteration focuses on improving the output quality.

Iteration 3: Step 8 - Visualise to-be process

Element Output

Procedure:

18. Selected improvement:

Table D9: Selected improvement - digital quality checklist

Area	Potential Implementation	Implementation purpouse	Implementation requriements
Product Management: Sub-area: Quality, labour-intensive processes Physical location: Workstation 3	**Digital quality checklist**	The quality control procedure is simplified by means of a digital quality control checklist. This reduced the workload of the employee, decreases the paper usage and increases the quality output of the value-creation process.	1. Hardware requirements: a. Computer or Tablet 2. Software requirements: b. Macro-enabled MS Excel

19. Cause-and-effect:

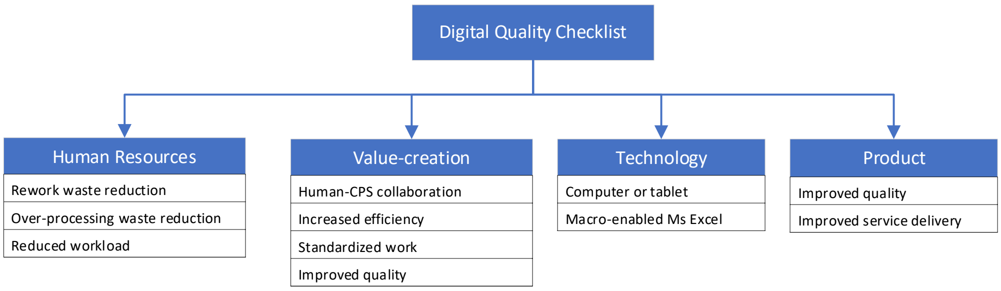


Figure D28: Potential digital quality checklist cause-and-effect

20. Map:

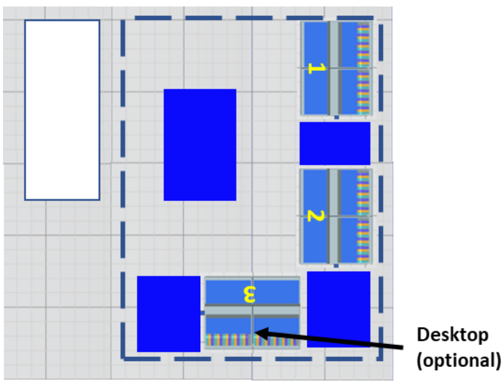


Figure D29: Physical location of DT support method

SOP change: Employee uses desktop or tablet to access checklist, checklists places unit in designated quality check area, once on side view and once on top view,

21. RA update:

Value creation:

- Process, collaboration & synchronization: Human-CPS collaboration, standardised work, improved quality and efficiency Semi-RT tracking, cycle time analysis, variance, analysis,

Human-Resources:

- Training: Simplified training
- Reduced waste

Data Management

- Collection: Anomaly detection, digital collection of quality control sheets
- Connection: All units are checked
- Process modelling & Performance monitoring: new data leads to new analysis, calculation, and new process improvement design.

Products:

- Quality Improved quality
- Customer requirements: Improved service delivery

Technology:

- Digital quality checklist and Associated Software

Iteration 1: Step 9 - Implement low levels of digital support

Element Guideline

Implementation overview and procedure:

Various Macro-enabled checklist templates are available online. The existing quality checklist is digitised on such a template, where the employee can now check items off as necessary, and the completion is also shown to the employee. The checklist is accessed via a Raspberry Pi acting as a desktop where the checklists are linked to Google sheets.

1. The checklist can be accessed by a mobile phone, desktop or display at workstation 3.

Implementation Operation:

1. Employee competes checklist online.

Implementation Output:

SLF Quality Checklist Completion Rate 47%

#	Check Items (double click topics to expand / collapse)	Quantity	Status (double click to change)
1	**Driver Train**		▣
1.1	Base Plate	1	☑
1.2	Roof	1	☑
1.3	Bogie	2	☑
1.4	Long screw	2	☑
1.5	Electrical system (front)	1	☑
1.6	Tank system (back)	1	☐
1.7	Normal screw	24	☑
1.8	Partition wall (middle)	2	☐
1.9	Face plate	2	☐
1.10	Side plate (two doors)	2	☐
1.11	Narrow seats single	4	☐
1.12	Narrow seats double	4	☐
1.13	Wide seat single	3	☐
1.14	Wide seats doublee	4	☐
1.15	Middle-size seat	3	☑

Figure D30: SLF quality checklist

The technology helps with the quality control process by eliminating the requirement for quality inspection of each unit and freeing up the quality controller's time to focus on other, more important responsibilities, such as ensuring the seats supplied by the UR3 robot are attached.

Iteration 3: Step 10 - Analysing the improved process

Aim:
Analyse the area(s) after the low-level implementation.

Element Output
This low-level solution can help the environment use less paper by replacing paper-based checklists. Additionally, the checklists are kept online, eliminating the inventory and motion wastes produced by the paper-based approach. Additionally, allowing employees to interact with a low-level implementation may make a higher-level implementation easier to accept and may help train staff members on the final workstation and perhaps other workstations. After the implementation, it was decided to move to a more advanced method to improve the quality of the final workstation.

Iteration 3: Step 11 - 12

Aim:
Analyse the area(s) after the low-level implementation.

Element Output
Based on the previous implementations, it was decided to investigate the use of higher-level DT support methods in the quality management repair process for higher-level support in the final inspection. A new high-level DT method was identified using the mind map methodology: Product management -> quality -> final inspection/ digital checklist -> machine vision based

Iteration 3: Step 13 - Visualise to-be process

Element Output

Procedure:

22. Selected improvement – DEMO:

Table D10: Selected improvement - Machine vision-based quality control system

Area	Potential Implementation	Implementation purpose	Implementation requirements
Product Management: Sub-area: Quality, labour-intensive processes Physical location: Workstation 3	**Raspberry PI Camera Qaulity control system**	The quality control procedure is simplified by means of a digital camera quality control system, that assists the quality controller in quality defect identification. This reduced the workload of the employee and increases the quality output of the value-creation process.	1. Hardware requirements: a. Raspberry Pi b. Raspberry Pi Camera module 1. Software requirements: a. Python development software b. OpenCV c. Photo database

23. Cause-and-effect:

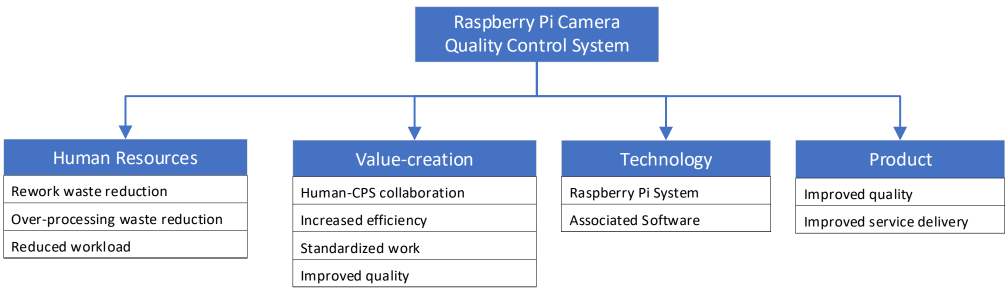


Figure D31: Potential machine vision-based quality control system cause-and-effect

24. Map:

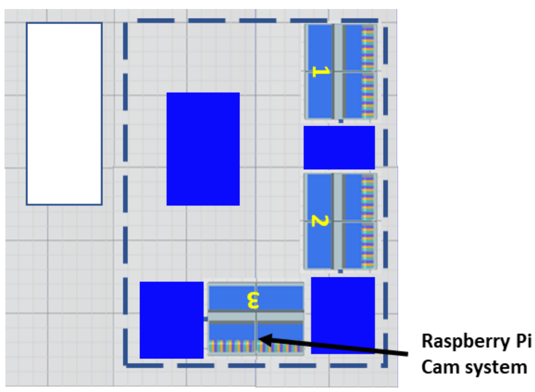


Figure D32: Physical location of DT support method

SOP change: Employee places unit in designated quality check area, once on side view and once on top view,

25. RA update:

    Value creation:
    - Process, collaboration & synchronization: Human-CPS collaboration, standardised work, improved quality and efficiency   Semi-RT tracking, cycle time analysis, variance, analysis,

    Human-Resources:
    - Training: Simplified training
    - Reduced waste

    Data Management
    - Collection: Anomaly detection
    - Connection: All units are checked
    - Process modelling & Performance monitoring: new data leads to new analysis, calculation, and new process improvement design.

    Products:
    - Quality Improved quality
    - Customer requirements: Improved service delivery

    Technology:
    - Raspberry Pi System and Associated Software

Iteration 3: Step 14 - Implement low levels of digital support

Element Guideline

Implementation Overview:

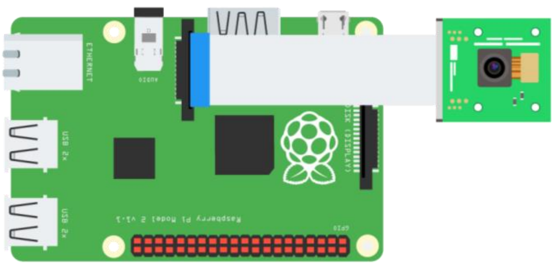


Figure D33: Raspberry Pi with camera module

The quality control station uses the Raspberry Pi Camera system (workstation 3). The presence of all necessary components in part undergoing quality control is checked using camera detection. OpenCV and a database of finished units are employed to assess the quality of the train under inspection. The quality checker is notified if the unit has passed the quality check or if any rework is necessary. If rework is needed, the quality check identifies the issue and marks the unit for rework.

Implementation Procedure:

A previous student's bachelor's thesis was utilised with a pre-existing system and code. The programming was carried out with the OpenCV software, relevant uploaded databases, and the configuration shown in the figures above.

2. The system is attached to workstation 3, quality control.

Implementation Operation:

2. Employee places unit for quality check on side view to camera in designated area.
3. Camera systems perform quality control
4. Employee places unit designated for quality check on top view to camera in designated area.
5. Camera systems perform quality control
6. If anomalies are detected the quality controller is informed
7. The quality controller identifies the defect and assigns the item for rework.

Implementation Output:

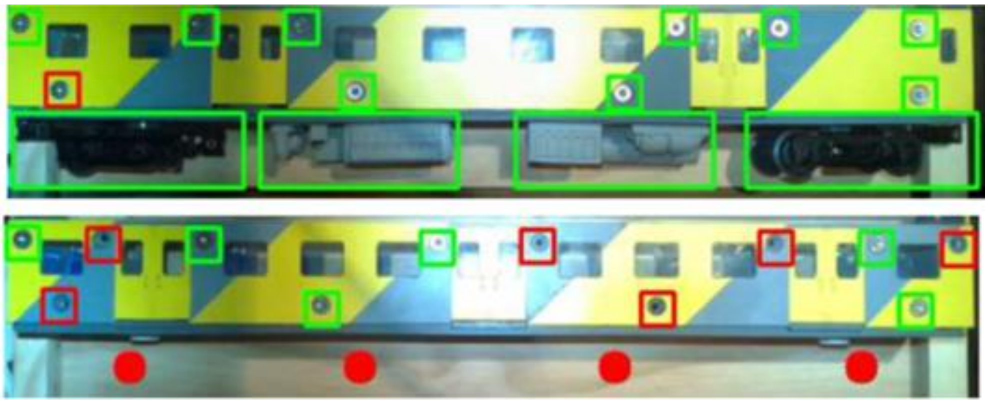


Figure D34: Machine vision-based quality control output

The technology helps with the quality control process by eliminating the requirement for quality inspection of each unit and freeing up the quality controller's time to focus on other, more important responsibilities, such as ensuring that the seats supplied by the UR3 robot are attached.

Iteration 3: Step 15

Aim:
Analyse the area(s) after the low-level implementation.

Element Output
Finally, the opinions on the demo are collected from the middle manager group, and it is determined that the solution is an adequate solution. After that, the roadmap can once again be restarted, and additional areas can be selected from the roadmap in the continuous improvement cycle. The final set of practical validation questions was presented to the middle managers, whereafter, the roadmap approach validation questions were presented to the group and a discussion was held on the roadmap.

Middle management opinion validation survey

Name: ______________________________ Department: ______________________________

Please rate the following information on a scale of 1 to 5, with 5 being "strongly agree" and 1 being "strongly disagree".

Rationale validation:

RV1: Organisations find it challenging to enact value-adding digital transformation in these environments.

1	2	3	4	5

RV2: There is often hesitation to implement solutions in digital transformation in these types of environments.

1	2	3	4	5

RV3: A practical approach to Industry 4.0/ Digital Transformation is required.

1	2	3	4	5

Practical validation – Iteration 1

PV1a: The results of these solutions could be used to gather data and gain a better understanding of our value-creation processes.

1	2	3	4	5

PV1b: These solutions could minimize our paper trail.

1	2	3	4	5

PV1c: Our value-creation processes would not be significantly disrupted by the low-level RFID system.

1	2	3	4	5

PV1d: Utilization of the previous low-level RFID and PIR systems could make it easier to integrate an IoT system into our environment.

Practical validation – Iteration 2

PV2a: Our value-creation processes could become more productive with these types of lower-level digital lean techniques.

1	2	3	4	5

PV2b: Collaboration between human and cyber-physical systems at a more basic level can serve as a testbed for more advanced human-robot or human-CPS collaboration strategies.

1	2	3	4	5

Practical validation – Iteration 3

PV3a: Quality control methods such as these two can be used to simplify quality assurance in our environment

1	2	3	4	5

PV3b: By employing a simpler digital quality assurance method first, it can inspire staff that more complex methods, such as the camera quality assurance system, could be put to use to help them in their work.

1	2	3	4	5

PV4: Please provide any feedback or issues that you have with any of the technologies used in the studies indicated above.

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Roadmap approach validation

RAV1: The incremental approach to digital transformation would work better in my department.

1	2	3	4	5

RAV2: It is valuable to have a reference architecture to help choose the best location for these type of digital or technological implementations.

1	2	3	4	5

RAV3: This incremental approach could help employees in these environments to be more comfortable with digital and technological support methods and digital transformation.

1	2	3	4	5

RAV4: These experiments' logical progression demonstrates how technology may be introduced incrementally and with minimal disruption in my department.

1	2	3	4	5

RAV5: The eventual higher-level digital transformation of the environment may benefit from having a prototype or lower-level method implemented first.

1	2	3	4	5

RAV6: Employing simpler methods now could encourage staff to use more complex ones later.

1	2	3	4	5

RAV7: Do you feel that this solution is an adequate starting point to digital transformation?

Yes	No

RAV8: The learning factory environment effectively demonstrated how technology might be used in industry.

1	2	3	4	5

RAV9: This kind of use of the learning factory can result in increased cooperation between industry and academia.

1	2	3	4	5

RAV10: What changes would you suggest or request to add to the usability of the roadmap?

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