Development of an Industry 4.0 competency maturity model

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‘‘The farther back you can look, the farther forward you are likely to see’’.

- Winston Churchill (1871–1947).

ABSTRACT

Coined as Germany's high-tech strategy, Industry 4.0 (I4.0) is being adopted globally and is happening exponentially. Furthermore, I4.0 impacts manufacturing processes, technology, and systems and extends to employees' competency requirements and, consequently, the preparation of graduates who will be ready to practice engineering with professional-level technical know-how and non-technical skills in I4.0.

However, sub-Saharan African developing countries such as South Africa are still to catch up with the phases of the industrial revolution that have already played out in developed countries. In addition, South Africa seek to achieve its National Development Plan (NDP) and United Nations' Sustainable Development Goals (SDGs). Therefore, South Africa faces the challenge of achieving sustainable adoption of I4.0 in its manufacturing industry. Factors such as noticeable youth unemployment and lack of workforce competencies contributes to this challenge. The problem responded to in this research is the lack of I4.0 competency reference models, which could align industry competency requirements and skills development.

This research applied elaborated Action Design Research (eADR) diagnosis and design phases to develop an I4.0 competency maturity model (I4.0CMM) that simultaneously guides and assesses I4.0 competency development and industry competency requirements within the South African context. The Delphi technique was incorporated in the I4.0CMM development iteration stage to ensure consideration of expert input. The diagnosis and design phases comprised two and four iterations, respectively, presented as academic articles.

The I4.0CMM can be used by engineering education and workplace human resources development providers as a benchmark framework for aligning graduate attributes (GAs) and required professional competencies and identifying improvement points required to match curriculum provisions to the current and future industry requirements resulting from the fourth – and later – industrial revolutions. Furthermore, it can aid students and graduates in self-evaluating and self-regulating their achievement of I4.0 skills requirements and planning their professional development. Therefore, enhancing I4.0 competencies development in both the industry and academic institutions through training, reskilling, and upskilling could potentially drive sustainable adoption of I4.0 in the country's manufacturing industry.

Furthermore, the research significantly adds to the knowledge of factors that inhibit sustainable adoption of I4.0 in the context of the South African environment. The results and findings of the investigations conducted in this research significantly contribute to filling the literature gap in the in the South African manufacturing industry's understanding about I4.0 and its accompanying

skills requirements. The research further distinctively contributes to comprehending specific I4.0 skills requirements in the South African manufacturing industry. This research, therefore, offers a direction for broader investigations of sustainable adoption of I4.0 in the sub-Saharan African developing countries.

Four industrial engineering capability functions were used to illustrate the model. However, the research did not implement and test the I4.0CMM in a real-world situation. The I4.0CMM presented industrial engineering capability functions in the capability functions domain and did not specify the capability functions levels, i.e., technician, technologist, and engineer. Therefore, future work could consider implementing and testing the model in a real-world situation, incorporating the capability functional levels, and adapting the capability functions domain to other engineering professions.

Keywords: Competency maturity model, maturity model, Industry 4.0, Fourth Industrial Revolution, sustainability, elaborated Action Design Research, Delphi technique, readiness assessment, systematic mapping review, skills requirements,

PREFACE - THESIS BY ARTICLE FORMAT

This thesis is presented in an article format in accordance with the Academics Rules (A rules) of the North-West University (approved on 21 September 2017).

Rule A.5.10.5 states:

> *"Where a candidate is allowed to submit the research product in the form of research articles, such research product must be presented for examination purposes as an integrated unit, supplemented with a problem statement, an introduction and a synoptic conclusion as prescribed by faculty rules and the manuscript submission guidelines, or the url link to the manuscript guidelines of the journal or journals concerned".*

Rule A.5.10.8 states:

> *"Where any research article, manuscript or internationally examined patent to which the candidate for a doctoral degree and other authors or inventors have contributed is submitted as the research product of a doctoral degree programme, the candidate must obtain a written statement from each co-author and co-inventor in which it is stated that such co-author or co-inventor grants permission for the research product to be used for the stated purpose, and in which it is further indicated what each co-author's or co-inventor's share in the research product concerned was".*

Rule A.5.10.9 states:

> *"Where co-authors or co-inventors as contemplated in rule 5.10.8 were involved in the development of the research product, the candidate must mention this fact in the preface, and must include the statement of each co-author or co-inventor in the thesis, mini-thesis or research report immediately following the preface to the research product".*

Five journal articles and one international conference paper have been published as part of this study. Figure 1 presents an overview of how the overall study integrates the academic articles.

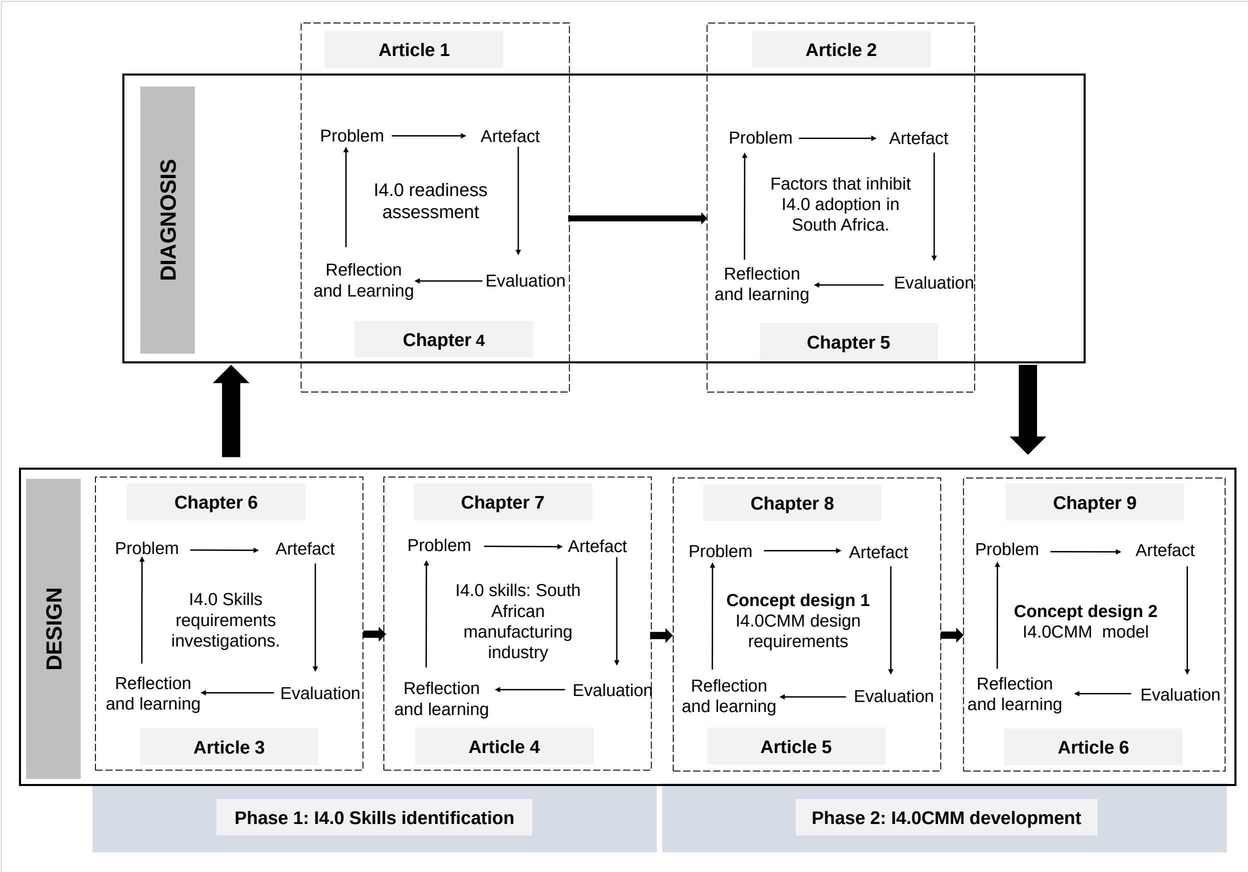

Figure 1: Thesis compilation

Published Journal papers:

- **Article 1:** W. Maisiri and L. van Dyk. 2019. **Industry 4.0 readiness assessment for South African industries**. *South African Journal of Industrial Engineering* November 2019 Vol 30(3) Special Edition, pp 134-148. DOI: http://dx.doi.org/10.7166/30-3-2230
- **Article 2:** W. Maisiri, L. van Dyk and R. Coetzee. 2021. **Factors that inhibit sustainable adoption of Industry 4.0 in the South African manufacturing industry**. *Sustainability*, Vol 13, 1013. DOI: https://doi.org/10.3390/su13031013
- **Article 3:** W. Maisiri, H. Darwish and L. van Dyk. 2019. **An Investigation of Industry 4.0 skills requirements**. *South African Journal of Industrial Engineering*, Vol 30(3) Special Edition, pp 90-105, DOI: http://dx.doi.org/10.7166/30-3-2230
- **Article 4:** W. Maisiri and L. van Dyk. 2021**. Industry 4.0 skills: A perspective of the South African manufacturing industry**. *SA Journal of Human Resource Management* 19(0), a1416, DOI: https://doi.org/10.4102/sajhrm.v19i0.1416
- **Article 6:** Whisper Maisiri, Liezl van Dyk and Rojanette Coetzee. 2021. **Development of an Industry 4.0 Competency Maturity Model.** *SAIEE Africa Research Journal*, 112 (4),

pages 189-197 [published online] Development of an industry 4.0 competency maturity model | SAIEE Journals & Magazine | IEEE Xplore.

International conference paper

- **Article 5:** W. Maisiri, and L. van Dyk. 2020. **Industry 4.0 Competence Maturity Model design requirements: A systematic mapping review**, in 2020 IFEES World Engineering Education Forum-Global Engineering Deans Council (WEEF-GEDC), Cape Town, pp. 124-130, DOI: https://doi.org/10.1109/WEEF-GEDC49885.2020.9293654

Presenting this thesis in an article format will have implications on the numbering, referencing and literature review layout:

Numbering

The page numbering of the thesis is interrupted where research articles have been inserted. The inserted research articles maintain the numbering in their original publication, which differs from the thesis numbering.

Format

The published research articles adhere to the author guidelines as stipulated by the editor of each journal on submission, and they may appear in a different format from the other thesis sections. The headings and the original technical content of the research articles are presented with no alterations.

Referencing

References used in the research articles are presented as a single unit with the article and will not appear in the thesis reference section if not used in the other chapters of the thesis.

Literature review layout

The thesis does not have a chapter dedicated to reviewing all relevant literature for the various topics that form the foundation of this research. Relevant literature appears in different sections of the thesis as presented in Table 1 (Chapter 1).

STATEMENT OF CO-AUTHORS

To whom it may concern

The listed co-authors hereby give consent that **Whisper Maisiri** may submit the research article(s) as part of his thesis titled, **"Development of an Industry 4.0 competency maturity model"** for the degree Doctor of Philosophy in Industrial Engineering, at North-West University.

This letter of consent complies with rules **A5.10.8 and A.5.10.9** of the academic rules, as stipulated by the North-West University.

Signed at Potchefstroom

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Date

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“Beware that thou forget not the Lord thy God...” Deuteronomy 8:11. Thank you Yahweh for the strength to endure the rugged road. Today I am here.

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CHAPTER 1

INTRODUCTION TO THE STUDY

1.1 Background and rationale

When Toynbee (1927) wrote about the 'Industrial Revolution' in his lecture series titled 'Lectures on the Industrial Revolution in England', he referred to Industrial Revolution as "the process of change from an agrarian and handicraft economy to one dominated by industry and machine manufacturing" (Britannica, 2021). This constituted the first Industrial Revolution. Since then, the "industrial revolution" metaphor was used to describe other universal paradigms shifts: The second industrial revolution refers to a period of rapid industrialisation, automation and standardisation at the turn of the 20th century, this was followed by the third industrial revolution characterised by the computing, automation and digital technologies through the use of electronics, computers and telecommunications (Sanchez, 2019; Schwab, 2017)

Coined to drive Germany's high-tech strategy (Caliskan *et al.*, 2020; Xu, 2020), Industry 4.0 (I4.0) is a manufacturing industry initiative driving the Fourth Industrial Revolution (4IR) (Jeon *et al.*, 2020). Representatives of industry, universities, and government conceptualised and promoted I4.0 to drive and maintain the competitiveness of Germany's manufacturing industry and its leadership in technology innovation (Bittencourt *et al.*, 2019; Kang *et al.*, 2016; Vrchota & Frantíková, 2020). Today, many developed countries have adopted I4.0, and its application has become standard practice in their manufacturing industries (Kowalikova *et al.*, 2020; Mariani & Borghi, 2019), and other developing countries such as China and India are following the trend (Maurya, 2019; Salah *et al.*, 2020).

1.1.1 The South African perspective

Though the impact of I4.0 is being experienced globally, the manufacturing industry in the sub-Saharan African developing countries still has to catch up with the industrial revolution phases that have already played out in developed countries (Ajayi *et al.*, 2019). The manufacturing industry task environment in these countries faces challenges of inequality and inclusiveness (Hartmann & Hattingh, 2018). Therefore, sustainable adoption of I4.0 includes addressing these aspects, especially in developing countries.

In 2012, the South African government established the national development plan (NDP); this was followed by the United Nations establishing the United Nations 2015 sustainable development goals (SDGs). A significant correlation (74%) between the SDGs and NDP

(Department of the Presidency, 2019; Statistics South Africa, 2019b) is evident. The NDP and SDGs both emphasize an end to poverty, protection of the environment, and inclusive prosperity (Department of the Presidency, 2013; Department of the Presidency, 2019; Statistics South Africa, 2019b)

In 2019, the President of South Africa established a “Presidential Commission on the 4th Industrial Revolution” to coordinate the 4IR national response plan (Department of Telecommunications and Postal Services, 2019). The commission was tasked to develop an integrated 4IR national strategy and plan and advise on strategies to enhance global competitiveness. The commission reported its findings and recommendations in 2020 (Department of Telecommunications and Postal Services, 2020). The report identified human capital development and deployment of technological infrastructure and information and communication technology as the major priorities to drive South Africa’s economic competitiveness in the 4IR. Furthermore, the report comprehensively exposed and emphasised human capital challenges and recommendations to close the skills gap in South Africa (Department of Telecommunications and Postal Services, 2020). However, the report did not provide a competency reference model that could assist in aligning skills requirements and skills development in the country.

The adoption of I4.0 does not involve ‘one-size-fits-all’ but varies with country needs and challenges to be addressed (Horváth & Szabó, 2019; Raj *et al.*, 2019). Sustainable adoption of I4.0 in South Africa should focus on and give equal importance to social, environmental, and economic sustainability to advance the NDP and SDGs goals. Industry 4.0 has the potential of driving the achievement of these goals through enhancing sustainable production and manufacturing (Bonilla *et al.*, 2018; Machado *et al.*, 2020; Stock *et al.*, 2018). However, if not correctly adopted, I4.0 can adversely impact socio-economic aspects such as inequality, “unemployment and skills development” (Sanchez, 2019; Van Rensburg *et al.*, 2019).

Though the shortage of I4.0 competencies requirement is a global challenge (de Sousa Jabbour *et al.*, 2018; Horváth & Szabó, 2019; Raj *et al.*, 2019), the challenge is higher in sub-Saharan African developing countries such as South Africa. The noticeable extent of youth unemployment characterises the skills challenge in South Africa (Department of Telecommunications and Postal Services, 2020; Hartmann & Hattingh, 2018; Van Rensburg *et al.*, 2019), as opposed to developed countries, characterised by ageing populations (Horváth & Szabó, 2019; Türkeș *et al.*, 2019).

1.1.2 The research problem

South Africa faces the challenge of not achieving a sustainable adoption of I4.0 in its manufacturing industry due to certain factors such as lack of required workforce competencies. Inadequate alignment between industry competency requirements and skills development strategies due to deficiencies in the education system magnifies this challenge. Therefore, the problem to be addressed in this research is the lack of I4.0 reference models, which could align industry competency requirements and competency development. A detailed I4.0 competency models gap analysis is presented in Chapter 8 (Article 5)

1.1.3 Competency maturity model

According to OASIS (Organization for the Advancement of Structured Information Standards) a reference model is:

> *an abstract framework for understanding significant relationships among the entities of some environment, and for the development of consistent standards or specifications supporting that environment. A reference model is based on a small number of unifying concepts and may be used as a basis for education and explaining standards to a non-specialist. A reference model is not directly tied to any standards, technologies or other concrete implementation details, but it does seek to provide a common semantics that can be used unambiguously across and between different implementations. (OASIS, 2020).*

A maturity model is a type of reference model with five maturity levels (initial, repeatable, defined, managed, and optimizing) used to assist organizations in adopting best practices in a targeted domain (Gillies *et al.*, 2003; Röglinger *et al.*, 2012). Maturity models can serve both a descriptive and prescriptive purpose (Becker *et al.*, 2009; Pöppelbuß & Röglinger, 2011).

A competency model is a type of reference model which lists statements in which critical knowledge, skills, attitudes, and behaviours for specific roles are defined (El Asame & Wakrim, 2018; Teodorescu, 2006). A competency model can be presented in “a list, graphic, spreadsheet, or interactive program” that lists the competencies perceived to be required for specific job functions (Teodorescu, 2006).

The research is premised on competency maturity models. A competency maturity model is a reference model that is both a maturity model and a competency model as illustrated in Figure 2. For this study, a competency maturity model can be defined as a reference model that provides a holistic view of a person's competencies (knowledge, skills and abilities) required to perform a specific job function (El-Baz & Zualkernan, 2011), and enables tracking the competencies evolution over time. Furthermore, a competency maturity model can be used to define, standardise, develop and optimise these competencies.

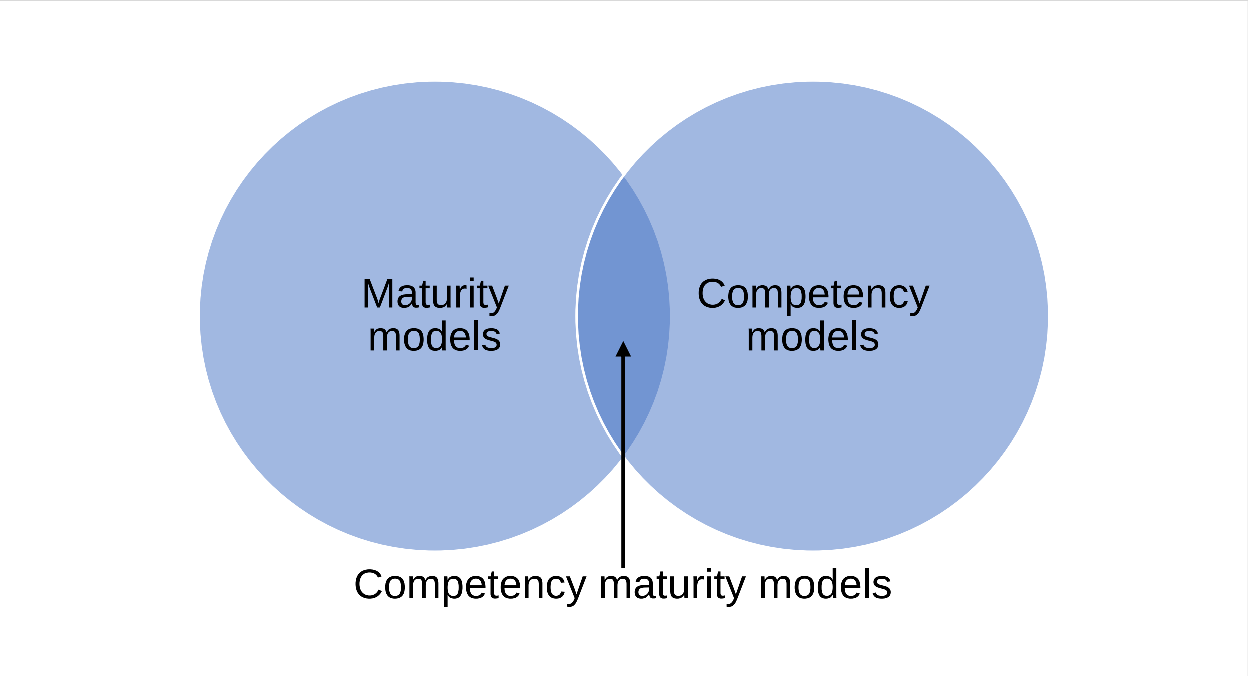

Figure 2: Relationship between competency maturity models, maturity models and competency models

1.2 Research aim

The study aims to develop an I4.0 competency maturity model (I4.0CMM) that simultaneously guides and assesses I4.0 competency development and industry competency requirements within the South African context.

This "research aim" section marks the departure point for the rest of the chapter, which comprises: outlining the research objectives in section 1.3, presenting of the research outline in section 1.4, discussing research significance discussion in section 1.5, a literature overview in section 1.6 and a conclusion of the chapter is section 1.7.

1.3 Research objectives

Considering the problem background, problem statement, and aim of the study, the objectives that guide the research are as follows:

1. to assess I4.0 readiness for South African industries;

2. to explore factors that inhibit and that could enhance sustainable adoption of I4.0 in the South African manufacturing industry;

3. to investigate I4.0 skills requirements and development approaches;

4. to identify I4.0 skills requirements in the South African manufacturing industry;

5. to establish the design requirements for an I4.0 competency maturity model and perform an I4.0 competency models gap analysis;

6. to develop the I4.0CMM using industrial engineering capability functions; and

7. to confirm the validity of the research problem, the design requirements, and the research output.

1.4 Research outline

This research thesis is compiled in an article-based format where chapters 4 to 9 comprise published peer-reviewed research articles. Figure 3 shows the coherent overview of the whole study and where each article fits in the study. The study is divided into six stages: introduction, study initiation, problem diagnosis, model design, verification and validation, and conclusion.

1.4.1 Study initiation

Study initiation comprises chapter 2 and chapter 3. Chapter 2 (Industry 4.0 and the Fourth Industrial Revolution) presents a systematic literature review to explore the impact of I4.0 and 4IR on sustainable development. The systematic literature review also seeks to clarify the terms I4.0 and 4IR and explore nuances specific to the usage of these terms. Chapter 3 (Research design) first explores alternative research methods to achieve the research aim before presenting the research design followed in this study.

1.4.2 Problem diagnosis

The problem diagnosis stage includes two studies, presented in chapter 4 and chapter 5, to formulate further and validate the research problem relevant to the South African context. Chapter 4 reports on an empirical quantitative study aimed to explore the readiness for the South African industry to adopt I4.0. Chapter 5 presents an empirical qualitative study that seeks to investigate factors that inhibit the sustainable adoption of I4.0 in the South African manufacturing industry.

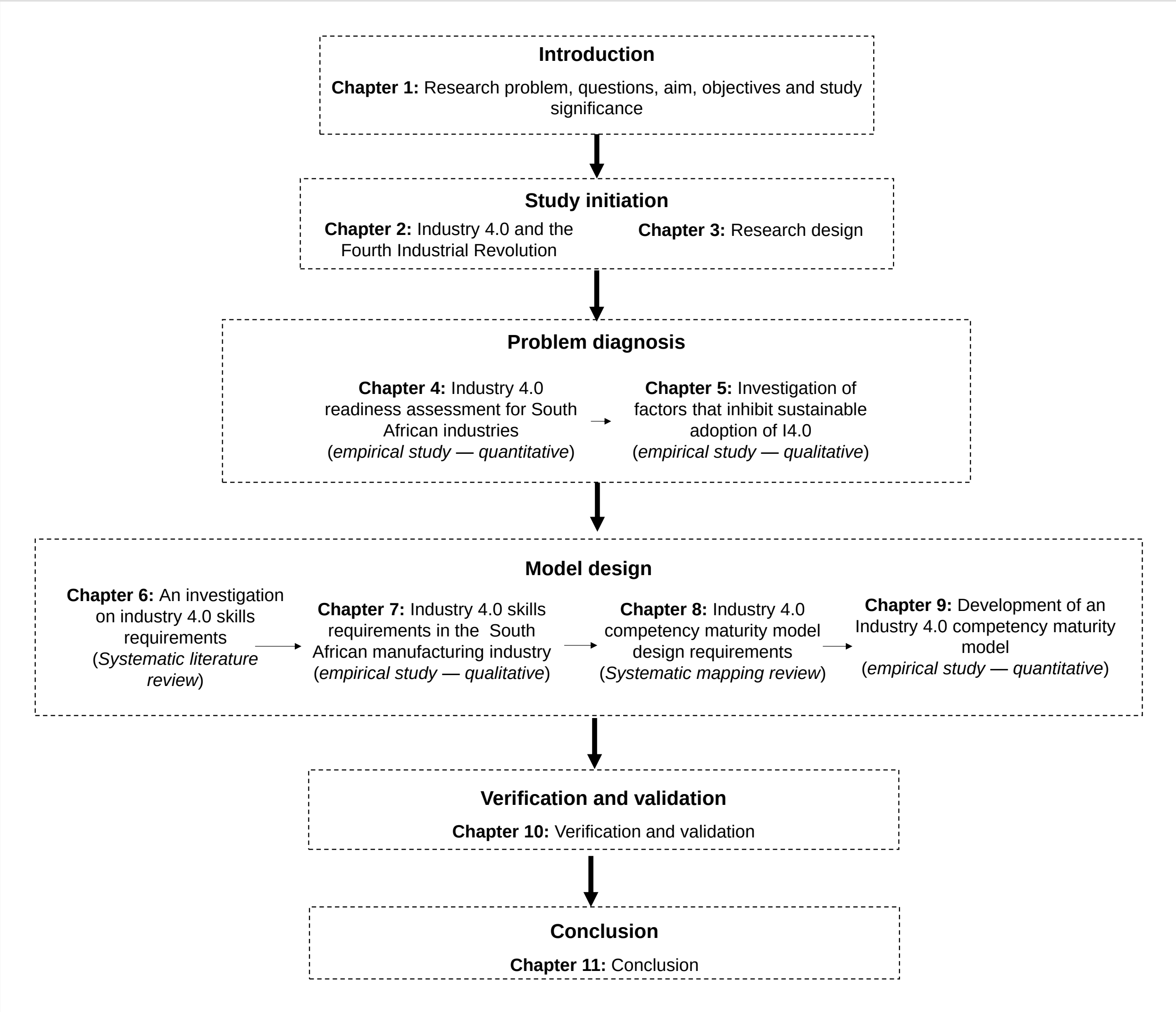

Figure 3: Research outline overview

1.4.3 Model design

The problem diagnosis identified that I4.0 skills significantly influence the sustainable adoption of I4.0 within the South African context. The purpose of the model design stage was to develop an I4.0CMM that simultaneously guides and assesses I4.0 competency requirements and I4.0 competency development in the South African manufacturing industry. The design stage comprises two phases: I4.0 skills requirements identification and I4.0CMM development. The I4.0 skills requirements identification phase comprises two published peer-reviewed articles presented in chapters 6 to 7. Chapter 6 conducts a systematic literature review to explore the I4.0 skills requirements, and Chapter 7 reports an empirical qualitative study identifying I4.0 skills relevant in the South African manufacturing industry. The I4.0CMM development phase comprises two published peer-reviewed articles presented in chapter 8 and chapter 9. Chapter

8 presents a systematic mapping study that seeks to establish the design requirements for an I4.0CMM and perform a gap analysis. Using expert views through a Delphi study, chapter 9 presents the I4.0CMM design iteration.

1.4.4 Verification and validation

The verification and validation incorporate some findings from the Delphi study presented in Chapter 9. The overview results from the verification and validation phases are presented in chapter 10.

1.4.5 Conclusion

The conclusion is presented in Chapter 11 and includes an overview of the research findings and results, the contribution of the study and its limitations and recommendations.

1.5 Research significance

Industry 4.0 is happening exponentially, and a quick response is necessary for survival. I4.0 is presenting technological advancements that are causing universal disruptive changes in the manufacturing industry. Embracing and adopting I4.0 is unavoidable for manufacturing organizations to survive and grow their global competitiveness (Sanne, 2018). Furthermore, to understand what I4.0 is, exploring ways to achieve sustainable adoption of I4.0 in developing countries is essential in achieving inclusive and sustainable growth (Mandaha, 2018).

Understanding specific country factors that inhibit sustainable adoption of I4.0 in the manufacturing industry could be a step towards sustainable adoption of I4.0. Several studies that investigate factors that drive and inhibit the sustainable adoption of I4.0 for specific countries such as Romania (Türkeș *et al.*, 2019), Hungary (Horváth & Szabó, 2019), Germany (Müller, 2019; Müller *et al.*, 2018), India (Kamble *et al.*, 2018; Raj *et al.*, 2019), China (Lin *et al.*, 2018) and Denmark (Stentoft *et al.*, 2020) are recorded in the literature. However, to the best of the researcher's knowledge, such empirical studies for South Africa are lacking in the literature and, therefore, there is a need to undertake such studies. This research seeks to add to the knowledge of I4.0 in the context of the South African environment. The results and findings of the investigations conducted in this study significantly contribute to filling the literature gap about I4.0 in the South African manufacturing industry and the necessary I4.0 skills requirements. Thus, the study contributes to understanding strategies required to drive sustainable adoption of I4.0 in the South African manufacturing industry and beyond. The research further distinctively contributes to comprehending specific I4.0 skills requirements in the South African manufacturing industry.

A lack of I4.0 competency assessment models and tools that can assist in assessing and directing the development of relevant I4.0 competencies was acknowledged in the literature (Acerbi *et al.*, 2019) and confirmed with a systematic literature review conducted by Maisiri and van Dyk (2020). The research sought to contribute to closing this gap by developing an I4.0CMM. The developed I4.0CMM model could assist engineering education providers and workplace human resource development providers to align graduate attributes and professional competencies. The industry could use the model to assess their workforce's “as-is” I4.0 capabilities and provide guidance on the employees’ skills requirements in order to contribute meaningfully to I4.0 and future requirements.

The I4.0CMM could be used by engineering education and workplace human resources development providers as a benchmark framework for aligning GAs and required professional competencies and identifying improvement points required to match curriculum provisions to the current and future industry requirements resulting from the fourth – and later – industrial revolutions. Furthermore, it could aid students and graduates in self-evaluating and self-regulating their achievement of I4.0 skills requirements, and planning their professional development. Therefore, enhancing I4.0 competencies development in both the industry and academic institutions through training, reskilling, and upskilling could potentially drive sustainable adoption of I4.0 in the country’s manufacturing industry. This research offers a direction for broader investigations of sustainable adoption of I4.0 in the sub-Saharan African developing countries.

1.6 Literature overview

Since this study is presented in an article format, the literature is distributed over different sections of the thesis. Table 1 explains where in the thesis the different topics of the literature are presented.

Table 1: Literature review overview

Chapter	Literature presented
Chapter 2	I4.0, 4IR and sustainability (Systematic literature review)
Chapter 3	Section 3.2 – Action Research and Design Research Section 3.3 – Design Science Research paradigm Section 3.4 – Action Design Research and elaborated Action Design Research.
Chapter 6	I4.0 skills requirements and skills development (A systematic literature review on).
Chapter 8	Section 8.2 – Maturity models Section 8.3 – Competency models
Chapter 9	Industrial engineering intercept with the industrial revolutions.

1.7 Conclusion

The current chapter presented the research background and the research problem to be addressed in this study. Furthermore, the chapter reported the research aim and objectives that guided the study, along with the study's significance. This study is presented in an article-based format, because of which a coherent overview of the whole study was presented in this chapter.

Chapter 2 presents a systematic literature review to explore the impact of I4.0 and 4IR on sustainable development, and to clarify the terms I4.0 and 4IR and explore nuances specific to the usage of these terms.

CHAPTER 2

INDUSTRY 4.0 AND THE FOURTH INDUSTRIAL REVOLUTION

2.1 Introduction

This study aims to develop an Industry 4.0 competency maturity model (I4.0CMM) that simultaneously guides and assesses I4.0 competency development and industry competency requirements within the South African context. This is done to address South Africa's challenge of not achieving sustainable adoption of I4.0 in its manufacturing industry and to feed into the South African NDP that drives social, economic, and environmental sustainability.

Sustainability includes economic, environmental, and social dimensions (Khanzode *et al.*, 2021; Krajčo *et al.*, 2019; Stock *et al.*, 2018). Yadav *et al.* (2020) pointed out that sustainability has emerged as a notable subject, and identifying enablers of its adoption is essential. Developing countries significantly lag in adopting sustainability across manufacturing industries (Yadav *et al.*, 2020). Industry 4.0 technologies and principles can directly or indirectly impact sustainable development dimensions (Bai *et al.*, 2020; Yadav *et al.*, 2020). Therefore, manufacturing organisations should give considerable attention to the sustainable adoption of I4.0 (Bai *et al.*, 2020). Furthermore, academia and industry are confronted with the challenge of a lack of a standard definition of the terms I4.0 and 4IR (Amaral & Peças, 2021; Bonaccorsi *et al.*, 2020; Culot *et al.*, 2020; Nakayama *et al.*, 2020), leading to noticeable 'limitations to theory building and research comparability' (Culot *et al.*, 2020). According to Kowalikova *et al. (*2020), various definitions of I4.0 and 4IR in literature pose challenges in interpreting the concepts.

This chapter, therefore, presents a systematic literature review aimed to explore the impact of I4.0 and 4IR on sustainable development. The systematic literature review further seeks to clarify the terms I4.0 and 4IR and explore nuances specific to the usage of these terms. The chapter is organised as follows:

- Section 2.2 presents the systematic literature review design;
- Section 2.3 explores the impact of I4.0 and 4IR on sustainable development;
- Section 2.4 discusses I4.0and 4IR; and
- Section 2.5 concludes the chapter.

2.2 The systematic literature review design

This review employed Kitchenham (2004) and Brereton *et al.*'s (2007) guidelines on systematic literature review in combination with Moher *et al.*'s (2009) PRISMA used by Liao *et al.* (2018).

2.2.1 Systematic literature review questions

The study utilised four systematic literature review questions:

1. How does I4.0 and 4IR impact sustainable development?
2. What is the origin of the terms I4.0 and 4IR?
3. How are I4.0 and 4IR defined in the literature?
4. What are the technologies that drive I4.0 and 4IR?

2.2.2 Systematic literature review inclusion and exclusion criteria

The inclusion and exclusion criteria framework of Liao *et al.* (2018) was applied in this systematic literature review to identify research papers that answered the review questions. Table 2 presents the inclusion and exclusion criteria.

Table 2: Systematic literature review inclusion and exclusion criteria

Exclusion/ Inclusion	**Criteria**	**Description**
Exclusion	Duplication **(DP)**	The research articles appear more than once in the same search criteria.
	Language compatibility **(LC)**	Only the title, abstract and key words are accessible in English.
	No full text **(NF)**	The full text of the research article cannot be accessed
	Casually used **(CU)**	The research article mentions without defining or discussing the origin or principles or technologies that drive I4.0 and 4IR
Inclusion	Closely related **(CR)**	**CR1:** The research paper relates I4.0 and 4IR to sustainable development. **CR2:** The research paper provided either I4.0 and 4IR definition or origin or principles or driving technologies.

2.2.3 Search strategy

The search terms used in the SLR were 'Industry 4.0' and the 'Fourth Industrial Revolution', with variations in spellings accommodated according to Table 3. The search string was constructed using the Boolean operator AND, which restricts retention of papers to those with all relevant key terms, and using the operator OR to accommodate alternative spelling and synonyms (Kitchenham, 2004). The systematic literature search was conducted on Scopus and Web of Science online databases. The concept of I4.0 was initiated in Germany at the Hanover fair in 2011 (Park, 2018; Safar *et al.*, 2018); thus, the SLR considered research output from January 2011 to February 2021.

Table 3: Search team alternative spellings and synonyms

Search term	Alternative search word
'Industry 4.0'	I4.0, 'Industrie 4.0'
'Fourth Industrial Revolution'	4IR, '4th Industrial revolution'

2.2.4 Selection of research papers

The exclusion and inclusion criteria presented in Table 2 were used to select the documents following a four-stage selection process illustrated in Figure 4.

The identified papers from the search criteria were taken through the initial step of removing all duplicate (DP) research papers. This was followed by eliminating research papers written in languages other than English (LC) and papers with no accessible full text (NF).

Further screening was conducted on the research papers that passed the first step to testing their inclusion eligibility. The second screening stage eliminated research papers that casually used the terms I4.0 and 4IR without providing their definition or discussing their origin or underpinning principles, or providing their driving technologies (CU). The research papers used I4.0 and 4IR to situate their studies within this narrative, not to explain the concepts.

The papers that met the inclusions criteria and that were not removed based on the exclusion criteria, were considered eligible for further analysis and classified into two categories: papers that relate I4.0 and 4IR to sustainable development (CR1) and papers that provide either the definition, or origin, or principles, or driving technologies of I4.0 and 4IR (CR2).

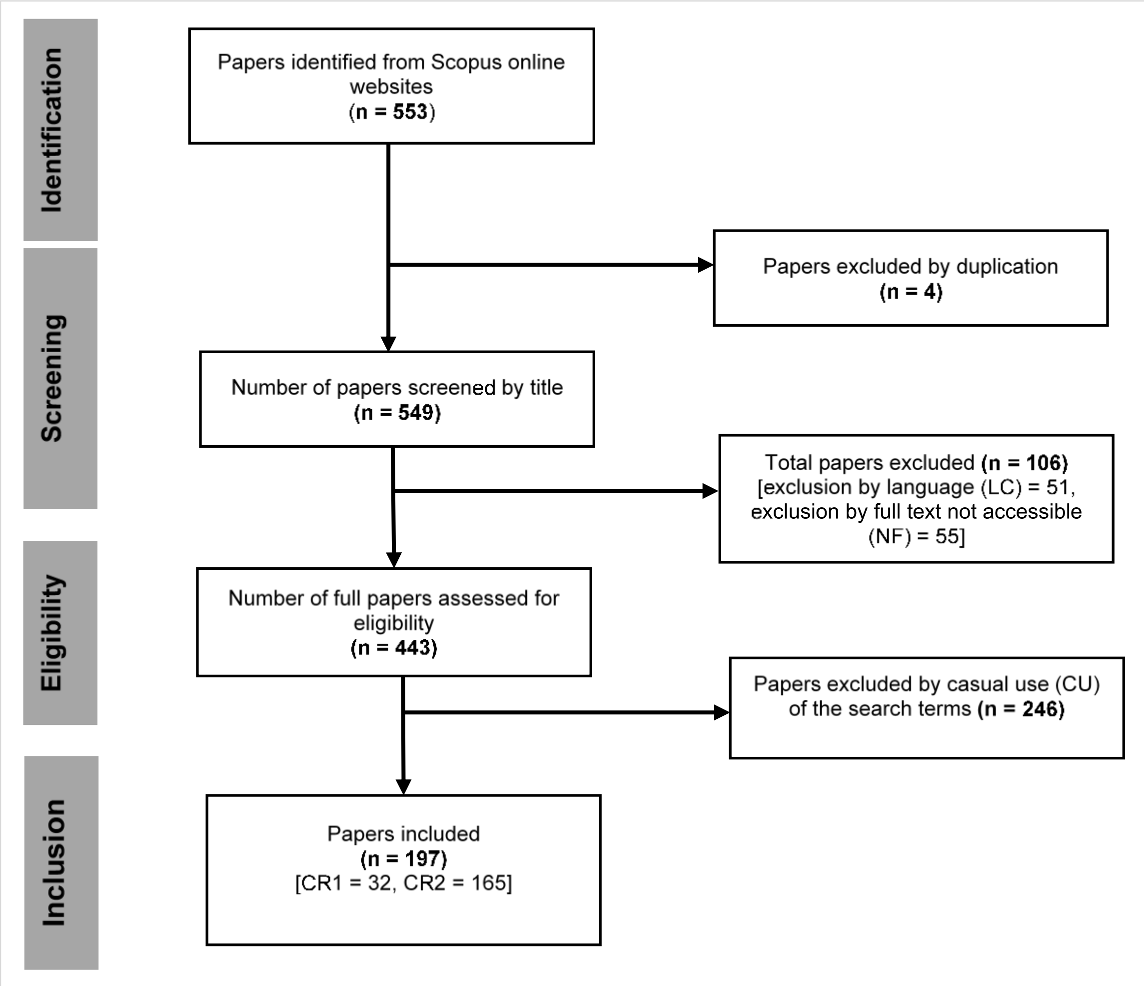

Figure 4: Systematic literature review research paper selection

2.2.5 Data extraction and analysis

The systematic literature reviews questions presented in section 2.2.1 guided the data extraction process. The objective was to gather data that would aid in identifying the impact of I4.0 and 4IR on sustainable development and clarifying the terms I4.0 and 4IR and nuances specific to the usage of the terms. The data were categorised into two groups: one highlighting the relationship between I4.0 and 4IR to sustainable development in section 2.3, and the other dealing with I4.0 and 4IR origins, definitions, and driving technologies, as presented in section 2.4.

2.3 Industry 4.0, the Fourth Industrial Revolution, and sustainable development

Roda-Sanchez *et al.* (2018) pointed out that “sustainability is a major concern for emerging paradigms [I4.0]”. This view suggests that sustainability should be at the core of the adoption of I4.0. Sustainable Development can be summarised as the development that addresses the present generation's needs without impeding the ability of future generations to meet their own needs (Krajčo *et al.*, 2019; Stock *et al.*, 2018). Therefore, the SDGs were crafted to drive sustainable development within the global economies (Stock *et al.*, 2018).

Within the confines of the SDGs, sustainable value creation should include three dimensions: economic, social, and environmental (Krajčo *et al.*, 2019; Stock *et al.*, 2018). Ziaei Nafchi and Mohelská (2018) emphasised that business is supposed to add value to society through supporting the caring of the environment and climate and meeting the social needs of people. That is, the three dimensions of sustainability should receive equal attention to enable sustainable development. However, the current global trends reveal "growing socio-economic inequality, climate change, increasing environmental degradation..." (Stock *et al.*, 2018). Thus, sustainable adoption of I4.0 means promoting economic development within the scope of social equality and environmental sustainability.

Industry 4.0 can intensify global inequality and hinder achieving the SDGs (Sanchez, 2019; van Niekerk, 2020) and the South African NDP (Maisiri *et al.*, 2021). Taking no measures could lead I4.0 to hinder achieving goals such as SDG 8, which promotes "sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all" and aligns with NDP Chapter 3 (economy and employment). Also, SDG 10 (reduction of inequality within and among countries) and SDG 9 (inclusive and sustainable industrialization) could be detrimentally affected by I4.0.

2.3.1 Economic sustainability

According to Stock (2018), economic sustainability entails "the upholding of competitive advantages and efficient market orientation while aiming at conserving resources and increasing the quality of life". Industry 4.0's driving principles seek to achieve competitiveness and ensure the effectiveness of the manufacturing industry (Safar *et al.*, 2018). Thus, Brozzi *et al.* (2020) pointed out that the impact of I4.0 on economic opportunities received significant attention in the literature more than its impact on the environment and social sustainability. Stock (2018) argues that I4.0 essentially focuses on improving the economic sustainability dimension – productivity, efficiency, and increased throughput of manufacturing systems, thus ensuring profitability.

Industry 4.0 merges advanced technologies to ensure integration of business and processes allowing flexible, efficient, and sustainable production with high quality and low cost (Machado *et al.*, 2020). The use of cyber-physical systems and the internet of things permits the interconnection of resources, machines, and the whole supply chain to optimise the efficiency of the production process (Kovacs, 2018). Pérez-Pérez *et al.* (2018) add that shorter production runs and customised production lower raw material costs and thus boost profitability. Culot *et al.* (2020) support other authors by stating that "Industry 4.0 will improve productivity and flexibility, [and lead to] economic growth". Therefore, it implies that the potential of I4.0 to promote economic sustainability cannot be overemphasised.

The impact of I4.0 across industries, occupations, and countries will not be homogeneous (Kim *et al.*, 2019; Pérez-Pérez *et al.*, 2018) due to the lack of uniform distribution of wealth, productivity, and technologies (Kim *et al.*, 2019). Van Rensburg *et al.* (2019) highlighted that "African countries are lagging in technological progress, marked by a digital divide". Ajayi *et al.* (2019) support this observation by pointing out that developing nations have missed many of the first three industrial revolutions' opportunities offered. Furthermore, African countries are more on the consumer side regarding technological advancements (Van Rensburg *et al.*, 2019) and are burdened with "economic sustainability and survival challenges" (Ajayi *et al.*, 2019). Thus, developed countries have a significant advantage over African developing countries regarding competitive advantage (Ziaei Nafchi & Mohelská, 2018). However, African developing countries can grab the opportunity offered by I4.0 technologies and leapfrog to the level of technologically prepared countries (Ajayi *et al.*, 2019).

The emphasis of I4.0 on competitiveness, such as in the European Union countries (Park, 2018), could result in investment being pushed back into developed economies (Hartmann & Hattingh, 2018), which means a possible decrease in opportunities for developing countries to offer "low-cost labour, which is an established pathway for development" (Kim *et al.*, 2019). Labour-intensive production economies such as in African developing countries will suffer a drop in employment, resulting in negative economic growth (Park, 2018). Therefore, to support sustainable economic growth in African developing countries, the objective of adopting I4.0 in developed countries should be to "sustain competitiveness without the need to shift their factories to poorer countries with cheaper labour" (Krajčo *et al.*, 2019).

2.3.2 Environmental sustainability

Stock *et al.* (2018) state that environmental sustainability involves preserving natural resources and minimising emissions due to human activities. According to Brozzi *et al.* (2020), several studies highlighted the potential of I4.0 to drive the environmental dimension of sustainability.

Advance technologies driving I4.0 could potentially drive environmental sustainability by reducing greenhouse emissions, energy efficiency, and growth in renewable energy consumption (Iqbal *et al.*, 2020; Krajčo *et al.*, 2019; Park, 2018). Sustainable manufacturing and production systems and emphasis on efficiency and effectiveness promote minimisation of waste production (Brozzi *et al.*, 2020; Pérez-Pérez *et al.*, 2018).

The promotion of green technologies in I4.0 has a far-reaching effect on reducing energy consumption and enhancing product life-cycle management (Nouiri *et al.*, 2019; Park, 2018). The adoption of cleaner production methods, improving productivity, promoting resource efficiency and use of renewable material in production all decrease raw material consumption and enhance global resource security (Iqbal *et al.*, 2020; Nouiri *et al.*, 2019; Park, 2018). Therefore, I4.0 could promote sustainable consumption and production patterns. Balogun *et al.* (2020) and Bonilla *et al.* (2018), among others, provide evidence of applications of I4.0 technologies in mitigating the already present environmental challenges.

African developing countries' vital economic sectors include agriculture, mining, and tourism. Consequently, these countries could suffer significantly from climate change challenges (Balogun *et al.*, 2020). It means the adoption of I4.0 technologies in these developing countries could significantly drive sustainable environments for these countries.

2.3.3 Social sustainability

Kovacs (2018) argues that the success of I4.0 and 4IR not only depends on "technical feasibility but also on its social acceptability". Stock *et al.* (2018) indicate the scope of social sustainability, including "the equitable inclusion of human resources, taking into account social classes, gender, age groups, and cultural and regional identity". Social sustainability aims to promote social stability and social justice (Kovacs, 2018; Stock *et al.*, 2018).

Technological advancements can never be neutral but will always impact social sustainability (Avis, 2018). Kergroach (2017) supports this view by highlighting the potential impact of I4.0 emerging technologies on inequality challenges. South Africa significantly faces the challenge of inequality due to societal structural inequalities, a low level of education, and high levels of unemployment, among others (Hartmann & Hattingh, 2018). Van Rensburg *et al.* (2019) emphasise the inequality challenges in South Africa by stating that "the divide in living standards and economic opportunity will continue to grow if vulnerable communities are not digitally activated and enabled".

According to Worrall (cited by Soh & Connolly, 2021), "our world is being transformed before our eyes as new technologies give some organisations a huge competitive edge, and see others left behind". Therefore, inequalities challenges extend beyond societal inequalities to include organisational, national, and regional inequalities.

Various authors (Avis, 2018; Hartmann & Hattingh, 2018; Kergroach, 2017; Kovacs, 2018) agree that I4.0 driving technologies such as advances in machine learning, autonomous robotics, and artificial intelligence significantly impact labour demand and drive job displacement. The advanced technologies extend their impact beyond "physical or manual tasks, the dirty, dangerous, or dull tasks" (Kergroach, 2017) to many intellectual, cognitive, or analytical white-collar jobs (Hartmann & Hattingh, 2018; Kergroach, 2017; Park, 2018). This leads to technological unemployment (Avis, 2018) and exacerbates unemployment challenges faced by many developing countries. The impact of technology on employment will significantly differ between developed and developing countries. Ziaei Nafchi and Mohelská (2018) confirmed this view when they compared the impact of I4.0 on the labour force in Japan (a developed country) and Iraq (a developing country). Therefore inequality challenges are experienced between and within countries (Soh & Connolly, 2021).

Industry 4.0 and the 4IR will significantly influence "the demand and supply of skills, and the structure of occupations" (Kergroach, 2017). Park (2018) pointed out that the imbalance between jobs displaced and jobs created will intensify, resulting in a noticeable skills gap. Though new jobs and a new form of employment will be created in I4.0, it is concluded that the labour market will be characterised by skills requirements in complex jobs, thus raising the skills level (Krajčo *et al.*, 2019). This will directly impact skills development in industry and academic education and training (Avis, 2018). Thus, I4.0 will "impose new requirements for the education system and applied research"(Krajčo *et al.*, 2019).

Park (2018) pointed out that technology should enhance human capability instead of being a substitute for human work. Technology should be applied in performing routine and tedious activities, thus freeing employees to perform value-added tasks (Park, 2018). Consequently, reskilling and retraining become significantly important in organisations.

Ziaei Nafchi and Mohelská (2018) argue that special attention on skills development from both industry and government is required to move towards sustainable adoption of I4.0. Investment in human capital will significantly impact sustainable adoption of I4.0 and enhance economic growth (Pérez-Pérez *et al.*, 2018; Ziaei Nafchi & Mohelská, 2018). Competencies development through embracing technological advancements will have a noticeable contribution on sustainable socio-economic development.

2.4 Industry 4.0 and the Fourth Industrial Revolution

Concerning the previous industrial revolutions, the terms first, second, and third industrial revolutions have been used in the literature (Bretagnolle & Pumain, 2010; Chatzis, 2009;

Mowery, 2009). Contrary to this, the terms ‘Industry 1.0’, ‘Industry 2.0’ and ‘Industry 3.0’ had not been used in the literature until the coining of the term I4.0 in 2011 (Park, 2018; Safar *et al.*, 2018). However, casual use of I4.0 and the 4IR as synonyms is common in the literature. This section provides an overview of the systematic literature review findings on I4.0 and the 4IR as follows:

- Section 2.4.1 presents the origin of I4.0 and the 4IR, and
- Section 2.4.2 gives an overview and driving technologies of I4.0 and the 4IR.

2.4.1 Origin of Industry 4.0 and Fourth Industrial Revolution

The reviewed papers showed consensus amongst authors on the origin of I4.0. The literature pointed out that I4.0 was conceptualised in Germany by representatives from industry, academia, and government (Vrchota & Frantíková, 2020). Industry 4.0 was first presented and used at the Hannover Fair in 2011 in Germany (Caliskan *et al.*, 2020; Kang *et al.*, 2016; Müller, 2019; Ramos *et al.*, 2020) as a strategic initiative to drive the competitiveness of the Germany manufacturing industry.

Bonaccorsi *et al.* (2020) revealed that the Germany narrative of I4.0 focuses on the manufacturing industry. Another notion is that I4.0 describes trends in the manufacturing industry (Soh & Connolly, 2021; Sony, 2018). This view is strengthened by Kagermann (2016) (cited by Bonaccorsi *et al.*, 2020) in a statement: “the focus is on optimizing production processes in terms of quality, price, and flexibility and delivering better financial returns overall”. Culot *et al.* (2020) further support this view by stating that “Industry 4.0 suggests a new phase in manufacturing”. Thus, in its original conception, I4.0 described advanced technologies in manufacturing.

Though the label, I4.0, is being used worldwide, Bonaccorsi *et al.* (2020) posed an important question as to whether the original intent and understanding of the label have been maintained as it migrated to other countries. The delineation of I4.0 among various stakeholders could have “serious consequences on government policies and company strategies” (Bonaccorsi *et al.*, 2020). Kowalikova *et al.* (2020) stress that variations in definitions and understanding of I4.0 could significantly impact its adoption and use to solve problems.

Klaas Schwab formulated and promoted the fourth industrial revolution (4IR) at the World Economic forum in 2016 (Schwab, 2016; Trauth-Goik, 2021). The roots of the term Fourth Industrial Revolution can be traced to the term I4.0 (Soh & Connolly, 2021). Furthermore, Soh and Connolly (2021) argue that Klaas Schwab expanded the concept of I4.0 and promoted it as the 4IR.

2.4.2 Industry 4.0 and Fourth industrial revolution overview

According to Culot *et al.* (2020), literature generally describes I4.0 as the 4IR. The use of the following phrases in literature, among others, suggests some authors perceive I4.0 and 4IR to be synonymous terms: "Fourth Industrial Revolution (industry 4.0)" (Awan *et al.*, 2021; Lim *et al.*, 2021; Tao *et al.*, 2021), "Industry 4.0 also known as the Fourth Industrial Revolution" (Acioli *et al.*, 2021; Bakhtari *et al.*, 2021; Yoo *et al.*, 2021), "Fourth Industrial Revolution also referred to as industry 4.0" (Benassi *et al.*, 2020; Mian *et al.*, 2020; Steenkamp, 2020), "Fourth Industrial Revolution also termed Industry 4.0" (Benassi *et al.*, 2020; Ye *et al.*, 2020), "Fourth Industrial Revolution also labelled Industry 4.0" (Bai *et al.*, 2020), and "Fourth Industrial Revolution named Industry 4.0" (Godina *et al.*, 2020; Mahmud *et al.*, 2019).

Soh and Connolly (2021) argue that although some academics, companies, and analysts use I4.0 and 4IR as synonymous terms, some nuances require attention. The argument is supported by Culot *et al.* (2020), who state that using Industry 4.0 and 4IR as synonyms has "increased the sense of confusion around the scope and characteristics of the phenomenon".

A study by Culot *et al.* (2020) revealed that academic and grey literature present many different I4.0 definitions. Industry 4.0 is frequently defined descriptively to "capture a set of interactive technologies that, in their interdependence, will shape great social changes" (Kowalikova *et al.*, 2020).

Industry 4.0 definitions provided in the literature agree that it involves "the convergence of the real and virtual world" ((Bakhtari *et al.*, 2021) Kagermann, 2015) to enhance the manufacturing industry. Industry 4.0 focuses on the potential of cyber-physical systems to enhance the manufacturing industry (Soh & Connolly, 2021).

Many other labels are used synonymously to I4.0 (Culot *et al.*, 2020). Such synonyms include: smart manufacturing (Hofmann & Rüsch, 2017; Kumar, 2018; Shao *et al.*, 2021), integrated industry (Büchi *et al.*, 2020; Hofmann & Rüsch, 2017), industrial internet (Hofmann & Rüsch, 2017), intelligent manufacturing (Zhong *et al.*, 2017), advanced manufacturing (Kiss & Nedelka, 2020), cloud manufacturing (Zhong *et al.*, 2017), and digital manufacturing (Büchi *et al.*, 2020). These labels strengthen the notion that the term I4.0 is inclined to be used in the manufacturing industry although it is applied in other industries.

Sung (2018) argued that "concepts regarding the 4IR and I4.0 are similar". However, he asked an important question: can the two terms be used interchangeably? (Sung, 2018). Though the terms I4.0 and 4IR are commonly seen as synonymous, Soh and Connolly (2021) argue that a detailed analysis reveals that the terms do not mean the same thing. The following phrases in literature, among others, strengthen the above notion:

- “Industry 4.0 is the new productive paradigm that is driving the 4th industrial revolution” (Rafael *et al.*, 2020),
- 4IR “emerged from Industry 4.0, which is seen as the main component of the 4th industrial Revolution” (Marnewick & Marnewick, 2019),
- “This revolution (4IR) [was] commonly triggered by the German initiative Industrie 4.0” (Bokrantz *et al.*, 2017); and
- “Industry 4.0 provides the roadmap that leads to the 4th Industrial Revolution” Marnewick & Marnewick (2019) (citing (Perales *et al.*, 2018)).

Industry 4.0 is regarded as “the new productive paradigm” (Rafael *et al.*, 2020) that is driving the Fourth Industrial Revolution in the manufacturing industry (Rafael *et al.*, 2020; Ziaei Nafchi & Mohelská, 2018). The view is supported by Sung (2018) who pointed out that I4.0 focuses specifically on manufacturing. Furthermore, Shao *et al.* (2021) present I4.0 as “a by-product of the Fourth Industrial Revolution”. Kim *et al.* (2019) recognised I4.0 as the global shift in manufacturing towards promotion and adoption of the smart factory as a new standard.

Several authors (Li *et al.*, 2021; Soh & Connolly, 2021; Trauth-Goik, 2021) agree that the 4IR is depicted by the “fusion of physical, digital, and biological technologies” initially described by Schwab (2016). The 4IR is not restricted to any industry or sector but focuses on the synergistic interaction of various innovations. The 4IR extends its application to all “social, political and economic activities” (Soh & Connolly, 2021). The 4IR will impact all aspects of our lives, including how we work and relate to others (Marnewick & Marnewick, 2019; Schwab, 2016).

Comparing I4.0 and the 4IR, Sung (2018:41) states that the Fourth Industrial Revolution “refers to a systemic transformation that includes an impact on civil society, governance structures, and human identity in addition to solely economic and manufacturing ramifications”.

Though I4.0 has been globally accepted, it is regarded as Germany's initiative and strategy compared to other nation–wide innovation strategies (Min *et al.*, 2019; Salah *et al.*, 2020). These innovation strategies, I4.0 being the primary innovation strategy, are the foundations of and are driving the 4IR. This view is strengthened in the literature when I4.0 is compared to similar nation-wide initiatives in other countries such as:

- “Industrial Internet” or “Advanced Manufacturing Partnership” in the United States of America (Bakhtari *et al.*, 2021; Büchi *et al.*, 2020; Culot *et al.*, 2020; Trauth-Goik, 2021);
- “Made in China 2025 and Internet Plus” in China (Bakhtari *et al.*, 2021; Hermann *et al.*, 2016; Prause, 2019; Trauth-Goik, 2021)
- “Future of Manufacturing” in the United Kingdom (Bakhtari *et al.*, 2021; Büchi *et al.*, 2020; Machado *et al.*, 2020)
- “Alliance Industry of the Future” in France (European Commission, 2019)
- “Smart Industry” in the Netherlands and Sweden (European Commission, 2019; Machado *et al.*, 2020)
- “Japan Revitalization Strategy” and “Society 5.0/Super Smart Society” in Japan (Min *et al.*, 2019; Salah *et al.*, 2020; Trauth-Goik, 2021; Zhong *et al.*, 2017)
- “Manufacturing Industry Innovation 3.0” in Korea (Min *et al.*, 2019).

The current study concludes that I4.0 could be regarded as a sub-set of the 4IR as illustrated in Figure 5. Manufacturing is at the heart of I4.0 (Iqbal *et al.*, 2020), though its principles can be adopted in other industries. The 4IR has a broader scope, and it touches every aspect of human life (Park, 2018), and does not just narrowly focus on technical aspects of manufacturing (Avis, 2018). I4.0's scope is within cyber-physical systems, while the 4IR's context extends to biological systems (Jacobs & Pretorius, 2020).

Figure 5 illustrates that all I4.0 driving technologies are considered within the scope of the 4IR. However, there are other additional technologies that specifically refer to the 4IR, and not just I4.0 such as:

- Cryptocurrency (Bitcoin) (Jiao *et al.*, 2021; Le *et al.*, 2021; Ma *et al.*, 2020; Umar *et al.*, 2021),
- Block chain (Le *et al.*, 2021; Ma *et al.*, 2020; Yoo *et al.*, 2021)
- Autonomous vehicles (Alharbi, 2020; Popchev & Orozova, 2020) (Yoo *et al.*, 2021)
- Implantable technologies (Popchev & Orozova, 2020)
- Nanotechnology (Alharbi, 2020; Popchev & Orozova, 2020; Yoo *et al.*, 2021)

- Synthetic biology (Popchev & Orozova, 2020; Yoo *et al.*, 2021)

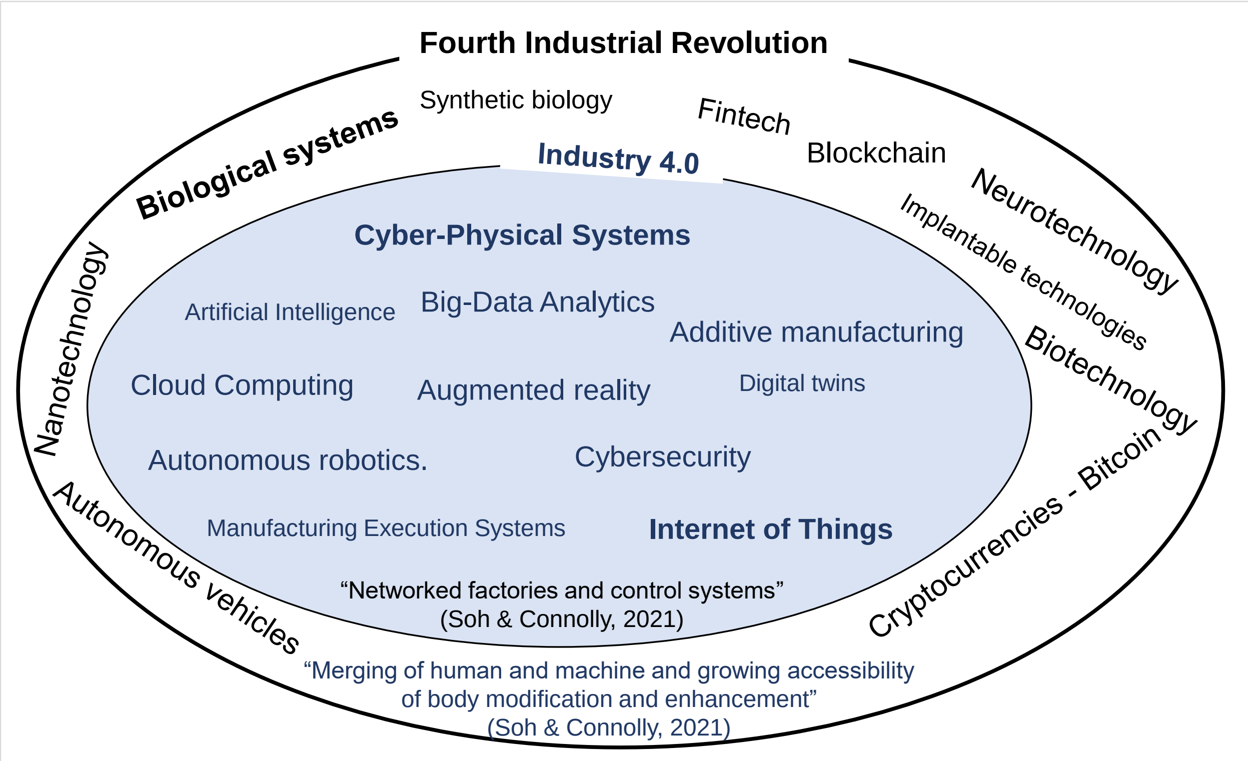

Figure 5: Industry 4.0 and the Fourth Industrial revolution relationship and driving technologies (Author presentation)

Industry 4.0 driving technologies commonly mentioned in literature included:

- Cyber-Physical Systems (Amaral & Peças, 2021; Amjad *et al.*, 2021; Jimeno-Morenilla *et al.*, 2021),
- Internet of Things (Jimeno-Morenilla *et al.*, 2021; Saniuk *et al.*, 2020; Shao *et al.*, 2021),
- Big-data and Big-data Analytics (Bakhtari *et al.*, 2021; Fatorachian & Kazemi, 2021; Saniuk *et al.*, 2020),
- Additive manufacturing: 3D-Printing (Hernandez-de-Menendez *et al.*, 2020; Jimeno-Morenilla *et al.*, 2021; Kruger & Steyn, 2020),
- Augmented reality (Acioli *et al.*, 2021; Bakhtari *et al.*, 2021; Kruger & Steyn, 2020),
- Cloud computing (Acioli *et al.*, 2021; Hernandez-de-Menendez *et al.*, 2020; Shao *et al.*, 2021),

- Autonomous robotics (Acioli *et al.*, 2021; Hernandez-de-Menendez *et al.*, 2020; Kruger & Steyn, 2020), and

- Cybersecurity (Acioli *et al.*, 2021; Hernandez-de-Menendez *et al.*, 2020; Saniuk *et al.*, 2020).

- Artificial intelligence (Fatorachian & Kazemi, 2021; Kruger & Steyn, 2020; Shao *et al.*, 2021)

Though there might be different opinions on I4.0 and the 4IR technologies and the use of these terms, this study maintains that I4.0 and the 4IR are similar concepts with different scopes. This study further emphasises that the adoption of I4.0 is unavoidable to keep pace with global technological developments. This study thus concurs with Hartmann and Hattingh (2018), when they state: “regardless of whether the revolution is well named, we recognise that the future competitiveness of organisations may depend on keeping pace with global industrial development”. The question to be answered is not whether to adopt it but how to achieve its sustainable adoption.

2.5 Conclusion

The chapter presented a systematic literature review to explore the impact of I4.0 and 4IR on sustainable development, clarify the terms I4.0 and 4IR and explore nuances specific to the usage of these terms. Subtle consequences on interchangeably using the terms I4.0 and 4IR exist and depend on which term refers to the other. Limiting the 4IR to I4.0 could result in countries and organisations limiting the sustainability aspects to the economic dimension due to the nature and originality of I4.0. However, since 4IR has a broader scope and is significantly driven by I4.0 concepts and initiatives, 4IR can refer to I4.0 with no negative impact on sustainability.

The adoption of I4.0 is unavoidable for survival and enhancing the capacity to play within the global markets. African developing countries face the challenge of achieving sustainable adoption of I4.0. Focusing on competencies development in educational institutions and workplace skills development could provide a firm foundation to achieve a sustainable and inclusive economy (Krajčo *et al.*, 2019; Sony, 2018).

Chapter 3 will summarise the literature which compares alternative research methods before, presenting the research design adopted in this thesis.

CHAPTER 3

RESEARCH DESIGN

3.1 Introduction

Sein and Rossi (2019) emphasised that a problem exists if there is a gap between the desired state and the current state, and solving the problem eliminates or reduces this gap. The problem to be addressed in this research is the lack of I4.0 reference models, which could align industry competency requirements and competency development.

Therefore, this study aims to develop an I4.0 competency maturity model (I4.0CMM) that simultaneously guides and assesses I4.0 competency development and industry competency requirements using the South African context. The development and illustration of the I4.0CMM used the industrial engineering capability functions.

The development of the I4.0CMM utilised the views of Mullarkey and Hevner (2019) and Sein and Rossi (2019) on elaborated Action Design Research (eADR). The Delphi technique was integrated into the study design to permit the collaboration between researchers and practising industry experts in co-generating knowledge, as is discussed in chapter 9, the development of I4.0CMM (Article 6).

The research design literature discussion is premised on the framework presented in Figure 6. Section 3.2 provides an overview comparison of Action Research (AR) and Design Research (DR) to understand the approaches on which Action Design research (ADR) is founded. ADR is a method within the Design Science Research (DSR) paradigm presented in section 3.3. Action Design Research and eADR are discussed in section 3.4. Since this study is presented in an article-based thesis, the detailed methodology for each research stage is presented in the published articles in the respective chapters. However, Section 3.5 presents an overview of the research design adopted in this research and section 3.6 concludes the chapter.

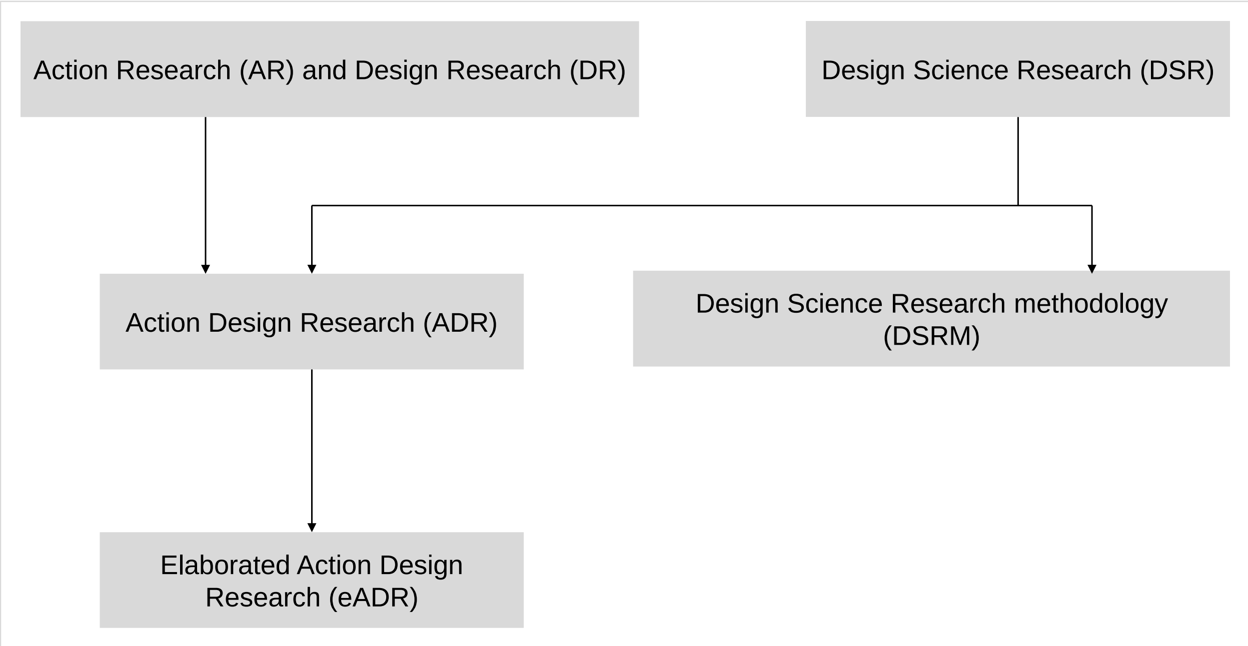

Figure 6: Research design literature premises

3.2 Action Research and Design Research comparison

The Action Research (AR) focuses on solving a practical organisational problem. However, AR lacks the iterative process of developing and evaluating the artefact (Gill & Chew, 2018). On the other hand, the Design Research (DR) focuses on creating knowledge through the experience of developing an innovative artefact (Gill & Chew, 2018; Hevner & Chatterjee, 2010). Table 4 gives an overview comparison of AR and DR.

Table 4: Action Research and Design Research summary

	Action Research	**Design Research**
General	• Occurs in a natural environment of the host organisation (Gill & Chew, 2018; Papas *et al.*, 2012) • Rooted in constructivist ideas (Papas *et al.*, 2012) • Collaboration between researchers and practitioners (Gill & Chew, 2018)	• Occurs in a natural environment (Papas *et al.*, 2012) • Rooted in pragmatism (Papas *et al.*, 2012) • Collaboration between researchers and practitioners (Gill & Chew, 2018) • More conceptual in nature and not grounded in practice (Gill & Chew, 2018; Papas *et al.*, 2012)
Focus	• Practise-oriented research method (Gill & Chew, 2018) • Organisational intervention at the core	• Practise-oriented research method (Gill & Chew, 2018) • Does not take organisational context as a

	(Coghlan & Brannick, 2019; Gill & Chew, 2018; Sein *et al.*, 2011; Somekh, 1995) • Bridges a gap between research and practice (Coghlan & Brannick, 2019; Saramunee, 2021; Somekh, 1995; Susman & Evered, 1978) • Learning and improved practise (Gill & Chew, 2018)	dimension in the design process (Sein *et al.*, 2011) • Solve a real and relevant problem through innovative artefacts (Gill & Chew, 2018; Hevner & Chatterjee, 2010; Sein *et al.*, 2011) • Artefact development and evaluation (Gill & Chew, 2018; Hevner & Chatterjee, 2010)
Problem solving approach	• Interventionist research method (Gill & Chew, 2018; Papas *et al.*, 2012) • Solve a practical problem through intervention and collaboration (Gill & Chew, 2018)	• Constructive research method (Gill & Chew, 2018; Papas *et al.*, 2012; Sein *et al.*, 2011) • Solve a practical problem through building and evaluating conceptual artefacts (Gill & Chew, 2018; Hevner & Chatterjee, 2010)
Contribution and theory generation	• Solve an organisational problem • Contextual, repeatable with generalisability (Gill & Chew, 2018; Papas *et al.*, 2012)	• Innovative artifact • Generalisability and transferability of artefact (Gill & Chew, 2018; Papas *et al.*, 2012)
Gap	• Lacks the iterative artefact development and evaluation aspect (Gill & Chew, 2018)	• Scant intervention and organizational context (Gill & Chew, 2018; Sein *et al.*, 2011)

Sein *et al.* (2011) and Gill and Chew (2018) pointed out that DR focuses on the building with rigour of artefacts at the cost of organisational relevance, while AR focuses on organisational relevance at the cost of building artefacts with rigour. Therefore, a method that combines the strengths of AR and DR could solve the problem. Consequently, Sein *et al.* (2011) conceptualised ADR as a genre of DSR that combines the principles of AR and DR (Gill & Chew, 2018; Sein *et al.*, 2011; Sein & Rossi, 2019). Section 3.3 discusses the DSR paradigm.

3.3 Design Science Research Paradigm

The Design Science Research (DSR) paradigm focuses on creating knowledge through the experience of developing an innovative artefact (Gill & Chew, 2018; Hevner & Chatterjee, 2010). Hevner and Chatterjee (2010) define DSR, as follows:

> *Design science research is a research paradigm in which a designer answers questions relevant to human problems via the creation of innovative artifacts, thereby contributing new knowledge to the body of scientific evidence* (Hevner & Chatterjee, 2010).

Design Science Research seeks to address two key issues: the role of artefacts and their "perceived lack of relevance" in research (Hevner & Chatterjee, 2010). The Design Science Research paradigm focuses on solving real-world problems by developing innovative artefacts (Hevner & Chatterjee, 2010).

Hevner *et al.*'s (2004) contribution, summarised by Hevner and Chatterjee (2010), contrasted two knowledge acquiring paradigms: behavioural science and design science. Behavioural science seeks to develop and justify principles and laws (theories) by applying natural science research methods (Hevner & Chatterjee, 2010; Hevner *et al.*, 2004). The theories provide insights into the design science paradigm (Hevner & Chatterjee, 2010).

Contrary to behavioural science, design science is a problem-solving paradigm with its roots in engineering and science (Hevner & Chatterjee, 2010; Hevner *et al.*, 2004). The Design Science Research paradigm seeks to create artefacts that provide utility to the behavioural science paradigm (Hevner & Chatterjee, 2010). Figure 7 illustrates how design science and behavioural science complement one another.

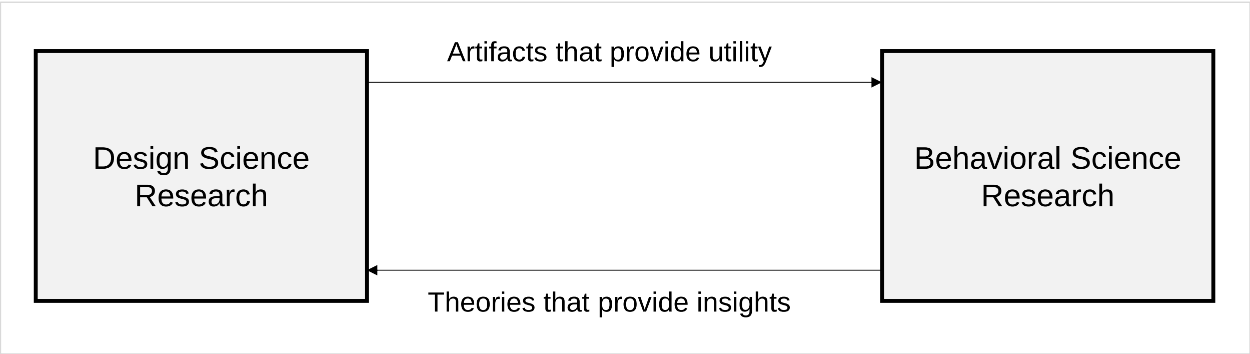

Figure 7: Complementary nature of DSR and Behavioural Science Research (Hevner & Chatterjee, 2010).

The Design Science Research framework presented by Hevner *et al.* (2004) and refined by Hevner (2007) consists of three cyclic processes (Hevner, 2007; Hevner *et al.*, 2004): relevance cycle, design cycle, and rigour cycle as presented in Figure 8.

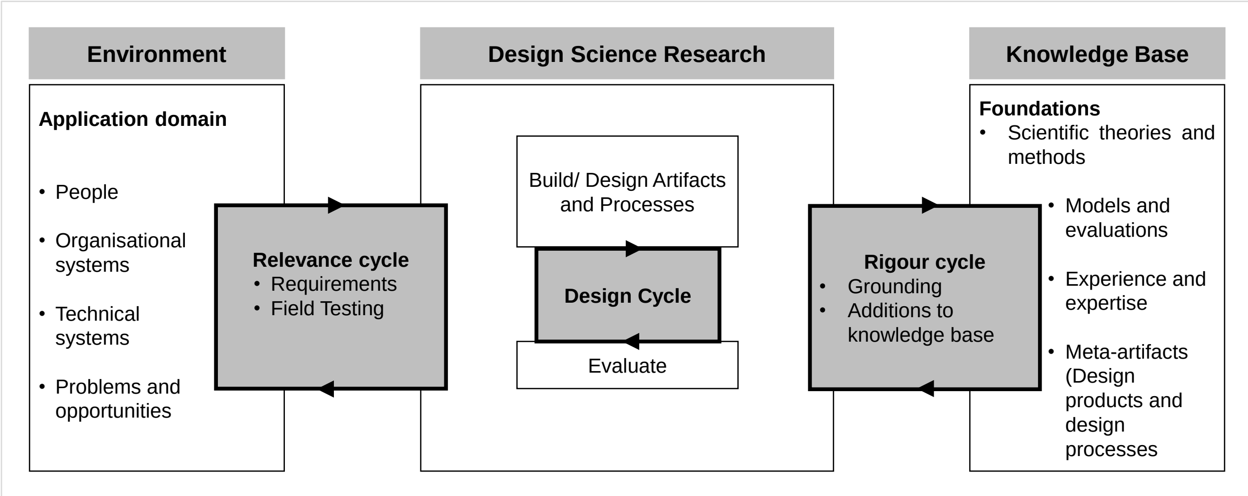

Figure 8: Design Science Research cycles (Hevner, 2007)

The relevance cycle links the environment in consideration to the design science activities, while the rigour cycle bridges the design science activities with the "knowledge base of scientific foundations, experience, and expertise that informs the research project" (Hevner, 2007). Details of the three cycles are presented in section 3.3.1 (relevance cycle), section 3.3.2 (design cycle) and section 3.3.3 (rigour cycle)

3.3.1 Relevance cycle

New and innovative artefacts in DSR should improve the application environment by solving real and relevant problems (Hevner, 2007). Design Science Research starts with a relevance cycle which identifies the problem or opportunity to be solved. The relevance cycle also defines the evaluation criteria of the research output. Hevner (2007) states that the research output can be studied and evaluated in the application domain through Action Research. Hence, it implies that DSR does not inherently embed Action Research in the design process. Consequently, there is a disconnect between artefact development and artefact evaluation for the application environment relevance. Although Hevner (2007) suggested iteration cycles for relevance evaluation depending on identified deficiencies in the artefact's functionality, the evaluation for relevance is not an inherent component of the design process.

3.3.2 Design Cycle

The design cycle seeks to ensure the development of new and innovative artefacts through the iteration process of generating and evaluating the artefact against design requirements (Hevner, 2007). The design cycle draws design requirements from the relevance cycle and pulls the evaluation theories and methods from the rigour cycle. Hevner (2007) realized the dependency of the design cycle on the relevance cycle and rigour cycle. However, he points out explicitly that there is a need for “appreciating its relative independence during the actual execution of the research” (Hevner, 2007). The design cycle iterations are independent of the rigour cycle and relevance cycle.

3.3.3 Rigour cycle

Drawing knowledge from the scientific theories and engineering methods base ensures the rigour of artefacts in DSR (Hevner, 2007). The additional knowledge base in developing innovative and new artefacts also includes expertise and experience in the research application domain and existing artefacts in the application domain.

The rigour cycle brings past knowledge that contributes to ensuring innovation in artefacts' development (Hevner, 2007). Thus, it enables distinguishing research contributions from “routine designs based upon the application of well-known processes” (Hevner, 2007; Hevner *et al.*, 2004). The ability to select and apply appropriate theories and methods in developing and evaluating an innovative artefact plays a significant role in establishing rigour in DSR (Hevner, 2007).

3.3.4 Design Science Research methods

Two DSR methods are commonly discussed in the literature (Sein & Rossi, 2019), which are DSR methodology (DSRM) and ADR (Peffers *et al.*, 2007; Sein & Rossi, 2019). Although Mullarkey and Hevner (2019) tried to combine the principles of these two methods, Sein and Rossi (2019) argue that they are epistemologically incompatible.

The DSRM seeks to present a process model for doing DSR comprising six steps: (1) problem identification and motivation, (2) the definition of the objectives for a solution, (3) design and development, (4) demonstration, (5) evaluation, and (6) communication (Mullarkey & Hevner, 2019; Peffers *et al.*, 2007; Sein & Rossi, 2019). The method follows a stage-gate perspective in solving the problem (Sein & Rossi, 2019).

On the contrary, Action Design Research follows a nested loops approach comprising the building, intervention, and evaluation process. Developing and understanding the artefact evolves through a series of trials and their evaluation (Sein & Rossi, 2019).

The Design Science Research methodology can be entered at four different entry points: problem centred, objective centred, development centred, and observation centred (Mullarkey & Hevner, 2019; Peffers *et al.*, 2007; Sein & Rossi, 2019). In contrast, the essence of the ADR is that it always starts with a problem, hence a single entry point (Sein & Rossi, 2019).

The current research utilised the ADR method elaborated by Mullarkey and Hevner (2019) and incorporated Sein and Rossi's views (2019). The method is preferable to the DSRM because it allows iterative nested loops and incorporates intervention at each stage of the process. This research was entered at the problem diagnosis stage, which is the essence of ADR (Sein & Rossi, 2019). Section 3.4 discusses the details of the ADR and elaborated Action Design Research (eADR).

3.4 Action Design Research (ADR) and elaborated Action Design Research (eADR)

Action Design Research provides a structure that combines AR and DR principles (Mullarkey & Hevner, 2019; Sein *et al.*, 2011). Therefore, ADR generates design knowledge through creating new and innovative artefacts that address required organisational intervention (Mullarkey & Hevner, 2019; Sein *et al.*, 2011).

Action Design Research eliminates the sequential approach of intervening and evaluating through interweaving these processes into an integrated process. The original ADR by Sein *et al.* (2011) has four stages: (1) problem formulation; (2) building, intervention, and evaluation; (3) reflection and learning; and (4) formulation of learning (Mullarkey & Hevner, 2019), as presented in Figure 9.

Although ADR presented by Sein *et al.* (2011) significantly contributed to the DSR methods, Mullarkey and Hevner (2019) elaborated this method to enhance effective execution of each intervention cycle and "make more explicit the knowledge generation of ADR". Accordingly, this made the method more accessible to researchers (Sein & Rossi, 2019).

Mullarkey and Hevner (2019) elaborated the ADR by including iterative cycles that cater for early artefacts realisation in research (Sein & Rossi, 2019). These early artefacts include: "defining concepts, system requirements, problem and solution models, design principles, and design features" (Mullarkey & Hevner, 2019; Sein & Rossi, 2019). The four distinct cycles in eADR are (1) diagnosis, (2) design, (3) implementation, and (4) evolution, presented in Figure 10. Each cycle comprises five activities: problem formulation, artefact creation, evaluation, reflection, and learning (Mullarkey & Hevner, 2019).

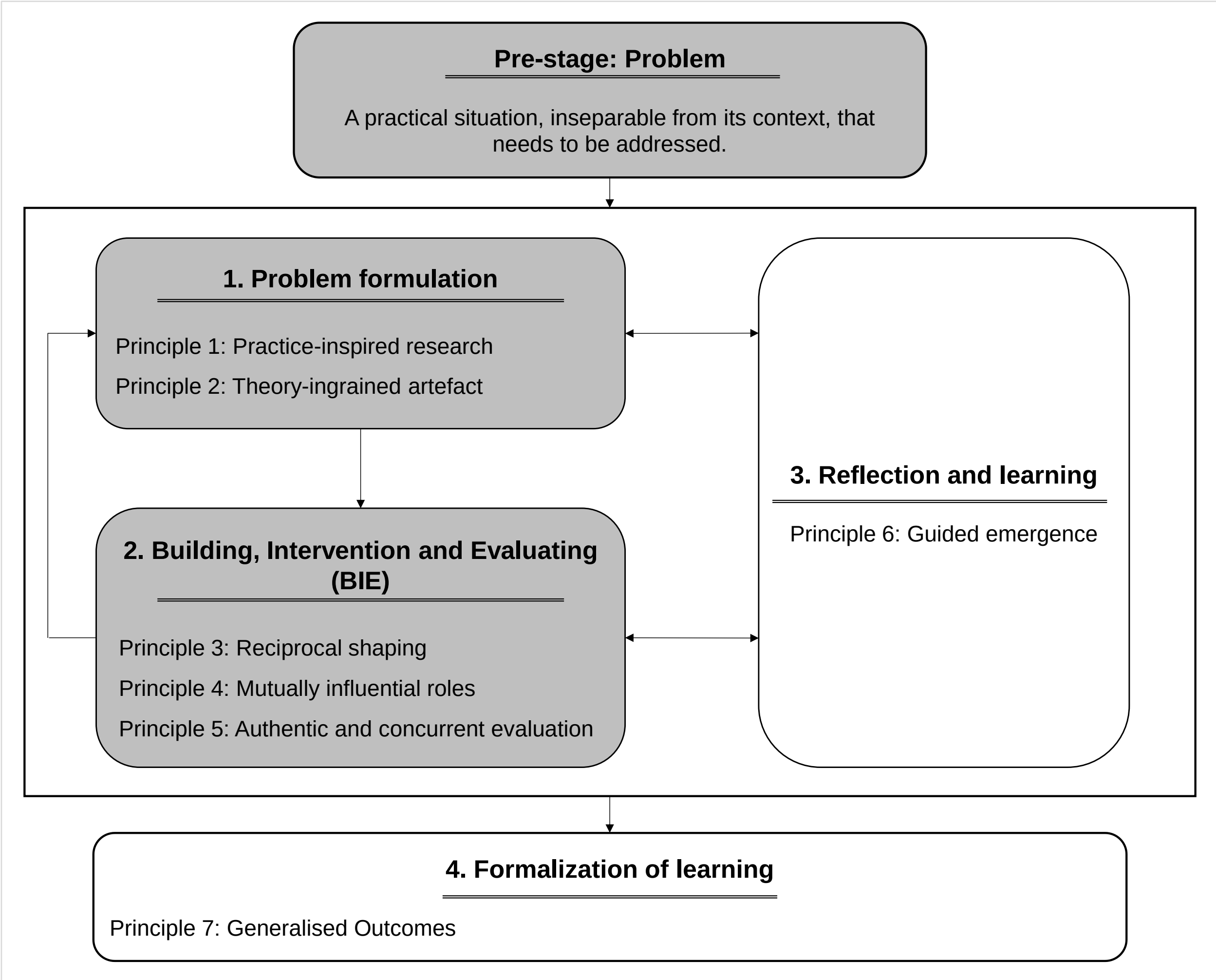

Figure 9: Action Design Research stages and principles – adapted from Petersson and Lundberg (2016); Sein *et al*., (2011)

Mullarkey and Hevner (2019) expanded the problem formulation (Figure 9) in the ADR to problem diagnosis (Figure 10). The diagnosis stage in eADR involves identifying the problem and investigating the importance of the problem. The diagnosis stage also performs an investigation on the relevance of the artefact to be developed. Sein and Rossi (2019) supported the elaboration of the ADR first stage and pointed out that problem diagnosing facilitates successful problem-solving. Problem diagnosis allows the researcher and practitioner to initiate ADR together (Mullarkey & Hevner, 2019).

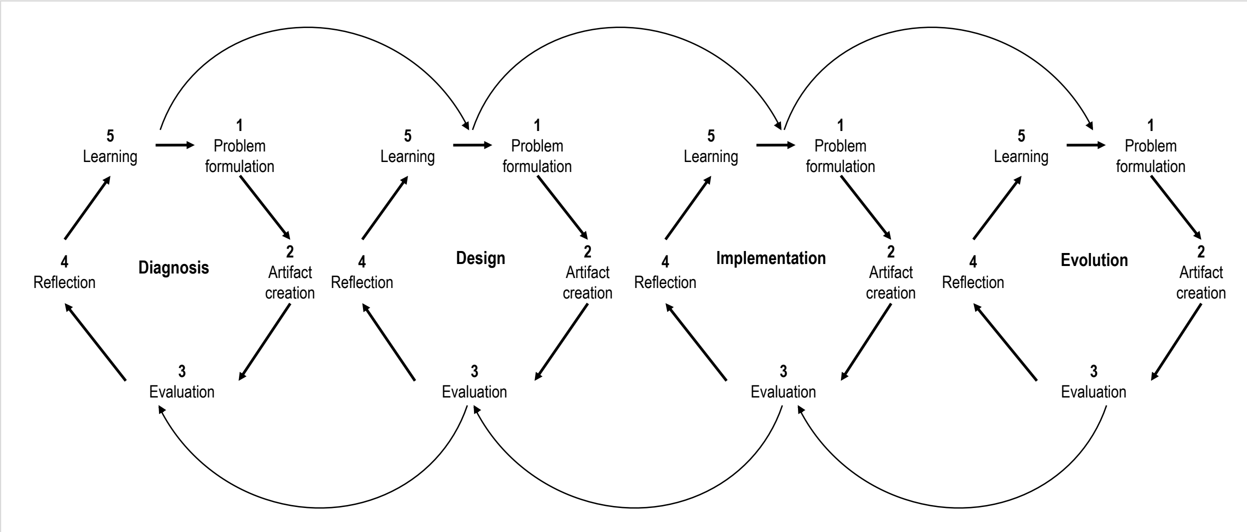

Figure 10: Elaborate Action Design Science cycles (Mullarkey & Hevner, 2019)

Sein *et al.*’s (2011) building, intervention and evaluation (BIE) cycle allows close integration of artefact build and evaluation in context (Mullarkey & Hevner, 2019). However, the BIE cycle was not explicitly elaborated, leaving interpretation to the researcher, making ADR challenging to apply in research (Sein & Rossi, 2019). Mullarkey and Hevner (2019) elaborated on ADR by pointing out that intervention is a core concept and must be inherent in each cycle of ADR. Each intervention cycle comprises five steps: (1) problem formulation, (2) artefact creation, (3) evaluation, (4) reflection, and (5) learning, as depicted in Figure 10. Thus, in addition to the seven principles of ADR pointed out in Figure 9, Mullarkey and Hevner (2019) included abstraction, which allows the development of early artefacts at different levels in the problem environment

The design stage in the eADR involves identifying and conceptualising the artefact (Mullarkey & Hevner, 2019). The set of activities in the design stage are focused on producing possible design solutions that address the problems identified in the diagnosis stage. The design process can go through iterations until a suitable design is identified (Mullarkey & Hevner, 2019). The eADR's unpacked stages that allow formalisation of learning at every stage is a distinct feature of this method (Sein & Rossi, 2019). Therefore, eADR could make a significant contribution to knowledge before completing all the process stages.

3.5 Research design

The research sought to solve the problem of the lack of I4.0 competency reference models, which could align industry competency requirements and skills development. The research utilised eADR, a research method within the DSR paradigm. The development of the I4.0CMM focused on eADR stage 1 (diagnosis), and stage 2 (design) of Mullarkey and Hevner's (2019) eADR stages, as applied by Coetzee (2019).

3.5.1 Research design overview

Figure 11 presents the research design overview discussed in sections 3.5.2 and 3.5.3, respectively. The findings of each iteration within the study are formalised in a research paper.

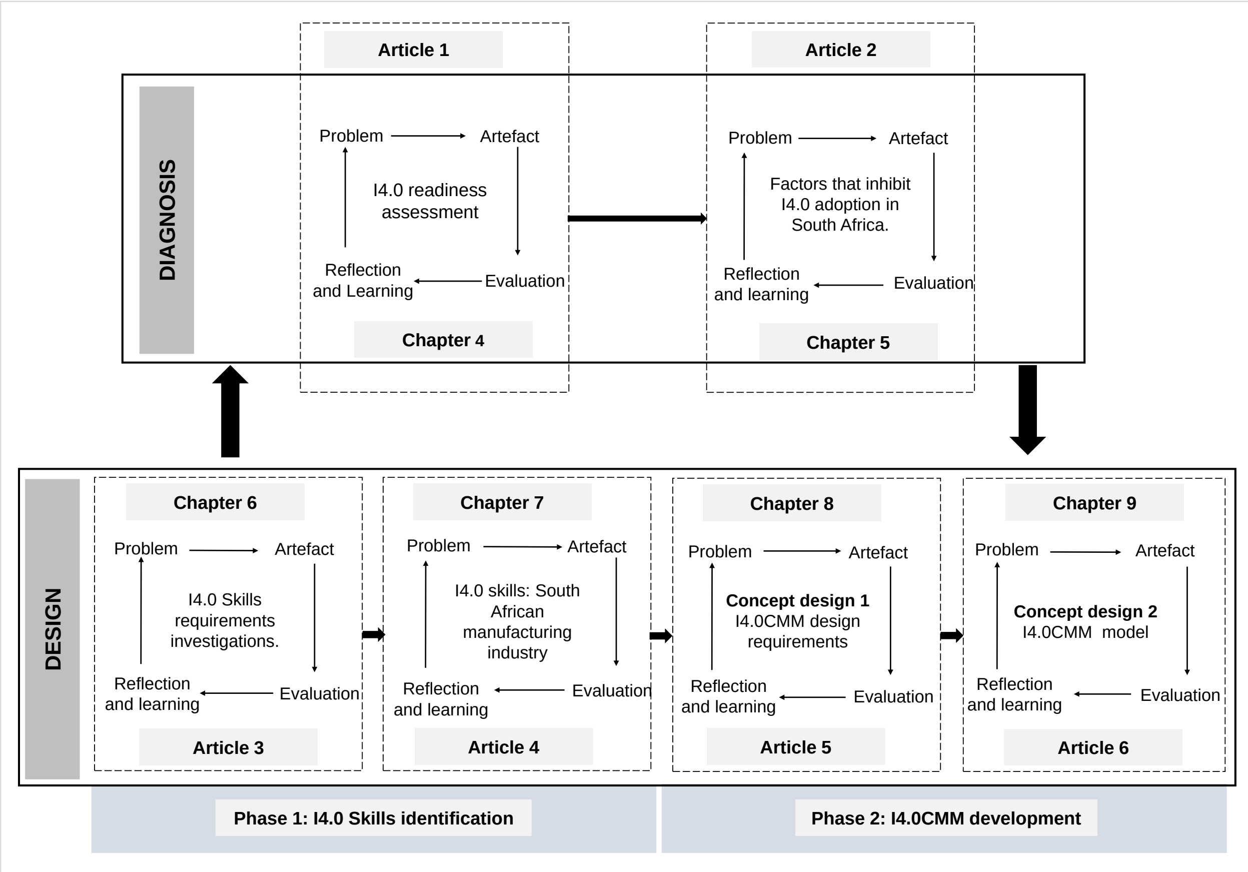

Figure 11: Research design overview – adapted from Mullarkey and Hevner (2019) as applied by Coetzee (2019)

The approach followed in this research was to first diagnose the problem through conducting empirical studies on I4.0 readiness assessment (Article 1) and factors that inhibit I4.0 adoption in South Africa (Article 2).

Subsequently, the design stage was initiated by identifying I4.0 skills requirements (represented as phase 1 in Figure 11). Design stage phase 1 included a systematic literature review to investigate I4.0 skills requirements (Article 3) and an empirical study focusing on I4.0 skills in the South African manufacturing industry (Article 4). Design stage phase 2 focused on developing the I4.0CMM. Design stage phase 2 involved the establishment of design requirements and conducting a gap analysis (Article 5) and developing the I4.0CMM using the example of industrial engineering capability functions (Article 6).

3.5.2 Diagnosis stage

The problem diagnosis stage aimed to formulate further and validate an I4.0 research problem relevant to the South African context. The stage comprises two iterations presented in separate research articles. Each iteration in the diagnosis stage is explained in Table 5 by means of: problem solved, the artefact that was created, the evaluation method used, and reflection and learning formalisation.

Table 5: Diagnosis stage overview

	Chapter 4 – Article 1	**Chapter 5 – Article 2**
Title	Industry 4.0 readiness assessment for South African industries.	Factors that inhibit sustainable adoption of Industry 4.0 in the South African manufacturing industry.
Problem	There was "uncertainty about the preparedness of businesses and industries in developing countries, including South Africa, to adopt Industry 4.0".	There was increased empirical research on barriers and drivers to I4.0 adoption in specific country contexts with no similar studies available that focus on the South African manufacturing industry.
Artefact	Industry 4.0 readiness level indicators for the South African industries.	Thematic documentation of factors that inhibit sustainable adoption of I4.0 in the South African manufacturing industry.
Evaluation	An empirical study was performed using a questionnaire instrument with quantitative criteria. The study evaluated participants' opinions on "organizations' readiness to embrace I4.0 across six readiness dimensions: organizational strategy, infrastructure, operations, products, data-driven services, and employees' skills availability”.	A qualitative empirical study was conducted with participants from various industries. The study “probed the views and opinions of 16 managers and specialists in the industry, as well as others in supportive roles”.
Learning	Article 1 formalised the knowledge contribution and the learning in this iteration.	Article 2 formalised the knowledge contribution and the learning factors that inhibit sustainable adoption of I4.0 in South Africa.

3.5.3 Design stage

The design stage comprised two phases: I4.0 skills identification and I4.0CMM development. Section 3.5.3.1 presents the I4.0 skills identification phase while 3.5.3.2 outlines the I4.0CMM development phase.

3.5.3.1 I4.0 skills identification phase

Phase 1 in the design stage focused on identifying skills requirements and skills development approaches. The process comprised two studies: a systematic literature review of I4.0 skills requirements and an empirical study on I4.0 skills requirements in the South African manufacturing industry. Table 6 summarises the problem solved, the artefact that was created, the evaluation method used, and reflection and learning formalisation in each study.

Table 6: Design stage – phase 1

	Chapter 6 – Article 3	**Chapter 7 – Article 4**
Title	An Investigation of Industry 4.0 skills requirements.	Industry 4.0 skills: A perspective of the South African manufacturing industry.
Problem	Engineering skills requirements evolved with industrial revolutions, and the definitions of I4.0 skills requirements and development were blurry.	Industry 4.0 (I4.0) was relatively new in the South African manufacturing industry and limited empirical research has been done on I4.0 skills requirements and skills development in the South African manufacturing industry.
Artefact	Industry 4.0 skills requirements and skills development framework.	A thematic documentation of the impact of I4.0, I4.0 skills requirements and I4.0 skills development in the South African manufacturing industry.
Evaluation	Investigated I4.0 skills requirements and approaches to developing these skills through a systematic literature review.	A qualitative empirical study was performed with professionals and experts practising in South Africa. The study evaluated the impact of I4.0 on jobs and skills, critical I4.0 skills required, and the strategies organisations are implementing to mitigate the impact of I4.0 on jobs and skills requirements in the South African manufacturing industry.
Learning	Article 3 formalised the learning on I4.0 skills requirements and approaches to developing I4.0 skills.	Article 4 formalised the knowledge contribution and the learning on the perspective of the South African manufacturing industry on I4.0 skills.

3.5.3.2 I4.0CMM development phase

The design stage phase 2 involved development of the I4.0CMM which followed the process of formulating and validating the design requirements and conducting a gap analysis (Article 5) and developing and refining the I4.0CMM structure through the Delphi technique (Article 6). Table 7 presents an overview of the problem model design process:

Table 7: Design stage – phase 2

	Chapter 8 – Article 5	**Chapter 9 – Article 6**
Title	Industry 4.0 Competence Maturity Model design requirements: A Systematic Mapping Review.	Development of an Industry 4.0 Competency Maturity Model.
Problem	There was no predefined design requirement that could direct the development of an I4.0CMM useful for both industry and academia.	The gap analysis conducted revealed a deficiency in the available I4.0 competency models and frameworks in meeting the design requirements.
Artefact	I4.0CMM design requirements	Industry 4.0 competency maturity model (I4.0CMM).
Evaluation	The formulated design requirements were evaluated and validated by practising experts through the Delphi technique in Chapter 9.	The Delphi technique was applied in the verification and refinement of the I4.0CMM structure. Experts reached consensus on the sufficiency of I4.0CMM structure in two iterations. The use of the I4.0CMM is illustrated using industrial engineering capability functions.
Learning	Article 5 presented the initial design requirements and the refined design requirements are presented in Chapter 9 Article 6.	Article 6 formalised the model structure verification and refinement

3.6 Conclusion

The present chapter presented a summary of the process followed and how the study utilised eADR in the development of an Industry 4.0 competency maturity model. The details of each stage are presented in the subsequent chapters.

CHAPTER 4

INDUSTRY 4.0 READINESS ASSESSMENT FOR SOUTH AFRICAN INDUSTRIES

4.1 Introduction

Following the study initiation, this chapter introduces the diagnosis phase of this study (Figure 12) by performing an I4.0 readiness assessment for South African industries.

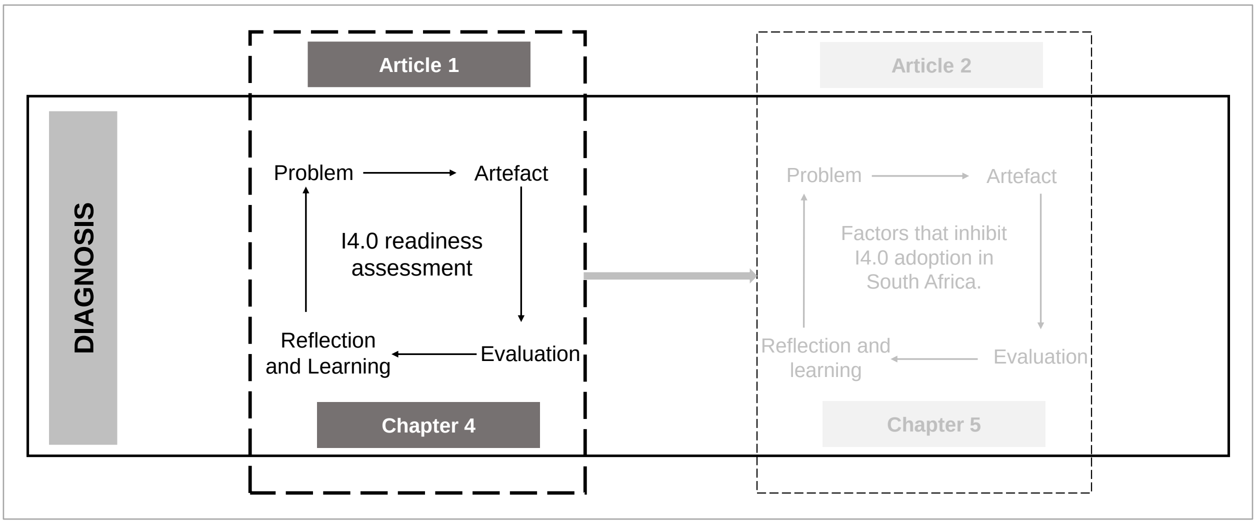

Figure 12: Problem diagnosis step one

This chapter addresses research objective 1: to assess I4.0 readiness for South African industries, presented as Article 1. The study revealed that a significant number of organisations in South Africa are either at the emerging level or developing level regarding adopting Industry 4.0. However, the results are skewed to the Gauteng province because it is the epicentre of economic activities in South Africa (Statistics South Africa, 2019a). The results further revealed that South African industry faces significant infrastructure challenges with regard to I4.0 and a lack of commitment to drive I4.0 initiatives. Industry 4.0 skills exist in pockets; thus, the study recommended further investigation in more detail regarding I4.0 skills requirements.

The chapter is organised as follows: section 4.2 presents Article 1 cover page, and section 4.3 concludes the chapter. Appendix A presents Article 1 in full.

4.2 Article 1 cover page

South African Journal of Industrial Engineering November 2019 Vol 30(3) Special Edition, pp 134-148

INDUSTRY 4.0 READINESS ASSESSMENT FOR SOUTH AFRICAN INDUSTRIES

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ABSTRACT

Technological advancements related to the fourth industrial revolution are causing disruptive changes that are widely felt at national, industry, and company level. Industry 4.0, an initiative driving the fourth industrial revolution, is happening at an exponential speed, and embracing and adopting it is unavoidable for survival and competiveness. Although noticeable progress has been made in the use of Industry 4.0 technologies, systems, and processes in developed countries, there is uncertainty about the preparedness of businesses and industries in developing countries, including South Africa, to adopt Industry 4.0. The purpose of this research paper is to explore the readiness of South African industry in this regard. A questionnaire instrument with quantitative criteria compiled by the Impulse Foundation of Verband Deutscher Maschinen- und Anlagenbau was used in this study. The exploratory study revealed that South African industry is faced with significant challenges in Industry 4.0 strategy formulation and equipment infrastructure to support Industry 4.0 requirements. The assessment pointed out that Industry 4.0 skills exist in pockets in South Africa, and so a further study to reveal more detail on Industry 4.0 skills requirements is essential.

OPSOMMING

Tegnologiese ontwikkelings met betrekking tot die vierde industriële rewolusie veroorsaak verreikende ontwrigtende verandering op nasionale, industrie-, en besigheidsvlak. Industrie 4.0, 'n inisiatief wat die Vierde Industriële Rewolusie aanvuur, geskied teen eksponensiële spoed en dit is noodsaaklik om dit te aanvaar en toe te pas, met die oog op oorlewing en mededingendheid. Alhoewel daar beduidende vordering is met betrekking tot die implementering van Industrie 4.0 in ontwikkelde lande, is daar onsekerheid oor die gereedheid van ontwikkelende lande, insluitend Suid-Afrika, om Industrie 4.0 te implementeer. Die doel van hierdie artikel is om die gereedheid van Suid-Afrikaanse industrieë in hierdie opsig te verken. 'n Vraelys-instrument met kwantitatiewe kriteria wat deur die Impulse Foundation van Verband Deutscher Maschinen- und Anlagenbau saamgestel is, is in hierdie studie gebruik. Die verkennende studie het getoon dat die Suid-Afrikaanse industrie beduidende uitdagings in die gesig staar wat betref strategieformulering en toerustinginfrastruktuur om Industie 4.0-eise te bevredig. Die ondersoek het getoon dat Industrie 4.0-vaardighede in geïsoleerde situasies in Suid-Afrika bestaan, en daarom is verdere studie om meer oor die vereistes vir Industrie 4.0-vaardighede te wete te kom, dringend nodig.

1 INTRODUCTION

The era of Industry 4.0 is upon us, and alignment with its requirements is inevitable for survival and competitiveness. Industry 4.0 is happening at an exponential rate, and facilitating its successful

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4.3 Conclusion

The chapter presented an empirical study that assessed the readiness of South African industries to adopt I4.0. Although the study pointed out challenging areas faced by South African industries in adopting I4.0, there was no focus on the barriers to sustainable adoption of I4.0 in South African industries. Therefore, Chapter 5 presents an empirical qualitative study investigating the inhibitors to sustainable I4.0, focusing on the South African manufacturing industry.

CHAPTER 5

FACTORS THAT INHIBIT SUSTAINABLE ADOPTION OF INDUSTRY 4.0 IN THE SOUTH AFRICAN MANUFACTURING INDUSTRY

5.1 Introduction

The current chapter presents an investigation of factors that inhibit sustainable adoption of I4.0 in the South African manufacturing industry and forms part of the research's problem diagnosis phase (Figure 13).

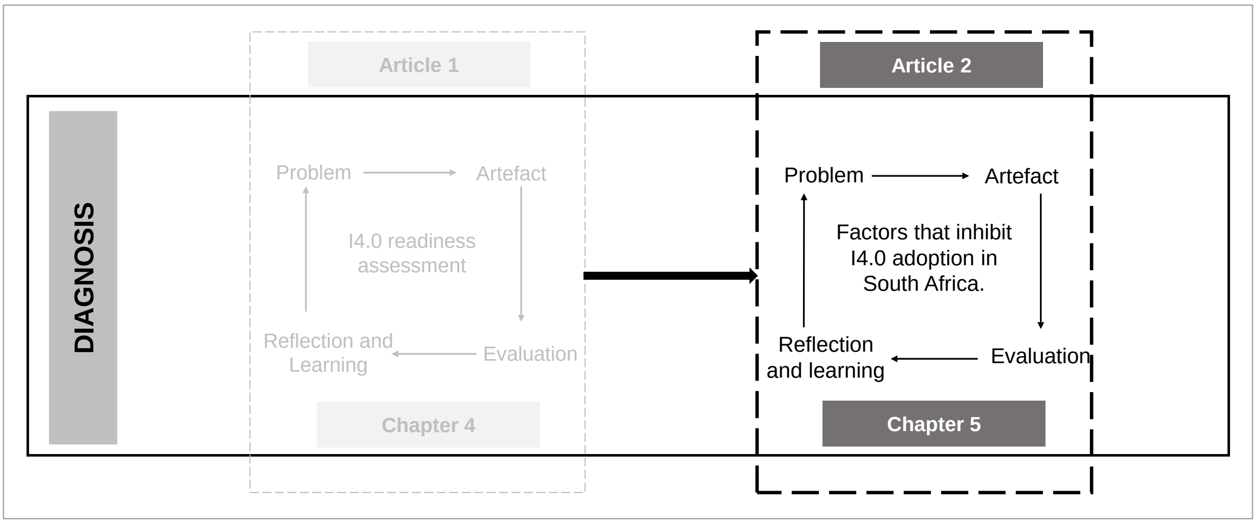

Figure 13: Problem diagnosis step two

The current chapter seeks to answer research objective 2: explore factors that inhibit and that could enhance sustainable adoption of I4.0 in the South African manufacturing industry, presented as Article 2. The study revealed a significant number of factors, including noticeable youth unemployment, social structural inequalities, a critical shortage of I4.0 skills, inadequate alignment between skills development and skills requirements and the potential negative impact of I4.0 on low-skilled and semi-skilled jobs. Furthermore, the study revealed strategies to promote I4.0 adoption in the South African manufacturing industry, such as enhancing skills development, and the selection of technologies and initiatives that enhance human capability and productivity. The study accentuates that sustainable adoption of I4.0 goes beyond the development of technological capabilities but also needs to consider social-economic aspects

The chapter presents Article 2 cover page in section 5.2, and the chapter conclusion in section 5.3. Article 2 full paper is presented in Appendix B.

5.2 Article 2 cover page

sustainability

MDPI

Article

Factors that Inhibit Sustainable Adoption of Industry 4.0 in the South African Manufacturing Industry

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Abstract: Industry 4.0 (I4.0) adoption in the manufacturing industry is on the rise across the world, resulting in increased empirical research on barriers and drivers to I4.0 adoption in specific country contexts. However, no similar studies are available that focus on the South African manufacturing industry. Our small-scale interview-based qualitative descriptive study aimed at identifying factors that may inhibit sustainable adoption of I4.0 in the country's manufacturing industry. The study probed the views and opinions of 16 managers and specialists in the industry, as well as others in supportive roles. Two themes emerged from the thematic analysis: factors that inhibit sustainable adoption of I4.0 and strategies that promote I4.0 adoption in the South African manufacturing industry. The interviews highlighted cultural construct, structural inequalities, noticeable youth unemployment, fragmented task environment, and deficiencies in the education system as key inhibitors. Key strategies identified to promote sustainable adoption of I4.0 include understanding context and applying relevant technologies, strengthening policy and regulatory space, overhauling the education system, and focusing on primary manufacturing. The study offers direction for broader investigations of the specific inhibitors to sustainable I4.0 adoption in the sub-Saharan African developing countries and the strategies for overcoming them.

Keywords: Industry 4.0; sustainability; manufacturing industry; South Africa; technology adoption drivers; technology adoption barriers; qualitative descriptive study

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1. Introduction

Adoption of Industry 4.0 (I4.0) has been on the rise in developed countries' manufacturing industries, with other developing countries, such as China and India, following suit. The term I4.0 was coined in Germany in 2011, and its principles were adopted to enhance the competitiveness and growth of the national manufacturing industry [1–3]. The subsequent wide-ranging adoption of this approach recognizes it as an enhancer of competitiveness and growth in the manufacturing industry [4,5].

Although acknowledged globally, the adoption of I4.0 in South Africa has not been analyzed in the literature. Its many benefits in the country could include enhancing global competitiveness and boosting productivity and revenue growth of the manufacturing industry [4,5]. The adoption of I4.0 therefore attracts significant interest from sectors related to and supporting the manufacturing industry, including the digital industry, public sector, research and development, and non-governmental organizations (NGOs). However, the adoption of I4.0 also has the potential of widening global inequality among and within countries, and could hinder the achievement of the United Nations 2015 sustainable development goals (SDGs) [6]. In particular, I4.0 could detrimentally affect the achievement of SDG 8 (the promotion of sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all), SDG 9 (inclusive and sustainable industrialization), and SDG 10 (reduction of inequality within and among countries) [7] in developing countries [8].

5.3 Conclusion

The chapter presented an exploratory qualitative study to identify factors that could inhibit the sustainable adoption of I4.0 in the South Africa manufacturing industry. Shortage of I4.0 skills and inadequate alignment between skills development and skills requirements were identified to significantly inhibit the country's sustainable development of I4.0 in the country. Therefore, this leads to the design stage, which resumes, in Chapter 6, by identifying I4.0 skills requirements.

CHAPTER 6

AN INVESTIGATION OF INDUSTRY 4.0 SKILLS REQUIREMENTS

6.1 Introduction

The design phase comprises phase 1 – Industry 4.0 (I4.0) skills identification and phase 2 – Industry 4.0 competency maturity model (4.0CMM) development, which responds to the findings of Article 1 (Chapter 4) and Article 2 (Chapter 5). Chapter 6 presents an investigation on I4.0 skills requirements (Figure 14).

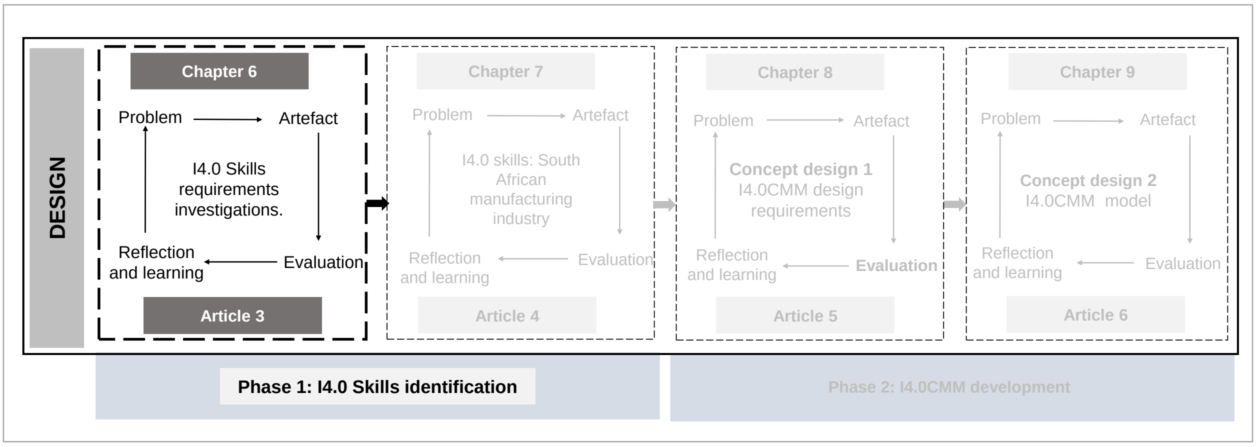

Figure 14: Design stage – step one of phase 1

This chapter addresses research objective 3: to investigate I4.0 skills requirements and development approaches, presented as Article 3. The article documented skills requirements and possible skills development approaches. The findings from the investigation revealed that non-technical skills, such as emotional intelligence, lifelong learning, innovation, and critical thinking, are regarded as equally important in I4.0. Furthermore, the South African social and economic issues ideally require cross-pollination and collaboration between technical and academic institutes to address skills challenges in the country. The study recommended further research on developing frameworks that could assist in bridging the gap between skills requirements and skills development.

The chapter is organised as follows: section 6.2 presents Article 3 cover page, and section 6.3 concludes the chapter. Appendix C presents Article 3 in full.

6.2 Article 3 cover page

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AN INVESTIGATION OF INDUSTRY 4.0 SKILLS REQUIREMENTS

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ABSTRACT

The Industry 4.0 wave is built on technological advancement that is bringing about significant change. The impact of Industry 4.0 is being felt across all industries, including the education sector. During the 2019 State of the Nation address, the President of South Africa pointed out that the government was seeking to respond to the change in skills requirements. In this paper, a systematic literature review will be performed to investigate Industry 4.0 skills requirements in the engineering profession and the role of capability development in meeting Industry 4.0 requirements. An exploration of the impact of Industry 4.0 on technical institutions as opposed to academic institutions will also be discussed. This paper incorporates this exploratory investigation into detailed research on developing a skills development framework that seeks to bridge the gap between Industry 4.0 skills requirements and development in South Africa.

OPSOMMING

Die verskynsel van Industrie 4.0 word gedryf deur tegnologiese vordering wat beduidende verandering teweegbring. Die impak van Industrie 4.0 is oor alle industrieë waarneembaar, insluitend die onderwyssektor. Gedurende die 2019-staatsrede het die President van Suid-Afrika daarop gewys dat die regering poog om die verandering in vereistes vir vaardighede te hanteer. In hierdie artikel word 'n sistematiese literatuuroorsig uitgevoer om vas te stel wat die vereistes is vir Industrie 4.0-vaardighede in die ingenieursprofessie asook die rol van vaardigheidsontwikkeling om aan Industrie 4.0-vereistes te voldoen. 'n Ondersoek na die impak van Industrie 4.0 op tegniese instellings in teenstelling met akademiese instellings word ook bespreek. Hierdie werkstuk inkorporeer hierdie verkennende ondersoek in gedetailleerde navorsing oor 'n vaardigheidsontwikkelingstruktuur wat ten doel het om die gaping tussen vereistes vir vaardighede vir Industrie 4.0 en ontwikkeling in Suid-Afrika te oorbrug.

1 INTRODUCTION

According to historians, human civilisation has, to date, undergone three industrial revolutions: the first industrial revolution (mechanisation), the second industrial revolution (mass production and electricity), and the third industrial revolution (automation) [1, 2]. These revolutions not only influenced production and business models: they also affected the skills required by future employees in various industries [3]. From one industrial revolution to the next, some jobs disappeared while others were created. More importantly, some skills became redundant while others became valuable. The upcoming fourth industrial revolution is no exception with regard to the replacement of jobs and skills. Industry 4.0, an acknowledged initiative driving the fourth industrial revolution, is characterised by significant technological advancement that requires a specialised and skilled workforce [3].

6.3 Conclusion

Chapter 6 presented a systematic literature review in investigating I4.0 skills requirements and skills development. Although the study documented the I4.0 technical and non-technical skills requirements, the study was not located within a specific environment. Therefore, Chapter 7 presents an investigation concerning a specific environment: the South African manufacturing industry.

CHAPTER 7

CONCEPT DESIGN 1: INDUSTRY 4.0 SKILLS EMPIRICAL STUDY

7.1 Introduction

The broader view of I4.0 skills requirement and development approaches was presented in Chapter 6. Chapter 7 seeks to complement this work by presenting an empirical investigation of I4.0 skills requirements within the context of the South African manufacturing industry context, presented as research Article 4 (Figure 15).

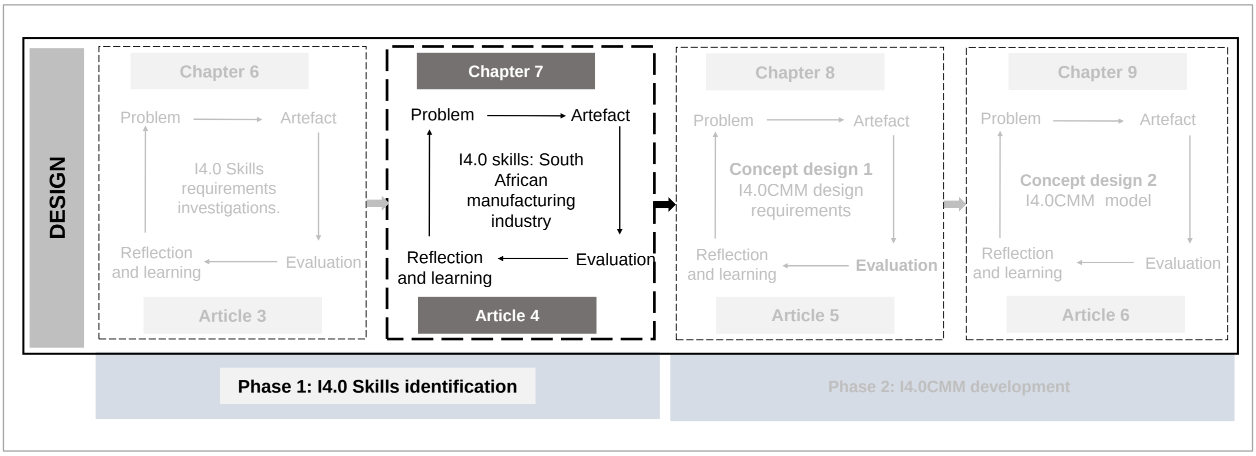

Figure 15: Design stage – step two of phase 1

The current chapter seeks to answer research objective 4: to identify I4.0 skills requirements in the South African manufacturing industry, presented as Article 4. The study applied qualitative descriptive analysis research design and presented thematic documentation of the impact of I4.0, skills requirements, and skills development in I4.0. The study revealed that soft skills (non-technical skills) are equally important as technical skills. I4.0 demands higher skills than those associated with conventional manufacturing. Consequently, the focus should be on skills development through upskilling, reskilling and experiential training. The study set the stage for developing an I4.0CMM that simultaneously guides and assesses I4.0 competency development and industry competency requirements within the South African context

The chapter presents Article 4 in section 7.2 and the chapter conclusion in in section 7.3. Appendix D presents Article 4 in full.

7.2 Article 4 cover page

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AOSIS

Page 1 of 9 Original Research

Industry 4.0 skills: A perspective of the South African manufacturing industry

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Orientation: Industry 4.0 (I4.0) is causing significant changes in the manufacturing industry, and its adoption is unavoidable for competitiveness and productivity.

Research purpose: This study investigated I4.0 skills using the views of professionals in the manufacturing industry and experts in digital transformation practising in South Africa.

Motivation for the study: I4.0 was coined originally for the manufacturing industry, and skills availability significantly influences its successful adoption. Furthermore, I4.0 is relatively new in the South African manufacturing industry, and there is still limited empirical research on the subject.

Research approach/design and method: A qualitative descriptive research design was used, and participants were enrolled using purposeful sampling via email, telephone and LinkedIn. Twenty semi-structured interviews were conducted face-to-face or telephonically, and thematic analysis was used to analyse the data.

Main findings: This study found that I4.0 demands higher skills than in conventional manufacturing, and companies should take the lead in facilitating upskilling and reskilling of their employees to preserve jobs. Experiential training could enhance I4.0 skills development in the manufacturing industry.

Practical/managerial implications: Agile changes in I4.0 require constant re-alignment of employees' skills in the manufacturing industry. This requires companies to make the human resource (HR) management function an integral part of business strategy.

Contribution/value-add: The study can help HR practitioners and manufacturing professionals in strategising and innovate technology to manage the evolving I4.0 skills requirements and preserve jobs. The study also asserts a foundation for further investigation of I4.0 skills competencies' development in the South African manufacturing industry.

Keywords: Industry 4.0; industrial revolution; manufacturing industry; skills sets; competencies; experiential training; human resource management; South Africa.

Introduction

The progression in industrial revolution has resulted in an incremental change in job complexity and skills requirements (Selamat, Alias, Hikmi, Puteh, & Tapsi, 2017). Industry 4.0 (I4.0), a Fourth Industrial Revolution initiative, is transforming the manufacturing industry into a more competitive environment in various ways that include the skills mix, attitudes and experiences required in the workforce (Baker, 2016; Gehrke et al., 2015; World Economic Forum, 2016). Skills requirements and skills development are amongst the factors that significantly influence successful adoption of I4.0 (Hartmann & Bovenschulte, 2013; Maisiri & Van Dyk, 2019). Thus, human resources (HR) and its management become vital in manufacturing companies (Paine, 2009).

The South African manufacturing industry makes a noticeable contribution to the country's economy (Republic of South Africa, 2018a, 2018b), and the adoption of I4.0 principles and technologies is unavoidable for survival and competitiveness. The South African manufacturing industry is currently characterised by significant numbers of unskilled and semi-skilled workers (MerSETA, 2018). Thus, the impact of I4.0 on skills requirements cannot be ignored and calls for an investigation.

In a recent study, Dhanpat, Buthelezi, Joe, Maphela and Shongwe (2020) considered HR professionals' roles in I4.0. Their study presented the skills required by HR professionals in I4.0 using the views of practising HR professionals (Dhanpat et al., 2020). This study complements

7.3 Conclusion

The chapter presented a qualitative descriptive analysis of the I4.0 skills requirements using the South African manufacturing industry context (Article 4). The chapter further pointed out the significance of I4.0 skills development both in industry and skills development institutions. The study led to the development of an I4.0CMM that simultaneously guides and assesses I4.0 competency development and industry competency requirements within the South African context, to be considered in Chapter 8.

CHAPTER 8

CONCEPT DESIGN 2: INDUSTRY 4.0 COMPETENCY MATURITY MODEL DESIGN REQUIREMENTS

8.1 Introduction

The design stage phase 2 resumes by establishing the Industry 4.0 competency maturity model (I4.0CMM) design requirements and performing a systematic mapping review gap analysis. Figure 16 shows the current step in the development of an I4.0CMM. The current chapter seeks to fulfil research objective 5: to establish the design requirements for an I4.0CMM and perform an I4.0 competency model gap analysis.

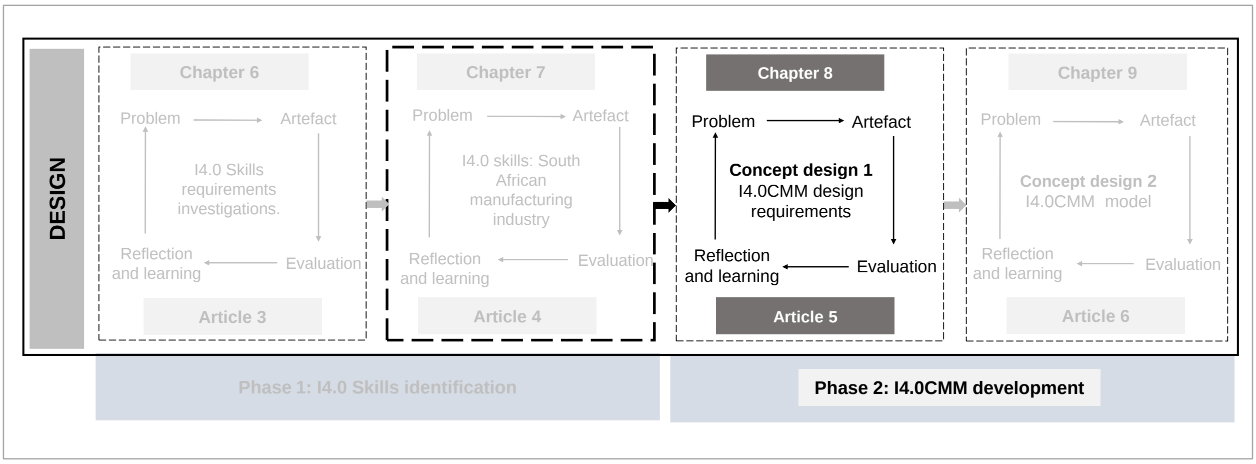

Figure 16: Design stage – step 1 of phase 2

In Chapter 1, a competency maturity model is defined as a reference model that provides a holistic view of a person's competencies (knowledge, skills and abilities) required to perform a specific job function (El-Baz & Zualkernan, 2011) and enables tracking the competencies' evolution over time. The scope of this definition differs from other competency maturity models existing in the literature, such as Von Rosing and Von Scheel's competency maturity model wheel. The competency maturity model wheel provides a holistic view of all significant organisational business and technical capabilities and resources (Von Rosing & Von Scheel, 2012). Contrary to this, the I4.0CMM focuses on employee-level competencies, similar to the employee competency maturity model (ECMM) presented by El-Baz & Zualkernan, 2011).

The I4.0CMM model was developed on the basis of the competency maturity model definition provided in Chapter 1. The I4.0CMM seeks to provide a reference model that provides competency evolutionary stages and competency levels for acquiring knowledge up to the expert level. Furthermore, the I4.0CMM should describe the competencies of individuals pursuing education or training in different engineering professions. Therefore, the I4.0CMM incorporates the maturity and competency models' principles as discussed in sections 8.2 and section 8.3. Article 5 cover page is presented in section 8.4, followed by the chapter conclusion in section 8.5. Article 5 full paper is presented in Appendix E.

8.2 Maturity models

The Capability Maturity Model (CMM) developed by the Software Engineering Institute of Carnegie Mellon University served as a pacesetter and triggered the development of various maturity levels (Mettler, 2011; Titov *et al.*, 2016; Van Dyk, 2013). There is significant adoption of CMM in various models that assist organisations in improving their capabilities (Titov *et al.*, 2016). The current section gives an overview of the literature on maturity models.

8.2.1 Maturity definition

According to the Oxford English Dictionary, maturity refers to "the state of being fully grown or developed". Becker *et al.* (2010) pointed out that maturity is "a measure to evaluate the capabilities of an organisation in regard to a certain discipline". Maturity systems increase capability with time towards the achievement of the desired future state. Schumacher *et al.* (2016) emphasise that "maturity can be captured qualitatively or quantitatively in a discrete or continuous manner".

8.2.2 Maturity models

Becker *et al. (*2010) define maturity models as conceptual models that map an evolutionary path towards maturity. Maturity models are utilised in the conceptualisation and measure of an organisation or process' maturity relative to a specific target state (Schumacher *et al.*, 2016). Maturity models thus provide a reference model for assessing actual practices (as-is situations) against the target requirements and derive and prioritise improvement measures (Becker *et al.*, 2009; Becker *et al.*, 2010; Schumacher *et al.*, 2016). Thus, the I4.0CMM assesses the current competency of an individual with reference to the industrial revolutions. Becker *et al.* (2009) viewed maturity models as artefacts "which solve the problems of determining a company's […] capabilities".

A typical maturity model consists of sequential maturity levels for various organisation capabilities (Becker *et al.*, 2009). The maturity levels are well-defined evolutionary plateaus for capability improvement (Essmann & Du Preez, 2009; Zhu, 2017). The evolutional stages are supposed to be distinct and discrete stages that provide a roadmap for improvement, with each stage superior to the previous stage (Becker *et al.*, 2009; Becker *et al.*, 2010). Moving from one maturity stage to the other involves continuous progression regarding capability performance (Becker *et al.*, 2009). Capability Maturity Models' (CMM) five distinct levels (initial, repeatable, defined, managed and optimised) are commonly used and adopted in the development of maturity levels (Becker *et al.*, 2010; Zhu, 2017).

A maturity model consists of domains and dimensions, and this study adopted the definition used by van Dyk (2013):

> *A domain is a sphere of activity, concern or function and represents an angle from which to view the use, consequences and implication of the entity under consideration.*
>
> *Dimension is the measurement of something in a particular direction.*

Three organisational capabilities focus areas that require improvement and can be measured using maturity models (Curtis *et al.*, 2009; Curtis *et al.*, 1995) are: processes, technologies, and people, as presented in Figure 17.

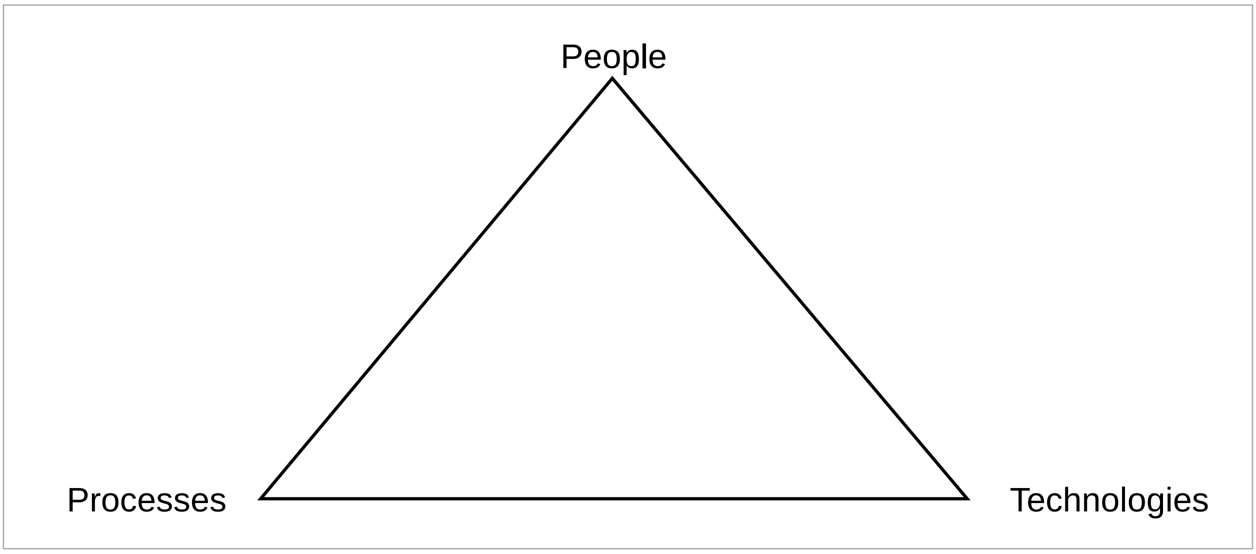

Figure 17: Organisational improvement focus areas (Curtis *et al.*, 2009; Curtis *et al.*, 1995)

Although significant maturity models have focused on processes and technologies, organisations have noticed that continuous improvement requires a significant change in managing and developing their human resources (Curtis *et al.*, 2009). Therefore, specialised maturity models such as the People Capability Maturity Model (PCMM) and Employee Competency Maturity Model (ECMM) that focus on continuous improvement and development of human resources are essential (Curtis *et al.*, 2009; El-Baz & Zualkernan, 2011; Titov *et al.*, 2016).

8.2.3 Classification of maturity models

Maturity models can be classified as (Knight *et al.*, 2013):

- Progression maturity models – they are models that represent simple progression or scaling of an attribute where the movement up the maturity levels indicates some progression.
- Capability maturity model – the measured dimension represents organisational capability around a set of attributes, characteristics, patterns, or practices.
- Hybrid maturity model – this "reflects transitions between levels that are similar to a capability model but architecturally uses the attributes, characteristics, patterns, or practices of a progression model".

The developed I4.0CMM is a hybrid maturity model. The model presents the progression of competency requirements from the first industrial revolution into future requirements. Furthermore, the model comprises the competency level dimension, which relates to the capability maturity models (El-Baz & Zualkernan, 2011).

8.3 Competency models

8.3.1 Definition of competency

Various definitions of competency exist in the literature (El Asame & Wakrim, 2018; Hoffmann, 1999), such as:

> *Competency can be regarded as [a] cluster of knowledge, skills, attitudes, and behaviours any individual must possess to perform a certain task successfully* (Sherman *et al.*, 2007).

> *Competency – knowledge, skills, mindsets, thought patterns, and the like – that when used whether singularly or in various combinations, result in successful performance* (Teodorescu, 2006)

> *Competency is […] more than the mere attainment of skills as it also involves other qualities such as attitudes, motives, personal insightfulness, interpretive ability, receptivity, maturity, and self-assessment* (Axley, 2008)

To have an in-depth understanding of the term competency El Asame and Wakrim (2018) provide characteristics of competencies, including:

- They solve a combination of knowledge, skills, motives, abilities, expertise, traits, values.
- They are associated with a specific performance that ranges from the lowest to the highest proficiency level.
- They depend on the specific context in which individuals or employees apply them.

Therefore, El Asame and Wakrim (2018) defined competency as "a set of personal characteristics (skills, knowledge, attitudes, etc) that a person acquires or needs to acquire, in order to perform an activity inside a certain context with a specific performance level".

The terms competency and competence are commonly interchangeably used in literature (Palan, 2007). However, Teodorescu (2006) distinguished competency from competence by stating that competence refers to a worthy performance that leads directly to the most efficient accomplishment of organisational goals. Competence can be further viewed as describing work tasks presented as job outputs (Palan, 2007).

The standard view in the definitions is that competency involves knowledge, skills, attitudes, and behaviours that enable an individual to perform a specific task successfully. The systematic literature review conducted Maisiri and van Dyk (2020) pointed out significant existing I4.0 models and frameworks based either on the knowledge or skills component of competency

8.3.2 Competency and competence models

Emanating from interchangeably using the terms competency and competence, competency models and competence models are often used as synonyms. The notation is exemplified by Brohman and Parent (2001) when they interchangeably used the terms competence maturity model and competency maturity model as implying the same thing (Brohman & Parent, 2001).

The initial iteration of the development of the Industry 4.0 competency maturity model assumed that competency models and competence models could be used to mean the same thing. Thus, Article 5 presented the model as an Industry 4.0 competence maturity model.

However, further inquiry in the second iteration of the development of the model revealed that competency models and competence models serve different purposes and could not be used as synonyms (Teodorescu, 2006; Teodorescu & Binder, 2004). Table 8 presents the contrast between competency models and competence models concerning focus, outputs and application.

Table 8: Competency Models versus Competence Models (Teodorescu, 2006)

	Competency Model	Competence Model
Focus	Definition of skills, knowledge, attributes, and behaviours that successful people have.	Definition of measurable, specific, and objective milestones describing what people have to accomplish to consistently achieve or exceed the goals for their role, team, division, and whole organisation.
Outputs	A list, graphic, spreadsheet, or interactive program that lists the skills, knowledge, attributes, and desirable behaviours thought to be required for successful performance for a specific job role.	Related tasks, best practices, knowledge and skills versus work results map, environmental support required to build, support and maintain desired performance and competence levels.
Application	Hiring, training and assessment of programs and processes.	Set clear, measurable, and specific expectations about how to produce the results the organisation needs. Measure, track, coach and improve performance.

According to Teodorescu and Binder (2004), competency modelling involves defining the skills, knowledge, and attributes required to succeed in a job. This understanding and the differences in Table 8 motivated the use of the competency model in the second iteration of the model development phase. Therefore, the model developed in this research could be better presented as an Industry 4.0 competency maturity model (Article 6). Competence modelling is beyond the scope of this study since it involves identifying the set of accomplishments individuals produce to achieve their job's mission and business goals (Teodorescu & Binder, 2004).

Sherman *et al.* (2007) viewed competency models as descriptive tools that identify the skills, knowledge, personal characteristics, and behaviours needed to effectively perform a role in an organization. In support, El Asame and Wakrim (2018) identified the competency model as a descriptive tool that identifies the competencies needed to perform a role effectively in the organization and help the business meet its strategic objectives.

Dimensions of a competency model include (El Asame & Wakrim, 2018):

- personal characteristics, namely skills and knowledge where the generic skills apply to a specific domain and act on knowledge;
- a competency level that is used to demonstrate the person's performance; and
- the context in which the individual's competency is applied.

Competency models can be used as a reference framework in designing programs and curricula to meet the educational needs of individuals (Sherman *et al.*, 2007). Furthermore, competency models could be applied as tools to describe the competencies of individuals pursuing education or training in different domains to develop, maintain and evaluate their competencies (El Asame & Wakrim, 2018).

8.4 Article 5 cover page

Industry 4.0 Competence Maturity Model Design Requirements: A Systematic Mapping Review

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***Abstract*—The impact of Industry 4.0 (I4.0) on the manufacturing industry's systems and processes extends to employees' competency requirements. This consequently requires a response in the preparation of graduates who will be ready to practice engineering with professional level technical know-how and soft skills in I4.0. The study focused on developing a conceptual I4.0 competency maturity model (I4.0CMM) and illustrating it using industrial engineering capability functions. Using the systematic mapping review approach, a gap analysis was conducted of design requirements for I4.0 competency models and frameworks in the literature as measured against predefined design requirements of an I4.0CMM. A total of 303 relevant research papers from Scopus, Web of Science online databases, and grey literature were retrieved. Twenty-five papers and documents were included in the study. The results of the review indicated that the predefined design requirements for an I4.0CMM were not all satisfied in literature. Thus, a conceptual I4.0CMM that is aligned to industrial engineering capability functions was developed and is illustrated. The I4.0CMM could be a solution in providing a comprehensive competency assessment framework for industrial engineering practice and education.**

Keywords—Industry 4.0, competency, maturity model, systematic mapping review, industrial engineering

I. Background to the Study

Workforce competencies significantly influence the successful adoption of Industry 4.0 (I4.0) in organizations [1]. The background of I4.0 and its application in the manufacturing industry [2, 3] require that engineers considerably drive its successful adoption. Accordingly, the engineering education role of "preparing the graduates to practice engineering with competent technical know-how and soft skills at professional level" [4] becomes particularly important.

Industry 4.0 demands higher competency levels and requires employees with substantial skills and qualifications [1, 5, 6]. Thus, the alignment of engineering education in producing graduate attributes that meet I4.0 competency requirements cannot be avoided [5].

A study by Acerbi et al. [7] pointed out that there was a lack of comprehensive I4.0 competency assessment models and tools in literature. To assess this gap in literature, design requirements for a conceptual Industry 4.0 competency maturity model (I4.0CCM) were generated while guided by literature [8, 9]. This was followed by a systematic mapping review to identify I4.0 competency models and frameworks existing in literature. A design requirements gap analysis measured against the predefined design requirements for an I4.0CMM was then conducted.

A conceptual I4.0CMM that aligns with the industrial engineering domain was developed and is presented in this paper. As I4.0 has the potential to significantly impact on the knowledge and skills of industrial engineers [10], the conceptual I4.0CMM is illustrated using industrial engineering capability functions.

II. Study Purpose

The purpose of this study was to develop a conceptual I4.0CMM and illustrate it by using industrial engineering capability functions. The study was guided by three research questions:

1) Which I4.0 competency models and frameworks exist in literature?

2) Do the existing I4.0 competency models and frameworks satisfy all the predefined design requirements for an I4.0CMM?

3) What are the domains and dimensions that could be used to formulate the conceptual I4.0CMM?

III. Industry 4.0 Competency Maturity Model (I4.0CMM) Design Requirements

The People Capability Maturity Model (PCMM) [11, 12] was developed to assist organizations in enhancing their workforce capabilities. Application of PCMM enables organizations to mature their "capability for attracting, developing, and retaining the talent" [11] needed.

Management of employees' competencies from graduate level to professional level is crucial for organizations' success [13]. Thus, continuous alignment of employees' competencies with "business objectives, performance and changing needs" [11] is essential for business success.

Maturity models can serve a descriptive purpose if they are applied for assessing the "as-is" capability by comparing the "capabilities of the entity under investigation with respect to given criteria" [8, 9, 14]. On the other hand, maturity models can serve a prescriptive purpose when it is used to show how to find a desirable maturity level and stipulate guidelines to achieve a better state [8, 9, 14].

The design requirements for an I4.0CMM were generated based on serving both descriptive and prescriptive purposes. Table I presents I4.0CMM design requirements which were generated guided by the maturity model design principles framework of Pöppelbuß and Röglinger [8] and as applied by Van Dyk [9].

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8.5 Conclusion

Chapter 8 presented overview literature on maturity models and competency models. Furthermore, the chapter presented the I4.0CMM design requirements and performed an I4.0 competency models gap analysis. Although the model was presented as an Industry 4.0 competence model (I4.0CMM) in Article 5, because of assuming that the competency model is synonymous with the competence model, further inquiry revealed that the two could not be interchangeably used. Therefore, Article 6 presented the model as an Industry 4.0 competency maturity model (I4.0CMM), which better present the work accomplished in this study. Regardless of the label used, the I4.0CMM conceptualised in Article 5 and further developed in Article 6 (Chapter 9) refers to the same model.

CHAPTER 9

CONCEPT DESIGN 2: I4.0CMM DEVELOPMENT

9.1 Introduction

Article 6 presented in this chapter aimed to refine the preliminary I4.0CMM design offered in Chapter 8 and validate its utility using the Delphi technique. The chapter is the last step in the design phase of the study (Figure 18).

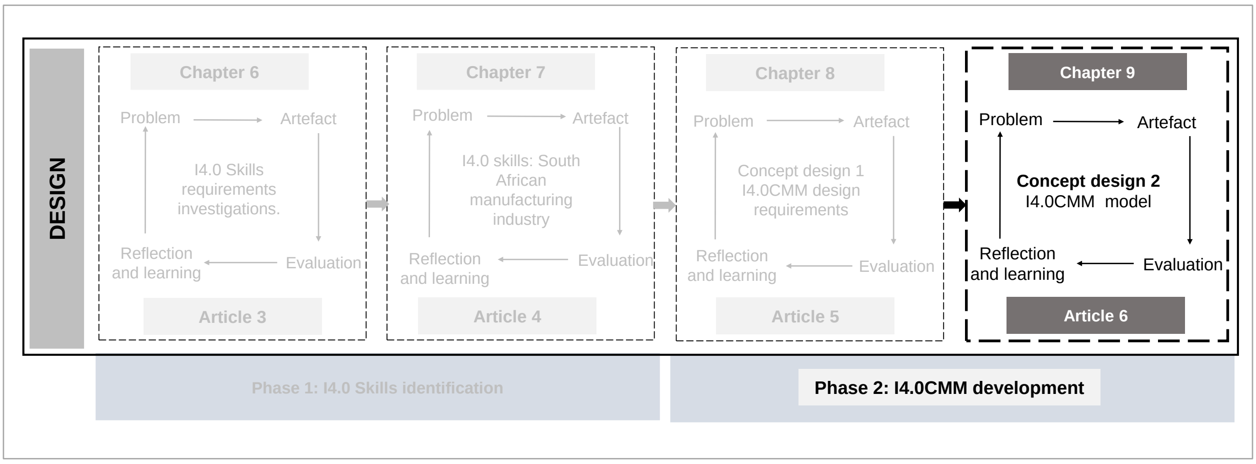

Figure 18: Design stage – step 2 of phase 2

This chapter addresses research objective 6: to develop the I4.0CMM using industrial engineering capability functions. The chapter is organised as follows: an overview of I4.0CMM domains establishment in section 9.2, Article 6 cover page in section 9.3, and the chapter conclusion in section 9.3. Appendix F presents Article 6 in full.

9.2 I4.0CMM dimensions establishment

Figure 19 illustrates the process that followed in the development of the I4.0CMM. The iterative development process focused on establishing, refining, and validating the design requirement and the model maturity levels, capability function domain and competency level domain. The process was initiated in Chapter 8 (Article 5), and refinement of various aspects was accomplished in Article 6 presented in this chapter. Sections 9.2.1 to 9.2.3 present the basis of the domain axis used in the I4.0CMM.

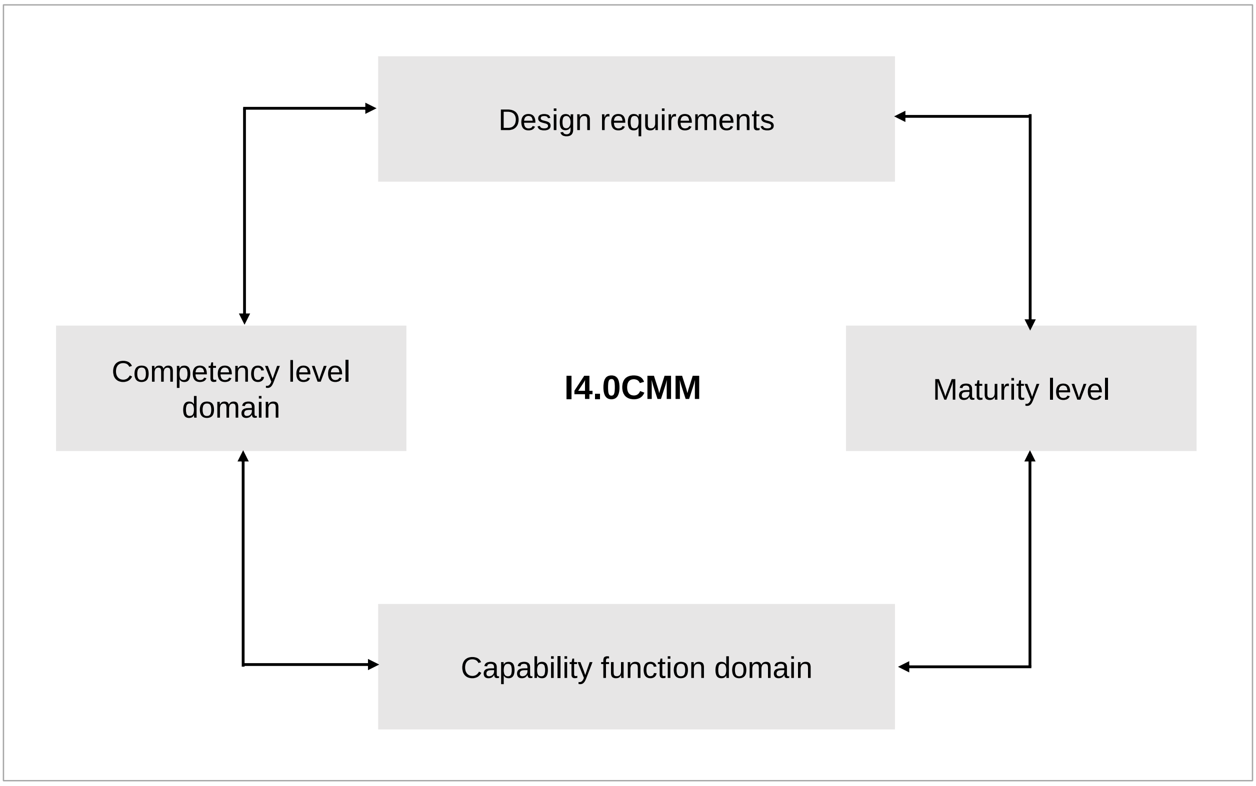

Figure 19: I4.0CMM iterative development process

9.2.1 Maturity levels domain

The words of American novelist Winston Churchill (1871–1947), "The farther back you can look, the farther forward you are likely to see", express the need of evaluation of various aspects of our engagement with life through references to the past.

Maturity models can serve a descriptive or prescriptive purpose, in the latter of which references to the past may be found (Becker *et al.*, 2009; Pöppelbuß & Röglinger, 2011; Van Dyk, 2013):

- Descriptive maturity models – are diagnostic models that can be used for internal and longitudinal benchmarking. They are used to assess the "as-is" situations.

- Prescriptive maturity models – provide guidelines on improvement measures based on historical data to map a specific and detailed course of action.

The I4.0CMM might serve both prescriptive and descriptive functions. The I4.0CMM might provide engineering education and workplace human resources development providers with a reference model for aligning graduate attributes and required professional competencies. The model may also identify improvement points required to match curriculum provisions to the current and future industry requirements resulting from the fourth – and later – industrial revolution. Furthermore, the model could also aid students and graduates in self-evaluating and self-regulating their achievement of I4.0 skills requirements and planning their professional development.

To achieve the prescriptive and descriptive functions, the maturity levels used in the I4.0CMM model must provide evolutionary stages that show continuous progression in competency requirements, with each stage superior to the previous stage. Therefore, the definition of the maturity axis must be interpolated into the previous competency requirements and focused on the future requirements.

The development from the agrarian and handicraft economy to machine domination paved the way for the industrial revolutions, which reflected distinct and discrete stages in development and requirements. Each industrial revolution proved to be superior to the previous one regarding competency requirements, technological advancements, and other developments. Therefore, the progression element in the industrial revolutions warrants the need for the adoption into maturity levels of the I4.0CMM. There are five maturity levels for the I4.0CMM: 1st industrial revolution, 2nd industrial revolution, 3rd industrial revolution, 4th industrial revolution and future requirements. The maturity levels enable the users to look further back in time and further into the future, aiding them to keep updated with competency requirements. As later industrial revolutions are being defined further maturity levels can be defined accordingly.

9.2.2 Competency function domain

According to Du Preez and Pintelon (1997) and Ravi (2008), the industrial engineering profession matured alongside the industrial revolutions. The industrial engineering profession is in a constant, continuous process of improvement (Du Preez & Pintelon, 1997). The relationship between industrial engineering and the industrial engineering profession is illustrated in Article 6. Therefore, the I4.0CMM capability functions domain refers to the industrial engineering profession.

The initial list of the industrial engineering profession capability functions was compiled through analysing various industrial engineering programmes from various universities and the handbook of industrial engineering (Salvendy, 2001). The industrial and systems engineering body of knowledge, literature (Kosky *et al.*, 2021; Ravi, 2008; Sackey & Bester, 2016) and experts views in the Delphi study iterations were used to compile the final list of the I4.0CMM industrial engineering capability functions. Figure 20 illustrates the initial and the final list of industrial engineering capability functions during the development of the I4.0CMM.

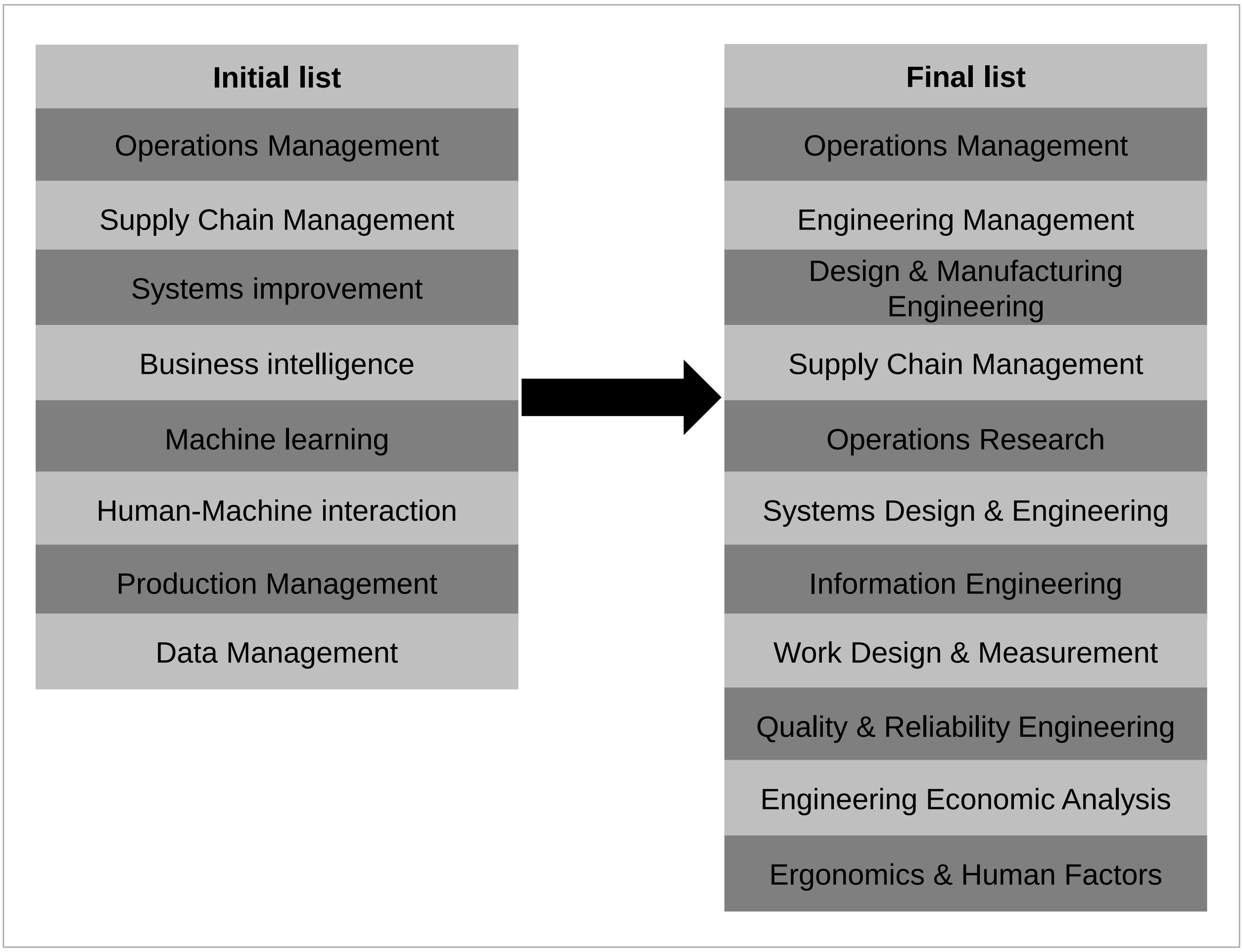

Figure 20: Industrial engineering capability functions domain

9.2.3 Competency level domain

The competency level domain presents the levels an individual goes through from first acquiring knowledge up to the expert level. The initial competency domain did not provide a self-evaluation function in the I4.0CMM. Using literature (Axley, 2008; Curtis *et al.*, 2009; Curtis *et al.*, 1995; El-Baz & Zualkernan, 2011; Krathwohl, 2002; National Institute of Health, 2020; Teodorescu, 2006) and experts' input in the Delphi study, the competency domain was changed to a competency level domain. Maisiri *et al.* (2021) elaborated on how the I4.0CMM incorporated Bloom's taxonomy. Figure 21 illustrates the changes in the model from competency domain to competency level domain.

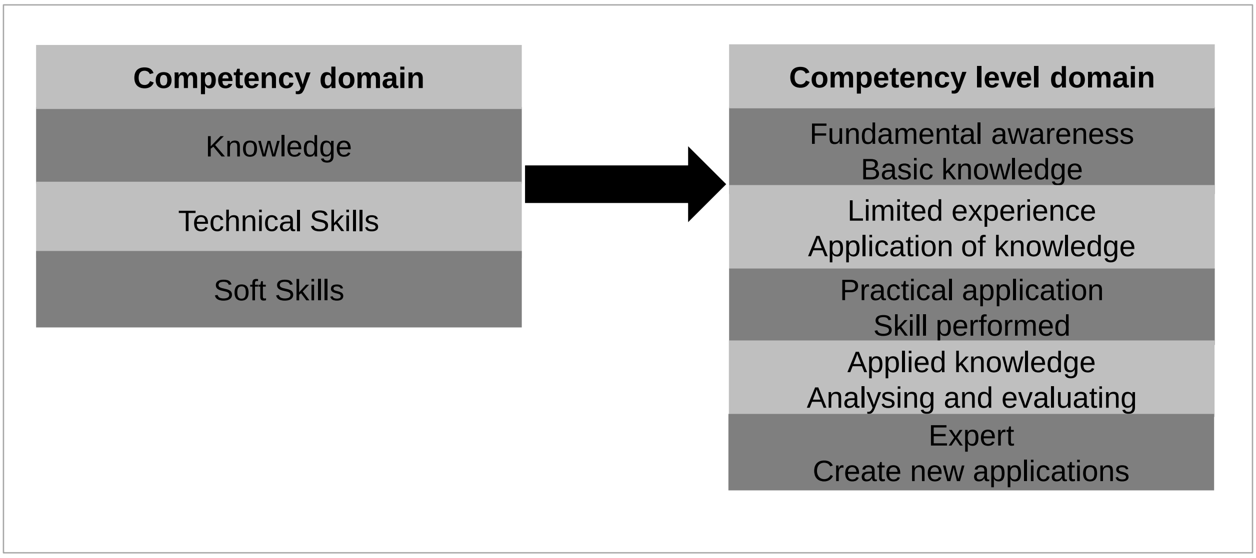

Figure 21: Competency domain versus competency level domain

The I4.0CMM development details are provided in Article 6, “Development of an Industry 4.0 Competency Maturity Model”

9.3 Article 6 cover page

Development of an Industry 4.0 Competency Maturity Model

Whisper Maisiri, Liezl van Dyk, and Rojanette Coetzee

***Abstract*—Industry 4.0 (I4.0) transformations in manufacturing industries impact technology, systems, and processes and extend to employees' competency requirements and, consequently, the preparation of graduates who will be ready to practice engineering with professional-level technical know-how and non-technical skills in I4.0. An I4.0 Competency Maturity Model (I4.0CMM) could be used as a tool to assess and guide the development of I4.0 and future skills requirements. This study applied the Delphi technique to evaluate the I4.0CMM's validity and utility, and the improvement thereof, using experts' opinions in two successive rounds. Purposeful sampling was employed to enroll 35 participants. Nineteen experts participated in round one survey, out of which 17 experts participate in round two of the survey. The study used a central tendency statistical tool (the mean) to evaluate expert consensus (mean score ≥ 75%) and used means graphs to present the data. The study results demonstrated the sufficiency and relevance of an I4.0CMM to both academic and industry practitioners. The I4.0CMM could provide a comprehensive competency assessment framework that guides the development of graduate attributes that align with the I4.0 competency requirements in the industry.**

***Index Terms*—competency, Delphi technique, graduate attributes, industrial revolutions, Industry 4.0, maturity model**

I. Introduction

Workforce competencies significantly influence the successful adoption of Industry 4.0 (I4.0) in organizations [1]. The evolution of all engineering professions – but particularly the industrial engineering profession – is interwoven with the progression from the initial to the fourth and further industrial revolutions (IR) [2, 3] as depicted by Fig. 1 [3]. Industry 4.0 and its application in the manufacturing industry [4, 5] magnify the role of engineers in driving its successful adoption. Therefore, the engineering education role of "preparing the graduates to practice engineering with competent technical know-how and soft [non-technical] skills at [a] professional level" [6] becomes critical.

Industry 4.0 demands high competency levels and requires broad skills and qualifications [1, 7-9]. The broad skills include professional skills [10], such as effective teamwork [10–13], people skills, such as creativity, empathy, and flexibility [9, 10, 12, 13], and technological skills [10, 11] such as "ability to work with the Internet of Things, autonomous robots, 3D printing, and other advanced technologies" [11, 12]. In addition, new qualifications will be about enhancing interdisciplinary knowledge and skills [9, 11, 14]. Thus, the alignment of engineering education in producing graduate attributes (GAs) that meet I4.0 competency requirements cannot be avoided [7].

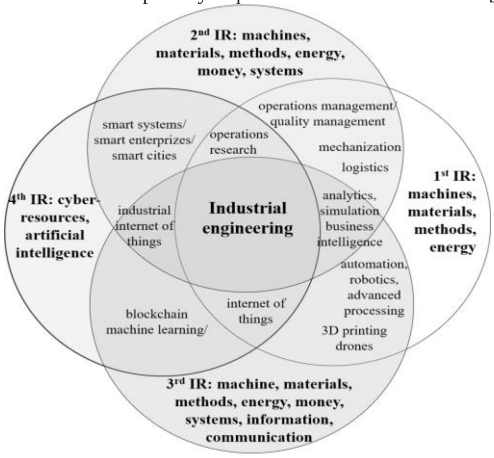

Fig. 1. Relation of Industrial Engineering to the Industrial Revolutions [3]

Literature [15, 16] stresses the significant transformation of the human capital role in I4.0, and thus innovative competency assessment models could assist in the development and assessment of the required competencies. Acerbi *et al*. [17] argued that there was a lack of comprehensive competency assessment models that focus on I4.0, leading Maisiri and van Dyk [18] to assess this gap by conducting a systematic mapping review of existing I4.0 competency models and frameworks in literature. The gap assessment was measured against predefined design requirements guided by literature [19, 20]. The systematic mapping review gap [18] suggested a lack of comprehensive I4.0 competency models and frameworks to assess and align workforce competency requirements in I4.0

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Based on "Industry 4.0 Competence Maturity Model design requirements: A systematic mapping review" by Whisper Maisiri and Liezl van Dyk which appeared in the Proceedings of 2020 IFEES World Engineering Education Forum - Global Engineering Deans Council (WEEF-GEDC), virtual

9.4 Conclusion

Chapter 9 concluded the design stage in the development of the I4.0CMM utilising the Delphi technique. The design requirements and the developed I4.0CMM were validated and verified, respectively. Chapter 10 presents the detailed verification and validation of the study.

CHAPTER 10

VERIFICATION AND VALIDATION

10.1 Introduction

The development of the Industry 4.0 competency maturity model (I4.0CMM) followed a process of diagnosing and validating the research problem, establishing, and validating the design requirements, and developing and verifying the I4.0CMM. The eADR method involves continuous evaluation, reflection, and formalisation of learning during the design iteration process (Mullarkey & Hevner, 2019; Sein & Rossi, 2019). The method permits integrating the verification and validation in the design process. The purpose of this chapter is to summarise and present the verification and validation inbuilt in the development of the I4.0CMM presented in the previous chapter in response to research objective 7: to confirm the validity of the research problem, the design requirements, and the research output.

The Delphi technique has various applications, including verifying and validating studies that involve the development of various instruments and models which require expert knowledge and input (Barroso-Osuna *et al.*, 2019; de Linhares *et al.*, 2019). Table 9 presents examples of studies that have used the Delphi technique to develop and validate artefacts. Therefore, the study incorporated the Delphi technique in developing, verifying, and validating the I4.0CMM (Article 6) in Chapter 9.

Table 9: Examples of studies that used the Delphi method for verification and validation purposes

Authors	Study focus	Purpose	Sampling technique	Participants	Rounds
(Tchouaket Nguemeleu *et al.*, 2020)	Developing and validating a new instrument based on expert opinion.	The Delphi technique was used to validate the content validity of the motion study.	Purposeful sampling	18	Two
(Wildeboer *et al.*, 2020)	To explore content validity of the International Classification of Functioning, Disability and Health core set for Diabetes Mellitus from nurses' perspective.	The Delphi techniquewas used to validate content using experts' opinions.	Purposeful sampling	27	Two

(Ski *et al.*, 2019)	To develop and test the Recommending Cardiac Rehabilitation scale (ReCaRe), designed to assess health professionals' attitudes, values and beliefs to CR referral.	The Delphi method was used to validate the Recommending Cardiac Rehabilitation scale content.	Purposeful sampling	13	Three
(Rastegari *et al.*, 2019)	Validating and developing a comprehensive home care program for mothers with preeclampsia.	The Delphi method was used to validate a designed primary home care program.	Purposeful sampling	15	Three
(Caino *et al.*, 2019)	To validate the format and contents of an instrument to assess research projects that apply for a fellowship by the Sociedad Argentina de Pediatría using an expert consultation technique.	The Delphi method was used to validate an instrument format and contents.	Purposeful sampling	17	Three
*(*de Linhares *et al., 2019)*	To develop and validate an instrument for evaluating primary health care professionals' assistance to people with suicidal behaviour.	The Delphi method was used to validate an instrument for the assessment of care provided to people with suicidal behaviour.	Purposeful sampling	7	Three
(Ahmad *et al.*, 2019)	To verify and validate the thematic elements of the Corporate Sustainable Longevity construct and generate a pool of items from the extant literature.	The Delphi method was used to verify the thematic elements and to perform content and face validity of the Corporate Sustainable Longevity construct.	Purposeful sampling	20	Four

The I4.0CMM development followed a process of solving a valid problem, establishing and proving that the design requirements are valid, and developing and verifying that the I4.0CMM adheres to the design requirements. Therefore, the present chapter comprises: a verification of the research method (Section 10.2), validation of the problem (Section 10.3), validation of the design requirements (Section 10.4), verification of the model against the design requirements (Section 10.5) and an illustration of the I4.0CMM (Section 10.6), and a conclusion (Section 10.7).

10.2 Research method verification

This section seeks to check (yes/no) the adherence of the research design followed in developing an I4.0CMM against the chosen research method. The section is divided into section 10.2.1 – verification of the correct use of the eADR, and section 10.2.2 – verification of the correct use of the Delphi technique.

10.2.1 Elaborated Action Design Research

The development of the I4.0CMM utilised Mullarkey and Hevner (2019) and Sein and Rossi's (2019) views on elaborated Action Design Research (eADR). The research focused on the diagnosis and design stages of the eADR method.

Table 10 demonstrates how this research addressed the eight principles that guide eADR (Mullarkey & Hevner, 2019; Sein *et al.*, 2011).

Table 10: Elaborated Action Design Research principles (Mullarkey & Hevner, 2019; Sein *et al.*, 2011)

Principle	Description	Yes/No	Comment	Reference
1. Practice-inspired	Emphasis on viewing field problems as knowledge-creation opportunities and the research activity is problem inspired.	Yes	The problem of the lack of I4.0 competency reference models, which could align industry competency requirements and skills development, was mapped from the input of practitioners. Furthermore, a gap analysis was completed.	Chapters 4, 5 and 8
2. Theory-ingrained	The artefact created should be informed by theory.	Yes	Systematic literature reviews and mapping review were conducted before and during the design stage	Chapters 2, 6 and 8
3. Reciprocal shaping	The artefact and the practise context should exert inseparable, equal forces.	Yes	Interaction with practitioners and experts was maintained from the diagnosis stage to the design stage.	Chapters 4, 5, 7 and 9
4. Mutually influenced roles	Mutual learning should take place among researchers and practitioners.	Yes	The Delphi iterations allowed researchers and practitioners the opportunity to share theoretical and practical knowledge,	Chapter 9

			respectively.	
5. Authentic and concurrent evaluation	Evaluation is not a separate stage of the research process but is an integral activity.	Yes	The evaluation was integrated into the iterations as presented in Chapter 3, Tables 5, 6 and 7.	Chapters 3 to 9
6. Guided emergence	The artefact must reflect both the preliminary design created by the researchers and ongoing shaping by practitioners and experts	Yes	Interaction with practitioners and experts was maintained from the diagnosis stage to the design stage.	Chapters 4, 5, 7 and 9
7. Generalised outcomes	Involves abstracting the learning into concepts for a class of problems, sharing outcomes with practitioners and formalising results for dissemination.	Yes	The research outcomes are generalised and formalised in the research articles and summarised in the concluding chapter.	Chapters 4 to 9, 12
8. Abstraction	Creation of different levels of artefacts for the current state of research goals in the problem environment.	Yes	All the iterations went through the problem formulation, artefact creation, evaluation, and reflection of learning as presented in Chapter 3, Tables 5, 6 and 7.	Chapters 3 to 9

10.2.2 The Delphi technique

The eADR method is grounded on the involvement of practitioners in the development of an artefact. The research utilised the Delphi technique to solicit expert opinion and views in developing and validating the I4.0CMM. The present section seeks to verify adherence to the Delphi technique principles and enrolment of participants.

Table 11 verifies the correct application of the Delphi technique principles (Skulmoski *et al.*, 2007) in this study.

Table 11: Delphi technique principles verification (Skulmoski *et al.*, 2007)

Principle	Description	Yes/No	Comment	Reference
1. Participant's anonymity	Allows the participants to freely express their options without undue social pressure to conform from others in the group.	Yes	No participant's identification was disclosed to any other participants during the data collection and reporting stages.	Appendix C, Appendix E and Article 6 (Chapter 9)
2. Iteration process	Allows the participants to refine their views considering the progress of the group's work from round to round.	Yes	Two iterations (rounds) were completed before reaching consensus.	Article 6 (Chapter 9), Appendix C and Appendix E.
3. Controlled feedback	Informs the participants of the other participants' perspectives and provides the opportunity for Delphi participants to clarify or change their views.	Yes	Other participants' round 1 views and opportunities to justify or change their perspectives were sent to participants.	Appendix D
4. Statistical aggregation of group response	Allows for quantitative analysis and interpretation of data.	Yes	Quantitative data analysis was conducted in Chapter 9.	Article 6 (Chapter 9)

Table 12 verifies the study participants' enrolment criteria as Delphi participants' criteria (Skulmoski *et al.*, 2007).

Table 12: Delphi technique participants enrolment verification.

Participants' enrolment criteria	Yes/No	Comment	Reference
1. The participants should have knowledge of and experience with the issues under investigation.	Yes	Purposeful sampling was used to enroll participants with a minimum of five years of known and demonstrated experience in industrial engineering. Furthermore, the participants should demonstrate an understanding of I4.0 competencies.	Appendix B and Article 6 (Chapter 9)
2. The participants should have	Yes	The study scope and requirements	Appendix B and Article

the capacity and willingness to participate.		were communicated to the participants, and participation in the study was voluntary.	6 (Chapter 9).
3. The participants should have sufficient time to participate.	Yes	The study duration and the expected time required to complete the survey were communicated in the invitation.	Appendix B
4. The participants must communicate effectively.	Yes	Though the criteria could be ascertained before the study, participants who agreed to participate responded to the surveys and provided comments.	-

10.3 Research problem validation

The problem solved in this research is the lack of I4.0 competency reference models, which could align industry competency requirements and skills development. The research problem was validated and cross-proved by the gap analysis and the Delphi study.

10.3.1 Gap analysis

Article 1 (Chapter 4) and Article 2 (Chapter 5) showed the significant challenges of I.40 skills requirements in the South African context. Furthermore, Article 2 pointed out that inadequate alignment between skills development and skills requirements notably inhibits the country's sustainable development of I4.0. Thus, the need to enhance I4.0 competency development.

A gap analysis was conducted through a systematic mapping review presented in Article 5 (Chapter 8). The gap analysis aimed at identifying I4.0 competency models in the literature and evaluating if they meet all the predefined I4.0CMM design requirements. The results revealed that I4.0 competency models and frameworks in literature satisfied some but not all the predefined design requirements for an I4.0CMM. Thus, the issue of the lack of I4.0 competency reference models was confirmed, which, if rectified, could align industry competency requirements and skills development.

10.3.2 Delphi study problem validation

The Delphi technique was used to solicit expert views on four research problem validity statements. An average of 3.75 (75%) rating on a five-point Likert scale was regarded as consensus among the experts. The expert consensus criteria are based on the various authors

(Caino *et al.*, 2019; da Cunha *et al.*, 2019; Hsu & Sandford, 2007; Nordin *et al.*, 2012; Wildeboer *et al.*, 2020).

Table 13 presents the research validation statements and the means score for the problem validation statements. The mean being greater than 3.75 proves that the research addressed a valid research problem.

Table 13: Research problem validation statements

Validation statement	Mean Score	Consensus
There is a misalignment between Industry 4.0 skills requirements in industry and skills development in the education system.	4.16	Yes
Industry 4.0 skills definition in the manufacturing industry is not clear.	4.26	Yes
There is a lack of I4.0 competency assessment models to assess and align workforce competency requirements in Industry 4.0 and future requirements.	3.95	Yes
There is a need for an I4.0CMM to assess and guide I4.0 competency requirements and development.	3.79	Yes

10.4 Design requirements validation

According to the researcher's knowledge, no predefined design requirements existed for the competency maturity model. Therefore, establishing design requirements was the first step in developing the I4.0CMM. The established design requirements needed to be proved for validity and utility to develop a relevant model that solves the defined problem. Each design requirement was tested for validity, followed by general statements that sought to cross-validate the design requirements.

Table 14 presents the Delphi study design requirements validation mean scores as presented in Article 6. The average mean score (>3.75) proves that the individual design requirements are valid.

Table 14: Individual design requirements validation

Design requirement	Validation statement	Mean Score	Consensus
DR1	The I4.0CMM must outline engineering profession competency requirements for the manufacturing industry and must be adaptable to other industries.	4.71	Yes
DR2	The I4.0CMM must provide a set of knowledge, skills, attitudes, values, and self-concepts required to perform specific capability functions.	4.71	Yes
DR3	The I4.0CMM must support and guide engineering professionals' practice and continuous professional development.	4.47	Yes
DR4	The I4.0CMM must provide competency reference standards for engineering education and quality assessment of engineering professionals along the career continuum.	4.29	Yes
DR5	The I4.0CMM must help to assess employees' competencies measured against the industrial revolutions and future requirements.	4.35	Yes
DR6	The I4.0CMM must have a self-assessment function against which users can gauge their level of competency	4.32	Yes
DR7	The I4.0CMM must be easily understood and be useful for researchers, academics, practicing professionals, and human resources practitioners.	4.47	Yes
DR8	The I4.0CMM must have a function to identify future competency requirements beyond I4.0 applications and technologies.	4.06	Yes
DR9	The I4.0CMM must include a competency levels domain, a capability functions domain, and a progressive maturity levels domain.	4.24	Yes
DR10	The I4.0CMM competency statements must be clearly defined and easy to interpret.	4.65	Yes
DR11	The competency statements must differentiate competency requirements progression through the different industrial revolutions.	4.47	Yes

Experts rated four statements designed to prove the validity of collective design requirements. Table 15 presents the mean scores (> 3.75) obtained in the Delphi study. Therefore, the Delphi study proved the validity of the design requirements in guiding the development of the I4.0CMM.

Table 15: Collective design requirements validation statement

Validation statement	Mean Score	Consensus
The design requirements are specific and easy to interpret.	3.76	Yes
The design requirements are sufficient to direct the development of an I4.0 competency model useful for both industry and academics.	4.12	Yes
The design requirements are sufficient to direct the development of an I4.0CMM that assesses and guides I4.0 competency requirements and development.	4.12	Yes

10.5 I4.0CMM verification against the design requirements

Valid design requirements guided the development of an I4.0CMM model. Hence, the I4.0CMM adherence to the design requirements might prove it a useful I4.0 competency model that could align industry competency requirements and skills development. A checklist and Delphi study were used to prove the utility of the I4.0CMM.

10.5.1 Verification check list

Table 16 presents the completed verification checklist used to prove the accomplishment of the design intent.

Table 16: I4.0CMM verification checklist

Design requirement	Description	Yes/No	Comment	Reference
DR1	The I4.0CMM must outline engineering profession competency requirements for the manufacturing industry and must be adaptable to other industries.	Yes	The model design was guided by I4.0 skills requirements in the manufacturing industry (Article 4) and the use of industrial engineering as an example of the engineering profession.	Article 4, Article 6 section 10.6
DR2	The I4.0CMM must provide a set of knowledge, skills, attitudes, values, and self-concepts required to perform specific capability functions.	Yes	The demonstration in section 10.6 exhibits the knowledge and skills requirements for specific industrial engineering capability functions.	Section 10.6
DR3	The I4.0CMM must support and guide engineering professionals' practice and continuous professional development.	Yes	The model provides a competency comparative function relative to the industrial revolutions, which can assist individuals, organisations, and educational institutions in self-evaluating their competencies.	Article 6 and Section 10.6
DR4	The I4.0CMM must provide competency reference standards for engineering education and quality assessment of engineering professionals along the career continuum.	Yes	The model could significantly contribute to engineering education by providing a reference framework to identify improvements points to match curriculum provisions to the current and future industry requirements.	Article 6 and section 10.6
DR5	The I4.0CMM must help to assess employees' competencies measured against the industrial revolutions and future requirements.	Yes	The I4.0CMM competency level and maturity level domains measure employees competency against the industrial revolutions.	Article 6 and section 10.6
DR6	The I4.0CMM must have a self-assessment function against which users can gauge their level of competency.	Yes	Individuals can use the I4.0CMM model to assess their competency levels relative to the industrial revolutions. Each competency level description is	Article 6

			provided in Article 6.	
DR7	The I4.0CMM must be easily understood and be useful for researchers, academics, practising professionals, and human resources practitioners.	n/a	This required input from the experts and is covered in the Delphi study.	n/a
DR8	The I4.0CMM must have a function to identify future competency requirements beyond I4.0 applications and technologies.	Yes	The I4.0CMM maturity level domain encompasses future requirements as demonstrated in section 10.6.	Article 6 (Chapter 9) and section 10.6
DR9	The I4.0CMM must include a competency levels domain, a capability functions domain, and a progressive maturity levels domain.	Yes	The I4.0CMM has three domains: competency levels domain, a capability functions domain, and a progressive maturity levels domain.	Article 6 (Chapter 9)
DR10	The I4.0CMM competency statements must be clearly defined and easy to interpret.	Yes	Though the implementation of the model to a specific setup is not within the scope of this study, the model was demonstrated in section 10.6 using the example of industrial engineering.	Section 10.6
DR11	The competency statements must differentiate competency requirements progression through the different industrial revolutions.	Yes	Though the implementation of the model to a specific setup is not within the scope of this study, the model was demonstrated in section 10.6 to show competency requirements progression through the different industrial revolutions.	Section 10.6

10.5.2 The Delphi study

Establishing the correct and relevant model dimensions is significant in the development of a useful model. Therefore, the model was verified for simplicity, usefulness (DR7), and relevant dimensions (DR9). Table 17 presents the mean scores (>3.75) for the verification statements. The mean scores prove that the model adheres to the specified design requirements.

Table 17: I4.0CMM verification against the design requirements

Design requirement	Validation statement	Mean Score	Consensus
DR7	The model structure is simple.	3.94	Yes
DR9	The model dimensions are sufficient and relevant.	4.12	Yes
DR9	The competencies dimensions are sufficient and relevant.	4.29	Yes
DR9	The functional capability areas are an accurate representation of the industrial engineering practice functional areas.	4.18	Yes
DR9	The maturity level dimensions are sufficient and relevant.	4.24	Yes

10.6 Model demonstration

Competency models can be used "to build training, hiring, evaluation, and assessment Programs" (Teodorescu, 2006). Sherman et al. (2007) pointed out that competency models "could be used as a framework to design programs" and curricula to meet the educational needs.

The I4.0CMM could be used by engineering education and workplace human resources development providers as a benchmark framework for aligning graduate and required professional competencies and identifying improvement points required to match curriculum provisions to the current and future industry requirements resulting from the fourth – and later – industrial revolutions. Furthermore, it could aid students and graduates in self-evaluating and self-regulating their achievement of I4.0 skills requirements and planning their professional development.

Though the implementation of the I4.0CMM is not within the scope of this study, the model is illustrated using four industrial engineering capability functions: operations management (Table 19), quality management (Table 20), ergonomics/human factors (Table 21), and supply chain management (Table 22). Two dimensions of competency are used: knowledge and skills (technical skills and non-technical skills). Literature was used in the construction of the competency descriptions, as presented in Table 18.

Table 18: Capability functions competency statements references

Capability function	Table	Literature
Operations management	Table 19	(Addo-Tenkorang & Helo, 2016; Chase & Apte, 2007; Guo *et al.*, 2021; Heineke & Davis, 2007; Jacobs, 2007; Mabert, 2007; Sprague, 2007; Watson *et al.*, 2007)
Quality Management	Table 20	(AQS, 2021; Balouei Jamkhaneh *et al.*, 2021; Jacob, 2017; Santos *et al.*, 2021; Zonnenshain & Kenett, 2020)
Ergonomics/Human factors	Table 21	(Kadir *et al.*, 2019; Karwowski, 2006; Laudante, 2017; Muñoz Morgado, 2018; Neumann *et al.*, 2021; Wilson & Daugherty, 2018; Wilson, 2000; Wilson, 2014)
Supply chain Management	Table 22	(Addo-Tenkorang & Helo, 2016; APICS, 2014; Ballou, 2007; Fatorachian & Kazemi, 2021; Frederico *et al.*, 2019; Garay-Rondero *et al.*, 2019; Gunasekaran *et al.*, 2017; Prajogo & Sohal, 2013; Queiroz & Telles, 2018; Zijm & Klumpp, 2016)

Table 19: Operations management capability function

Operations management	1st (1784)	2nd (1870)	3rd (1969)	4th (Today)	Future
Knowledge	• Standardization of machine and machine tools • Economy of machinery and manufacturers	• Manufacturing planning and control – reorder order point systems (base stock, continuous review, periodic review), economic order quantity and point • Material requirement planning • Tylor's Principles of Scientific management approach • Charles Babbage's ''systematic analysis" concepts • Statistical process control and analytical methods • Aggregate production planning and forecasting • Inventory management models inventory models	• Production and inventory management • Demand management • Manufacturing resource planning II (MRP-II), ERP • Computer integrated manufacturing (CIM) • Enterprise resource planning (ERP) • Theory of Constraints techniques • Manufacturing strategy • Poka-yoke method • Service design and management • Process improvement techniques –Toyota production system (TPS) Kanbans and Just-in-Time (JIT) • Flexible manufacturing systems	• IoT, CPS enabled manufacturing, cloud manufacturing • Synchroperation of production and manufacturing systems • Advanced Planning and Scheduling • Technology management • Big data and big data analytics	• Synchroperation of service, production, and manufacturing systems • Managing autonomous systems
Skills: Technical	• Solving emerging production problems	• Perform manual measurement and quantification • Material planning system using punched card approach • Use the PICS MRP application software • Carry out mathematical programming, CPM and PERT	• Use of COPICS, MMAS, MAPICS • Use various ERP software and system vendors – SAP, Lawson Software, PeopleSoft., Oracle • Use of Structured query language • Use of optimized production scheduling software programs • Use of thinking process tools • Process improvement	• Optimisation of synchronised production and operations systems • Use of hyperconnected physical internet-enabled Smart manufacturing platform (HPISMP) – digital twin and consortium blockchain	• Integration of customer in value creation process
Skills: Non-technical	•	• Analytical,	• Problem solving, innovation, communication, teamwork	• Flexibility and resilience, agility, complex problem solving, creativity	• Emotional intelligence, Ability to interact with autonomous systems

Table 20: Quality management capability function

Quality & Reliability	1st (1784)	2nd (1870)	3rd (1969)	4th (Today)	Future
Knowledge	• Quality inspection • Craftsmanship model, factory system, Taylor's system • Parts specifications	• Quality control & assurance • Process quality • Shewhart, Deming and Juran approaches • Juran quality trilogy • Process performance and understanding variations • Statistical quality control (SQC) techniques, control charts	• Quality management • Total quality control, total quality management • Service quality and productivity, Six Sigma quality, lean production • Quality function deployment, • Quality standards (ISO 9000 Standards Series)	• Quality design – product design quality • Quality 4.0, approach quality as data driven discipline • Application of industrial internet of things in quality improvement and monitoring • Technology innovations, big data, and big data analytics, simulating the behaviours of products systems • Integrating reliability engineering with quality engineering • Risk Management	• Quantitative data and evidence driven tools
Skills: Technical	• Product inspection • Aggregating data in ledgers for accounting and planning purpose • Checking parts against specifications	• Sampling inspection, constructing statistical model and probability • Use measuring devices like gauges, meters, callipers, and computers	• Promote design and production of quality products • Diagnosis abilities –- quality engineers make decisions based on intuition qualitative assessments • Manual quality metrics calculation • Quality Auditing	• Prognostics of process conditions and quality characteristics • Simulation and modeling – (MATLAB, Simulink…) • Advance analytics – turning data into actionable information, in a timely and useful manner	• Developing prognostic and prescriptive analytical models
Skills: Non-technical	• Attention to details • Hand/eye coordination • Consistency	• Analytical skills	• Attentive-to-detail members, low tolerance of risk and mistakes (watchdogs) • Teamwork	• Agility, flexibility, • innovative and creative thinking • Team culture, team harmony, increase team potency • Conflict management, • Identify hidden insights in vast quantities of data	• Interaction with autonomous machines and systems • Emotional intelligence

Table 21: Ergonomic/Human-factor capability function

Ergonomic / Human-factor	1st (1784)	2nd (1870)	3rd (1969)	4th (Today)	Future
Knowledge	• Understanding work – useful work and harmful work Interactions between people and their working environments	• Contemporary ergonomics – human factors and performance • Interaction between a person and one machine or job or behaving within an environment	• Understand interaction of humans with environmental system and the practise of improving such interactions. • Ergonomics unit of analysis • Domains of ergonomics – physical, cognitive, organisational • Technology driven ergonomics • Understanding operational context	• Virtual Ergonomics – virtualisation of process and use of virtual reality in offering valuable support in decision making, virtual organisations and virtual terms • Nanoergonomics and Systems ergonomics • Holistic understanding of I4.0 advanced technologies (such as AR, VR, CPS, Big Data Analytics) impact on human work organisation and performance	• Autonomous ergonomics • Ergonomics in shell company
Skills: Technical	• Identify and solve simple task, job related design problem	• Study interaction between a single operator and single machine to improve both worker health and work performance • Design of task, jobs and products • Fitting the job to the worker	• Drive human-centred design and re-design of interactions of humans with various systems for maximising the capabilities, and minimising the limitations of humans • Develop and test concepts and prototypes Use qualitative and quantitative methods to collect data	• Design of human-centric interactions that enhance and augment human capabilities • Systematic assessment of the impact of I4.0 technologies implementation on human workers and system performance • Analyze, understand, and design human work and Cyber Physical Systems in Industry 4. • Simulation and use of digital models in designing interactions between humans and system	• Design human-centric interactions with autonomous systems such as autonomous robots
Skills: Non-technical	• Communication, teamwork	• Participatory work design • Analytical	• Flexibility, timeliness, visionary, complex problem solving	• Cultural intelligence, systematic thinking, teamwork, fitting in organisational system, complex problem-solving, abstraction and managing complexity, independent, take responsibility, emotional intelligence	• Emotional intelligence, collaborate and not compete with autonomous robots.,

Table 22: Supply chain management capability function

Supply chain management	1st (1784)	2nd (1870)	3rd (1969)	4th (Today)	Future
Knowledge	• Classical domestic system and the craft guilds • Local supply and moving of goods	• Mass production and economies of scale • Procurement of raw materials and delivering of goods to • Demand creation and physical supply, containerization, and warehousing	• Supply chain management components and processes, supply chain network structures and flows • Supply chain operations reference model • Supply chain performance • Total information visibility concepts • Supply chain structural and behavioural management • Supply chain horizontal and vertical integration	• Digital supply chains models • Application of technologies such as big data and big data analytics, cloud computing, IoT, CPS • Sustainable supply chains (sharing, green economy), servitisation • Systems theory application in supply chain management	• Autonomous supply chains, sustainable supply chains
Skills: Technical	• Solving emerging production problem • Transactional and clerical tasks	• Supply customers with what is available • Use of Gantt charts • Demand creation Transactional and clerical task	• Coordination of sourcing, making, delivering, and returning activities • Demand forecasting and management • Supplier relationship management, customer service management, manufacturing flow management, product development and commercialization, returns management • Strategic planning and broader financial skills • Make use of available technology	• Design of autonomous supply chains	• Design human-centric interactions with autonomous systems such as autonomous robots
Skills: Non-technical	• Consistency, commitment	• Communication skills, trustworthy	• Communication, flexible team workers • Problem solving, flexibility	• Flexibility and resilience, workers' responsiveness and agility	• Artificial intelligence-based learning • Information sharing and collaboration

10.7 Conclusion

The purpose of this chapter was to address research question 7: to confirm the validity of the research problem, the design requirements, and the research output. Table 23 summarises the cross verification/validation of the research problem, design requirements and the I4.0CMM.

Table 23: Cross verification/validation summary

Verification /validation requirement	eADR principles	Delphi technique principles	Gap analysis	Delphi study	I4.0CMM checklist	Model illustration	Conclusion
Verify a valid research design was followed	confirmed (Table 10)	confirmed (Table 11)	n/a	n/a	n/a	n/a	Verified
Prove a valid research problem was solved	n/a	n/a	confirmed (Section 10.3.1)	confirmed (Table 13)	n/a	n/a	Validated
Prove relevant design requirements to direct the development of the I4.0CMM.	n/a	n/a	confirmed (Article 6)	confirmed (Table 14 and Table 15)	n/a	n/a	Validated
Prove that the I4.0CMM addresses the research question	n/a	n/a	n/a	confirmed (Table 17)	confirmed (Table 16)	confirmed (Section 10.6)	Validated

The summarised cross-verification/validation presented in Table 23 shows that:

- the research followed a valid research design,
- a valid research problem was solved,
- valid design requirements were established, and
- a valid I4.0CMM was developed.

Therefore, the validity of the research is confirmed. Chapter 12, which follows, presents the conclusion of the research.

CHAPTER 11

CONCLUSION

11.1 Introduction

This study aimed to develop an I4.0 competency maturity model (I4.0CMM) that simultaneously guides and assesses I4.0 competency development and industry competency requirements in the South African context. To conclude this study, Section 11.2 presents an overview of the research, and Section 11.3 highlights the study's contribution. The limitations and recommendations are presented in Section 11.4, and Section 11.5 concludes the research.

11.2 Research overview

The issue addressed in this research is the lack of I4.0 competency reference models, which could align industry competency requirements and competency development. The diagnosis phase presented two iterations with the objective of proving and elaborating the problem. The diagnosis phase allowed the investigation of aspects related to the problem.

The first step in the diagnosis stage (Article 1) assessed South African industries’ readiness to adopt I4.0 (Objective 1) using six dimensions: organisational strategy, smart factory, smart operations, smart products, data-driven services, and employees. The study revealed that South African companies are either at emerging or developing levels regarding adopting I4.0, thus addressing research objective 1. Furthermore, the study indicated the need to investigate I4.0 skills requirements in the South African context.

The second stage (Article 2) explored factors that inhibit the sustainable adoption of I4.0 in the South African manufacturing industry (Objective 2). The study pointed out inhibiting factors such as noticeable youth unemployment, a critical shortage of I4.0 skills and inadequate alignment between skills development and skills requirements. In addition, the study presented the strategies that could enhance sustainable adoption of I4.0 in South Africa, such as enhancing skills development, and the selection of technologies and initiatives that enhance human capability and productivity, thus addressing research objective 2.

The results and findings of the diagnosis stage emphasised the need to focus on I4.0 skills requirements and development to enhance sustainable adoption of I4.0 in South Africa. These findings led to the design stage, comprising phase 1 (I4.0 skills identification) and phase 2 (I4.0CMM development). The first step in the design stage, phase 1 (Article 3), performed a systematic literature review to investigate I4.0 skills requirements (Objective 3). The study documented various skills required for I4.0: technological skills, programming skills, digital skills, thinking skills, social skills, and personal skills. The study further documented possible skills development approaches, leading to addressing research objective 3.

The second step (Article 4) on the design stage, phase 1, involved an empirical study that established critical I4.0 skills required in the South African manufacturing industry (Objective 4). The study identified digital skills, soft skills (social skills, thinking skills), domain skills (engineering skills) and entrepreneurial skills as critical skills required in the South African manufacturing industry, addressing research objective 4.

The design stage, phase 2, step 1 (Article 5), focused on establishing the design requirements for the I4.0CMM and performed an I4.0 competency models gap analysis (Objective 5). The study established 11 design requirements and conducted a gap analysis that confirmed the lack of I4.0 competency reference models. The gap analysis revealed a significant need to develop a reference model that could assist in aligning skills development and skills required in industry, thus addressing research objective 5.

The last step (Article 6) in the design stage focused on developing and refining the I4.0CMM using industrial engineering capability functions (Objective 6). The I4.0CMM comprises three domains: industrial engineering capability functions, competency levels and maturity levels domain. Therefore, addressing research objective 6.

The eADR iterations enabled embedding the verification and validation process in the development of I4.0CMM. Alongside other verification and validation tasks completed and presented in Chapter 10, the I4.0CMM model was illustrated, using four industrial engineering capability functions. The verification and validation proved the validity of the research, consequently addressing research objective 7.

11.3 Contribution

The gap analysis revealed the existence of I4.0 competency models, although they did not meet all the predefined design requirements in this study to address the research problem. Significant competency models are developed within the framework of the social sciences. Therefore, using Gregor and Hevner’s (2013) DSR contribution framework (Figure), the study’s primary contribution is classified as an “exaptation” – that is, to extend the known solutions to new problems. It could be argued that a second contribution of the study lies within the improvement segment. However, the claim of a new solution could not be ascertained since there are competency maturity models in existence.

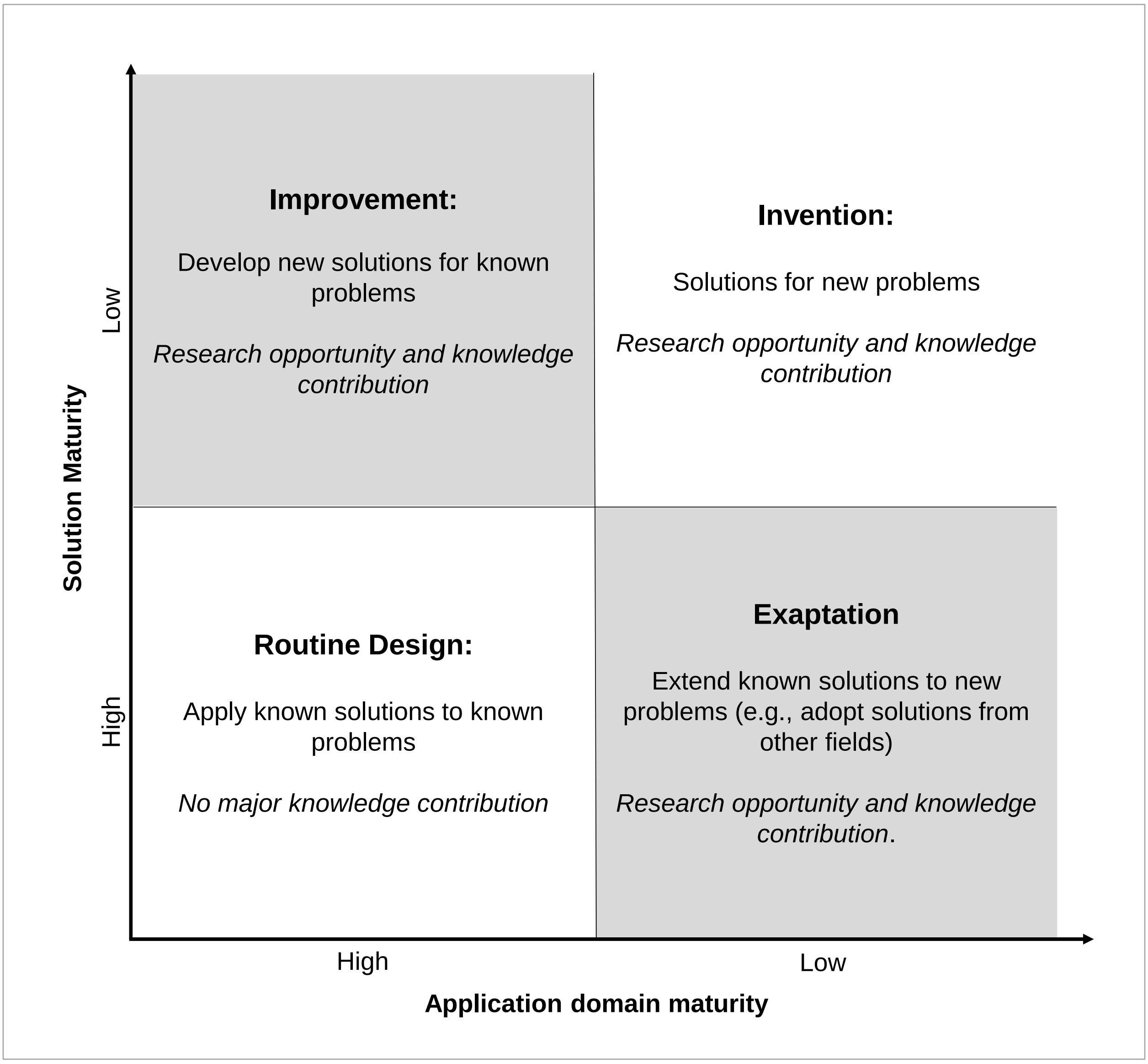

Figure 22: Design Science knowledge contribution framework (Gregor & Hevner, 2013)

Sein and Rossi (2019) emphasised that a contribution in solving a problem involves reducing or closing the identified gap. The identified gap was a lack of I4.0 competency reference models, which contributes to misalignment between industry competency requirements and skills development. Furthermore, there is a significant literature gap on sustainable adoption of I4.0 and I4.0 skills development and requirements in the context of South African industries. Therefore, the contribution of this study is twofold: an I4.0CMM and an addition to I4.0 literature in the South African context.

11.3.1 Industry 4.0 competency maturity model (I4.0CMM)

The study developed an Industry 4.0 competency maturity model that could be used as a competency reference model in developing I4.0 competency requirements. The intercept of industrial engineering and the industrial revolution was emphasised in this study.

The developed I4.0CMM could be used by:

- engineering education and workplace human resources development providers as a benchmark framework for aligning GAs and required professional competencies
- engineering education providers in identifying improvement points required to match curriculum provisions to the current and future industry requirements resulting from the fourth – and later – industrial revolutions
- students and graduates in self-evaluating and self-regulating their achievement of I4.0 skills requirements and planning their professional development

Though the I4.0CMM was illustrated using industrial engineering capability functions, the model could be adapted to other engineering professions by replacing the capability functions domain with a specific engineering profession.

11.3.2 Publication contribution

The study significantly contributed to the literature through six publications:

- Industry 4.0 readiness assessment for South African industries (Article 1);
- Factors that inhibit sustainable adoption of Industry 4.0 in the South African manufacturing industry (Article 2);
- An Investigation of Industry 4.0 skills requirements (Article 3);
- Industry 4.0 skills: A perspective of the South African manufacturing industry (Article 4);
- Industry 4.0 Competence Maturity Model design requirements: A Systematic Mapping Review (Article 5); and
- Development of an Industry 4.0 Competence Maturity Model.

The relevance of the publications to the literature is exemplified by Article 3, quoted as one of the articles contributing most in the category of human factor studies in a systematic literature review by Neumann et al. (2021)

11.4 Limitations and recommendation for future work

The development of an I4.0CMM followed the eADR method. Two iterations in the diagnosis phase and four iterations in the design phase were completed. The model was illustrated using four industrial engineering capability functions. However, there was no implementation and testing of the I4.0CMM in a real-world situation. Consequently, this provided an opportunity for future research to implement and test the model in a real-world situation.

The research completed four empirical studies to solicit the inputs of practitioners and experts. Table 24 shows the study type and the number of participants in each study. The number of participants could be regarded as small to generalise the findings of the studies. However, three articles out of four used purposeful sampling to ensure experts were enrolled who could provide relevant data for the studies. Future research could focus on including experts from various industries to ensure various views from different sectors.

Table 24: Empirical studies description

Paper title	Type of study	Sampling technique	Participants
Industry 4.0 readiness assessment for South African industries (Article 1)	Quantitative	Convenient	36
Factors that Inhibit Sustainable Adoption of Industry 4.0 in the South African Manufacturing Industry (Article 2)	Qualitative	Purposeful	16
Industry 4.0 skills: A perspective of the South African manufacturing industry (Article 4)	Qualitative	Purposeful	20
Development of an Industry 4.0 Competency Maturity Model (Article 6)	Qualitative	Purposeful	19

The I4.0CMM presented industrial engineering capability functions in the capability functions domain. However, the model did not specify the capability functions levels, i.e., technician, technologist, and engineer. Future work could consider incorporating the capability function levels in the model illustration. Furthermore, future work entails adapting the capability functions domain to other engineering professions.

11.5 Conclusion

South Africa faces the challenge of not achieving sustainable adoption of I4.0 in its manufacturing industry due to certain factors, such as lack of required workforce competencies. Therefore, the development of relevant I4.0 and future requirements competencies becomes critical in driving the South African NDP and the United Nations SDGs. The developed I4.0CMM could contribute to the alignment of industry competencies requirements and competencies development in the country

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APPENDIX A: ARTICLE 1

INDUSTRY 4.0 READINESS ASSESSMENT FOR SOUTH AFRICAN INDUSTRIES

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ABSTRACT

Technological advancements related to the fourth industrial revolution are causing disruptive changes that are widely felt at national, industry, and company level. Industry 4.0, an initiative driving the fourth industrial revolution, is happening at an exponential speed, and embracing and adopting it is unavoidable for survival and competiveness. Although noticeable progress has been made in the use of Industry 4.0 technologies, systems, and processes in developed countries, there is uncertainty about the preparedness of businesses and industries in developing countries, including South Africa, to adopt Industry 4.0. The purpose of this research paper is to explore the readiness of South African industry in this regard. A questionnaire instrument with quantitative criteria compiled by the Impulse Foundation of Verband Deutscher Maschinen- und Anlagenbau was used in this study. The exploratory study revealed that South African industry is faced with significant challenges in Industry 4.0 strategy formulation and equipment infrastructure to support Industry 4.0 requirements. The assessment pointed out that Industry 4.0 skills exist in pockets in South Africa, and so a further study to reveal more detail on Industry 4.0 skills requirements is essential.

OPSOMMING

Tegnologiese ontwikkelings met betrekking tot die vierde industriële rewolusie veroorsaak verreikende ontwrigtende verandering op nasionale, industrie-, en besigheidsvlak. Industrie 4.0, 'n inisiatief wat die Vierde Industriële Rewolusie aanvuur, geskied teen eksponensiële spoed en dit is noodsaaklik om dit te aanvaar en toe te pas, met die oog op oorlewing en mededingendheid. Alhoewel daar beduidende vordering is met betrekking tot die implementering van Industrie 4.0 in ontwikkelde lande, is daar onsekerheid oor die gereedheid van ontwikkelende lande, insluitend Suid-Afrika, om Industrie 4.0 te implementeer. Die doel van hierdie artikel is om die gereedheid van Suid-Afrikaanse industrieë in hierdie opsig te verken. 'n Vraelys-instrument met kwantitatiewe kriteria wat deur die Impulse Foundation van Verband Deutscher Maschinen- und Anlagenbau saamgestel is, is in hierdie studie gebruik. Die verkennende studie het getoon dat die Suid-Afrikaanse industrie beduidende uitdagings in die gesig staar wat betref strategieformulering en toerustinginfrastruktuur om Industie 4.0-eise te bevredig. Die ondersoek het getoon dat Industrie 4.0-vaardighede in geïsoleerde situasies in Suid-Afrika bestaan, en daarom is verdere studie om meer oor die vereistes vir Industrie 4.0-vaardighede te wete te kom, dringend nodig.

1 INTRODUCTION

The era of Industry 4.0 is upon us, and alignment with its requirements is inevitable for survival and competitiveness. Industry 4.0 is happening at an exponential rate, and facilitating its successful adoption in developing countries, South Africa included, is of significance for sustainable development.

Industry 4.0, a term coined in Germany [1, 2] to define a well-proven and established initiative driving the fourth industrial revolution [3, 4] and used by experts to describe it [5-7], has three distinct features that differentiate it from Industry 3.0 [8]: (a) the exponential pace at which technology is evolving; (b) the breadth and depth of technological advancement, which combines multiple technologies; and (c) the extent of the impact across the entire system, thus affecting companies, industries, and whole countries. This means that the disruptive effects of Industry 4.0 are widely felt at all levels, and require action to deal with their impact.

Rajnai and Kocsis [9] pointed out three pillars of Industry 4.0's technologies: information accessibility on a real-time basis; the ability to use data for optimisation at all times; and "integration of people, objects and systems into the value chain" [9]. On the other hand, Bittighofer *et al*. [10] singled out moving from mass production to the customisation of products and services as an attribute of Industry 4.0.

The purpose of this research paper is to explore the readiness of South African industries to adopt Industry 4.0. The paper reports on organisations' readiness to embrace Industry 4.0 across six readiness dimensions: organisational strategy, infrastructure, operations, products, data-driven services, and employees' skills availability.

In this paper, an overview of an Industry 4.0 readiness assessment is presented first in section 2. Section 3 outlines the methodology that was followed to perform this study. The survey's results and an analysis of them are presented in section 4, with a discussion of the results offered in section 5. Section 6 states the conclusions of this exploratory investigation.

2 INDUSTRY 4.0 READINESS ASSESSMENT OVERVIEW

Organisations can gain an understanding of their preparedness level by using Industry 4.0 readiness assessment tools [9]. Such tools can be used to benchmark and map an organisation's direction for successful digital transformation. Thus a successful journey of adopting Industry 4.0 can be initiated by performing an Industry 4.0 readiness assessment, which will help to identify focus areas that demand attention. Industry 4.0 readiness assessments can be performed in different structures, such as in a department in an organisation, in the entire organisation, or at a national level [11, 12].

Botha [13] pointed out that Industry 4.0 is a reality, and that its influence on how business is done cannot be avoided. Embracing Industry 4.0 is the way to remain competitive and relevant in the future. In the Industry 4.0 era, data will be recognised as an important asset, and competitiveness will hang upon organisations' ability to collect and analyse data for continuous improvement [14].

Industry 4.0 readiness extends beyond investing in advanced technologies by including issues such as organisational strategy and the availability of skills. Digital transformation is not an abrupt change; rather, it is a gradual change that includes many stages [9]. Accepting the point made by Rajnai and Kocsis [9], it is concluded that an Industry 4.0 readiness assessment seeks to identify the phase of an organisation in relation to digital transformation.

Organisations involved in a study by Judit [14] stated that Industry 4.0 was important, and that its impact was already being felt in the industry. Contrary to the findings of Judit [14], however, Rajnai and Kocsis [9] pointed out that surveys proved that a significant number of company leaders attested that, at the time of the surveys, they were not aware of Industry 4.0. The authors concluded that, amidst the hype, there was a possibility that the leaders of organisations were unaware of Industry 4.0.

3 RESEARCH METHODOLOGY

The primary objective of this study is to explore the Industry 4.0 readiness level of South African industries by obtaining quantitative primary data from individuals holding management positions. A quantitative research methodology is used in this study, and was chosen because calculating the Industry 4.0 readiness level requires chosen indicators to be scored. This section is organised as follows: section 3.1 outlines the available Industry 4.0 readiness assessment tools, and section 3.2 presents the Industry 4.0 readiness assessment indicators applied in this study. The questionnaire structure that was used in data collection is presented in section 3.3. The sampling technique and data analysis method are presented in section 3.4 and section 3.5 respectively.

3.1 Readiness assessment tools

A notable number of Industry 4.0 readiness assessment tools are in existence and are assessed in this section. In a review of the developmental stages of Industry 4.0, Judit outlined a macro- and micro-level Industry 4.0 readiness index by Blanchet, Rinn, von Thaden and de Thieulloy [15] and Geissbauer, Vedso and Schrauf [16] respectively. The macro-level Industry 4.0 readiness index classifies countries' Industry 4.0 readiness into four categories, as presented in Table 1.

Table 1: Industry 4.0 readiness categories at macro-level [14, 15]

Industry 4.0 readiness category	*Description*
Frontrunners	Manufacturing has a large share in the GDP, innovative, dictate technologies, path leaders.
Potentialists	Manufacturing on downward trend in previous years, innovative attitudes, and pathfinders.
Traditionalists	Manufacturing has noticeable share in the GDP, underdeveloped technologies and production methods.
Hesitators	Manufacturing and technology require development, uncertainty in adopting digitalisation.

The micro-level Industry 4.0 readiness index distinguishes four discrete development levels to which organisations can belong [9, 14]. Table 2 presents the categories of Industry 4.0 development through which organisations can go.

Table 2: Industry 4.0 readiness categories at micro-level [14, 16]

Industry 4.0 readiness category	*Description*
Digital novices	Isolated digital applications and solutions, focus on products and not customers, operate in functional silos, manual data collection dominates, fragmented IT architecture.
Vertical integrators	Emphasis on digitalisation, unstructured cross-functional collaboration, isolated analytical capabilities, limited integration with external supply chain.
Horizontal collaborators	Digitalisation activities across the whole value chain (internal and external), thorough data use, comprehensive data analytics, central business intelligence manages information sources (internal and external).
Digital champions	Develop novel digital models, collaboration extends beyond value chain partners, completely digitised with their partners, use of predictive analytics in real-time optimisation.

Rajnai and Kocsis [9] noted Forrester's four digital maturity dimensions: culture, technology, organisation, and insights. The digital maturity readiness level of the stated digital maturity dimensions can be evaluated using a set of criteria of four maturity levels, as presented in Table 3.

Table 3: Forrester's four levels of digital maturity readiness levels [9]

Digital maturity readiness level	*Characteristic*
Differentiators	Leveraging data to meet customer requirements
Collaborators	"Breaking down traditional silos"
Adopters	"Investing in skills and infrastructure"
Sceptics	Starting the digital transformation journey

Siemens [5] discusses four different Industry 4.0 maturity levels, as presented in Table 4. The reviewed literature points out that a significant number of authors use a four-level maturity model.

Table 4: Industry 4.0 maturity levels

Maturity level	*Description*	*Criteria (P)*
Emerging	Companies that are struggling to start digital transformation initiatives	<35%
Developing	Companies have embarked on initial steps towards digital transformation, but still face obstacles to progress.	35%<P≤65%
Established	Significant strides have been taken in the digital transformation journey, with room for improvement in some areas.	65%<P≤90%
Advanced	Companies have adopted digital transformation, and are regarded as mature.	90%<P≤100%

Rajnai and Kocsis [9] and Basl and Koop [17] discuss the Impulse Foundation of Verband Deutscher Maschinen- und Anlagenbau (VDMA) "Industrie 4.0 Readiness" self-assessment tool [18, 19], which is built upon six dimensions: organisational strategy, smart factory, smart operations, smart products, data-driven services, and employees [9, 18, 19].

In the VDMA survey, each of the six dimensions is evaluated, and the overall readiness score is obtained from the weighted average score. Table 5 presents the weighted score for each of the six dimensions considered. The VDMA "Industrie 4.0 Readiness" [19] model has six readiness levels, described in Table 6. Basl and Kopp [17], in their study evaluating the readiness of Czech companies, used the VDMA readiness model and categorised the preparedness levels using the criteria presented in Table 6 [17].

Table 5: Dimensions' weighted scores [9, 19]

Dimensions	*Weighted Score*
Organisational strategy	25%
Smart factory	14%
Smart operations	10%
Smart products	19%
Data-driven services	14%
Employees	18%

Table 6: Industry 4.0 preparedness categories [17, 19]

Readiness level	*Description*	*Criteria*
Level 0: Outsider	• Either no requirement is met, or Industry 4.0 is unknown and irrelevant.	0
Level 1: Beginner	• Pilot initiatives in Industry 4.0, investments in single area. • Infrastructure partially meets future requirements. • Skills are found in few areas.	0 < Points ≤ 50
Level 2: Intermediate	• Incorporating Industry 4.0 into the company strategy. • Investments in noticeable number of areas. • Partial automation in collection of data. • Skills available in some areas to pursue Industry 4.0.	50 < Points ≤ 90
Level 3: Experienced	• Strategy formulated. • Investments in significant number of areas. • Infrastructure may be upgradable. • Security in place for the information technology systems.	90 < Points ≤ 120
Level 4: Expert	• Industry 4.0 strategy in use. • Investment achieved in almost the entire organisation • Large amounts of data collected automatically and used for optimisation purposes. • Availability of add-on information technology functionality in the products.	120 < Points ≤ 145
Level 5: Top performer	• Industry 4.0 strategy implemented and monitored for progress. • Industry 4.0 investments in the entire company • Infrastructure satisfies all Industry 4.0 requirements.	145 < Points ≤ 160

Samaranayake, Ramanathan, Laosirihongthong [20] discussed the factors that influence digital transformation readiness, but did not present an Industry 4.0 readiness model. Six technological readiness dimensions were formulated: "improve and develop the internet system, knowledge of humans in technology and how to use it, improve ability of machine and device in connecting to internet, ability to manage big data, data sharing between or within organisation and develop the data security system"[20].

Industry 4.0 is a moderately new phenomenon [20]; so Rajnai and Kocsis [9] point out that there is no an universally agreed and proven methodology for assessing Industry 4.0 readiness. Thus the contribution by Botha [13] on the characteristics of the future readiness model to assess the Industry 4.0 readiness level is acknowledged. Botha [13] outlines a conceptual readiness model that will direct the evaluation of future readiness for Industry 4.0. Technology, the behaviour of both the external and internal markets (workforce and workers), and events were identified as the future-shaping factors in assessing the Industry 4.0 readiness level [13]. Although this contribution is substantial, it is not within the scope of this research, which seeks to explore the current readiness of South African industries to implement Industry 4.0 technologies and design principles.

The Industry 4.0 readiness assessment by VDMA [18, 19] is a well-grounded tool that has been used and suggested by researchers to perform exploratory Industry 4.0 readiness assessments [9, 17, 21]. Thus, to perform this exploratory study, the VDMA assessment tool was chosen from the existing and available Industry 4.0 readiness assessment tools. In line with good ethical practice, permission to use the VDMA questionnaire for research purposes was obtained.

3.2 Industry 4.0 readiness assessment indicators

Using the concept of indicators applied by Siemens [5], this study identified possible indicators to be used in the assessment of the Industry 4.0 readiness level. These indicators were formulated using the study by the VDMA [19], and are presented in Table 7.

Table 7: Industry 4.0 readiness assessment [5, 19]

Category	Sub-category	Indicator
Organisational strategy	Industry 4.0 strategy implementation	• Strategy implementation status • Strategy compatibility with overall organisational strategy
	Organisational investments	• Number of distinct areas with investments or plans to invest in Industry 4.0
	Systematic technology and innovation management	• Number of distinct areas with systematic technology and innovation management
	Industry 4.0 technologies	• Number of technologies in use
Organisational infrastructure	Equipment functionalities	• Level of use of IT to control machine systems • Level of use of Machine to Machine communication • Level of machines' interoperability
	Equipment functionalities' adaptability	• Level of use of M2M communication • Level of machines' interoperability
	Digital modelling	• Machine data collection and processing
	Systems, and interface to leading system	• Number of systems in use • Number of systems in use with leading interface
Smart operations	Cross-departmental information sharing	• Number of departments with internal integrated cross-departmental information sharing • Number of departments with external integrated cross-departmental information sharing
	Autonomous functionality	• Availability of autonomous workpiece guides • Availability of autonomous production process response in real time
	IT solutions	• IT organisation • Security solutions implementation level • Use of cloud services
Smart products	Products functionality based on ICT	• Number of add-on functionalities
Data-driven services	Data usage and analysis	• Use of data and process data to enable new services • Use of data analytics
Employees	Industry 4.0 skills	• Level of existing skills

3.3 Questionnaire structure

A questionnaire instrument with quantitative criteria was used as the research strategy in this study. The employed questionnaire instrument was adopted from a study performed by VDMA [18], with a few questions changed and modified to suit South African industries.

After making the necessary changes, the questionnaire instrument consisted of one qualitative question to investigate respondents' understanding of what Industry 4.0 is, and 23 quantitative questions. The questions were grouped into the following sections:

Section 1: General questions, which sought to gather respondents' information, such as industry type, organisational size, position, and general understanding of the term 'Industry 4.0'.

Section 2: Organisational strategy questions that assessed the strategy implementation status, organisational compatibility with Industry 4.0, and level of investment in Industry 4.0 initiatives. The section further identified technologies that the organisation was actually using at the time of the survey.

Section 3: Infrastructure questions sought to gather data on the level of equipment infrastructure adaptability to Industry 4.0 functional requirements that enable a link between the physical and virtual worlds.

Section 4: Questions on operations assessed the concept of vertical and horizontal integration, which is the enterprise-wide and cross-enterprise integration of the physical and virtual worlds.

Section 5: Products questions measured the capability to gather data on products, know the way through production, and communicate with higher-level systems. Respondents were asked to identify product information and communication add-on functionalities offered by their organisations.

Section 6: Data-driven questions sought to measure how organisations evaluated and analysed data collected on enterprise-wide integration. Respondents were asked whether they gathered data on production and in the usage phase, and analysed data for continual improvement.

Section 7: Questions on employees assessed the availability of employee skills for digital transformation. Respondents were asked to evaluate the skills available in their organisation for future requirements under Industry 4.0.

3.4 Sampling technique

Sampling techniques are grouped as probability and non-probability sampling methods, among others [22-24]. The convenience sampling technique, which is a non-probability sampling method, is applicable to quantitative research [22] and was selected for this study. Etikan, Musa, and Alkassim [22] state that the type of non-probability sampling selected for a study depends on the type, nature, and purpose of the study.

This study is an exploratory one to obtain primary data from a general group of respondents, thus making convenience sampling appropriate for the study [25]. In addition, Kindle, in answering Gurung [26], stated that convenience sampling is totally acceptable in an area of study that is fundamentally new — in this case, Industry 4.0. The survey instrument is designed in such a way that an organisational readiness assessment can be provided by any individual at management level. Using the argument of Etikan *et al.* [22], convenience sampling suits this study in view of the possibly large size of the population and the need to reach as many participants as possible.

In carrying out a pilot study to assess the state of Industry 4.0 across German companies, Bittighofer *et al.* [10] used convenience sampling of the 30 available employees. In the current study, the researchers used the available network, which included the SAIIE 29th conference contact list, Industry 4.0 platforms in South Africa [27], and LinkedIn contacts, to reach out to potential respondents. The participants were randomly selected on condition that they held a management position.

Etikan *et al.* [22] state that convenience sampling targets a population that satisfies practical criteria, such as ease of access, and that is keen to participate in the study. According to the researchers, easy accessibility can be interpreted to be the mode of identifying and accessing the population. In this study, online platforms were used to access potential participants, further justifying convenience sampling as an appropriate method.

The main disadvantage of convenience sampling is that it may be biased; the results would then not be representative of the population [22]. Skowronek and Duerr [28] pointed out that bias in convenience sampling can be eliminated by making the sample significantly representative, increasing its diversity by the way in which the survey instrument is distributed, and incorporating as much data as possible. In this study, convenience sampling bias was avoided by randomly distributing the questionnaire to as many people as possible in different industries, using different platforms.

3.5 Data analysis

Question 5 [29] of the questionnaire survey was an open-ended question, and could only be analysed qualitatively. Castleberry and Nolen [30] state that responses to open-ended questionnaire questions can be treated as qualitative data. The first three steps in the thematic analysis procedure outlined by Castleberry and Nolen [30] was used to analyse question 5. Using the 25 first cycle coding methods presented by Saldana [31], descriptive codes were applied in performing this analysis. The amount of textual data collected in this question was notably small, justifying the use of manual analysis. The response to this question contributed zero points in the calculation of the readiness dimension score.

Using descriptive statistics is deemed a necessary data analysis approach when dealing with convenience sampling data [32]; so it was applied in this study. Although statistical analysis results from convenience sampling data are not necessarily generalisable beyond the sample [22, 24], inferential statistics tools were applied in determining whether there was a significant difference between the dimensions' contributions to the overall readiness level.

A discussion by a group of researchers of the answer to the question, "What are the statistical tests applicable to a study that has recruited participants using convenience sampling?", it was pointed out that any statistical tests can be used [33]. The only limitation is that the results cannot be generalised to a broader population.

Questions 6 to 24 were quantitative in nature, and were coded in order to calculate the total score for each readiness assessment dimension. Table 8 presents the possible total score for each readiness dimension, which was determined by finding the possible total score for each question and adding up these scores for the questions belonging to that specific readiness dimension. The total score for each question was determined in two ways: (a) assigning a value of 1 to all the positive responses, as required by the question, and adding up all the possible total scores; and (b) assuming the Likert scales to be interval data, converting the verbal Likert rating scale to a numeric Likert rating scale, and adding up all the possible total scores for the question. The possible total score was used to calculate the percentage score for each readiness assessment dimension.

Table 8: Possible total score for each readiness dimension

Readiness dimension	Possible total score
Organisational strategy	36
Infrastructure	39
Operations	45
Products	9
Data-driven services	4
Employees	27

Table 9 shows the criteria that were used to identify the readiness level for each dimension. The overall readiness for each organisation was calculated using the proven VDMA [19] weighting percentages yardstick presented in Table 5, *although* these were originally established for the German industry, which has different constructs from the South African industry. It is assumed that, to assess Industry 4.0 readiness for any country in the true sense, the six dimensions should have similar weighting percentages in the assessment. The VDMA [19] and Siemens [5] models are merged to formulate the final categories in analysing the data.

Using the case of the VDMA [19], the dimension 'organisational strategy' had an additional criterion, which states that a company would automatically achieve level 0 if either question 6 or question 7 [29] carried zero points. This would make the dimension 'organisational strategy' carry no weight in the company's overall readiness level. Further to this, if respondents indicate that Industry 4.0 is not compatible with their organisation, this results in an overall readiness level of zero. Indicators in any questions contributed no score if the respondents chose not to enter any feedback.

Table 9: Readiness levels criteria by percentage (X) [5, 19]

Category	*Readiness level*	*Description*	*Criteria*
Emerging	Level 0	Outsider	0
	Level 1	Beginner	$0 < X \leq 30$
Developing	Level 2	Intermediate	$30 < X \leq 65$
Established	Level 3	Experienced	$65 < X \leq 80$
	Level 4	Expert	$80 < X \leq 90$
Advanced	Level 5	Top performer	$90 < X \leq 100$

Organisations were categorised into three main clusters: small, medium, and large enterprises. Aigbavboa and Thwala [34], Mahembe [35], van Scheers [36], and Mago and Toro [37] agree that there is no one-size–fits-all formula for classifying organisations into small and medium enterprises (SME).

This study uses the statistical definition of SME [35] that uses the number of employees as the quantifying factor. Table 10 presents a classification of organisations in terms of number of employees.

Table 10: Organisations' classification [34, 35, 38]

Category	Number of employees (Y)
Small enterprises	$20 \leq Y < 50$
Medium enterprises	$50 \leq Y < 200$
Large enterprises	≥ 200

Organisations were also further divided into five industry categories: manufacturing, mining, chemical, aerospace, and other. This was applied in the additional analysis of data obtained.

4 SURVEY RESULTS AND ANALYSIS

In this study, descriptive statistics and inferential statistics are used to analyse the primary data collected from the respondents. Section 4.1 will analyse the respondents' profile, and section 4.2 will outline the respondents' understanding of Industry 4.0. An assessment of the organisations' overall Industry 4.0 readiness is presented in section 4.3. Section 4.4 presents the results analysis by readiness dimensions.

4.1 Respondents' profile analysis

The total number of respondents in this study was 36. The sample size used in this study is comparable to that in a similar study undertaken by Bittighofer *et al*. [10]. According to the province in which respondents' organisations are situated, 69 per cent were from Gauteng, representing the majority of the respondents; 14 per cent were from the Western Cape; Mpumalanga, Limpopo, KwaZulu-Natal, the Free State, and North-West all yielded the same representation of three per cent.

Figure 1 shows the respondents' organisation by industry category, with 42 per cent and 36 per cent of the representation from the categories 'Other' and 'Manufacturing' respectively.

Figure 2 presents the respondents' organisations according to their size, as defined in Table 10. The majority of respondents, 61 per cent, indicated that they were from large enterprises, with 14 per cent and 25 per cent respectively representing small and medium enterprises.

4.2 Industry 4.0 definition analysis

Despite belonging to large organisations and holding relatively high positions, 11 per cent of the respondents indicated that they had no idea what Industry 4.0 was. The "what, who, when, where, why, how" concept suggested by Castleberry and Nolen [30] was used to identify codes that described how respondents understood Industry 4.0. Table 11 summarises the findings of the thematic analysis.

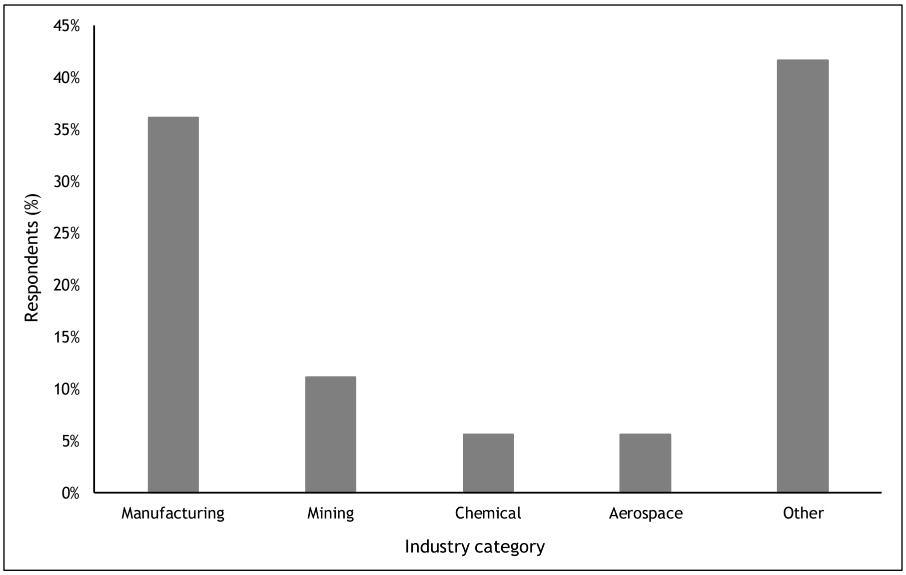

Figure 1: Respondents' companies by industry category

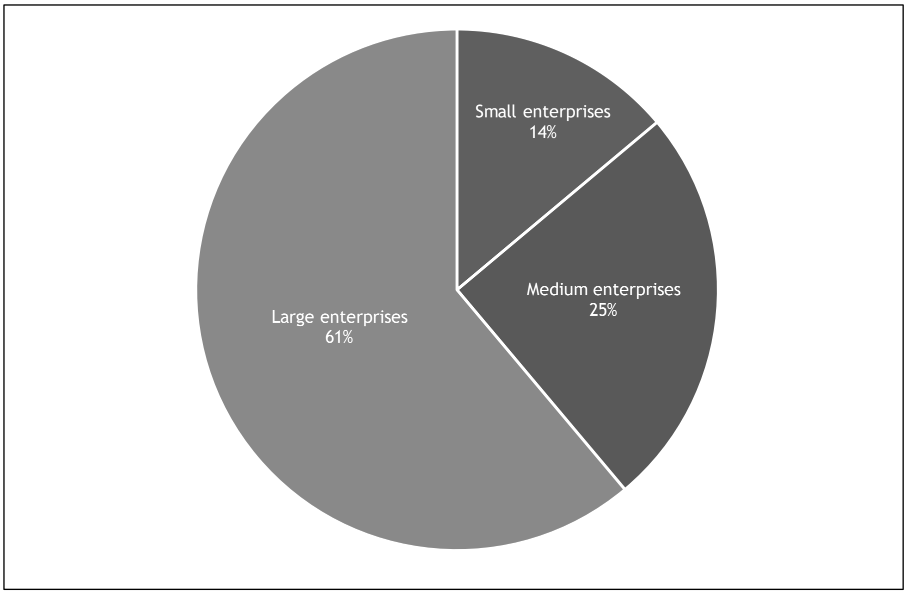

Figure 2: Representation by company size

Table 11: Respondents' views on "What is Industry 4.0?"

Theme	Codes	Comments
What is involved?	• 4th industrial revolution • Technology • Data • Customisation	Significant variation in understanding Industry 4.0, with some respondents pointing out that Industry 4.0 is synonymous with the 4th industrial revolution. Technological advancement and data were viewed as enablers of Industry 4.0.
Who is involved?	• People • All business • Industries • Manufacturing	Noticeable number of respondents were in agreement that Industry 4.0 affects all industries and businesses and that it involves people. However, there were others who defined it as only applicable to the manufacturing industry.
When should it take place?	• Now • Future	Some saw Industry 4.0 as happening currently; others viewed it as a future concept.
Why should it happen?	• Optimisation • Competitiveness	There was alignment in the thought that Industry 4.0 is meant to achieve business optimisation and increase competitiveness.
How can it be accomplished?	• Integration • Agility • Connectivity • Automation • Digitalisation	Respondents pointed out that Industry 4.0 will happen through the integration of digital, biological, and physical technological systems. A significant number of respondents pointed out that connectivity and automation will drive Industry 4.0.

Although respondents had different understandings of what Industry 4.0 is, there was agreement on what they thought was involved and why it should happen. The common understanding was that a large amount of data would be involved, and had to be analysed for the purpose of improving processes, systems, and services. Technological advancement was identified as one of the pillars of Industry 4.0.

4.3 Industry 4.0 overall readiness level

4.3.1 Overall readiness level

Figure 3 presents the results of the organisations' overall Industry 4.0 readiness level. The analysis revealed that the overall Industry 4.0 readiness level for all the organisations that were considered in this study ranged between level 0 and level 3; 47 per cent of the organisations qualified for readiness level 2, and 8 per cent were eligible for level 3.

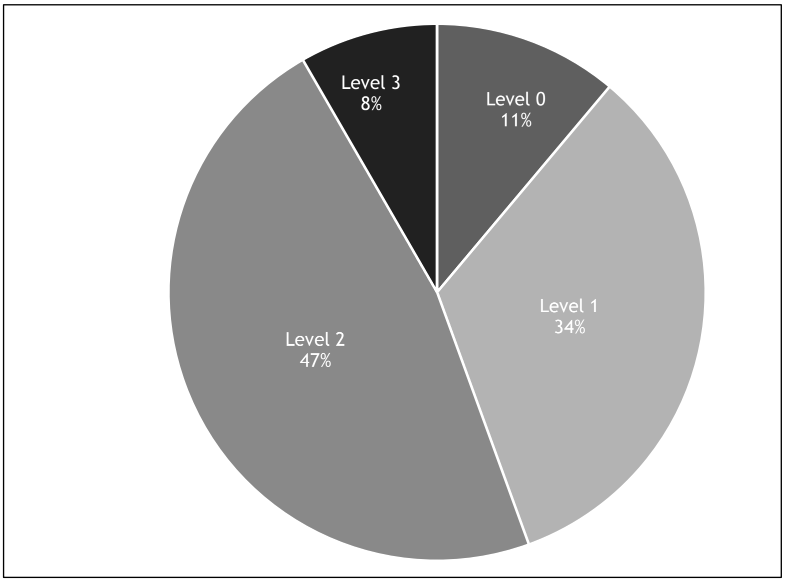

Figure 3: Organisations' overall Industry 4.0 readiness level

4.3.2 Overall readiness level by size of the organisation means graph

Figure 4 shows that the error bars in the means graph for the overall readiness level overlap. Accordingly, there is no significant difference between the mean average readiness level for small enterprises, medium enterprises, and large enterprises that are represented in this study within a 95 per cent confidence level (CI: 95 per cent). The graph shows that large enterprises have a smaller variance, meaning that they are more certain about their readiness level.

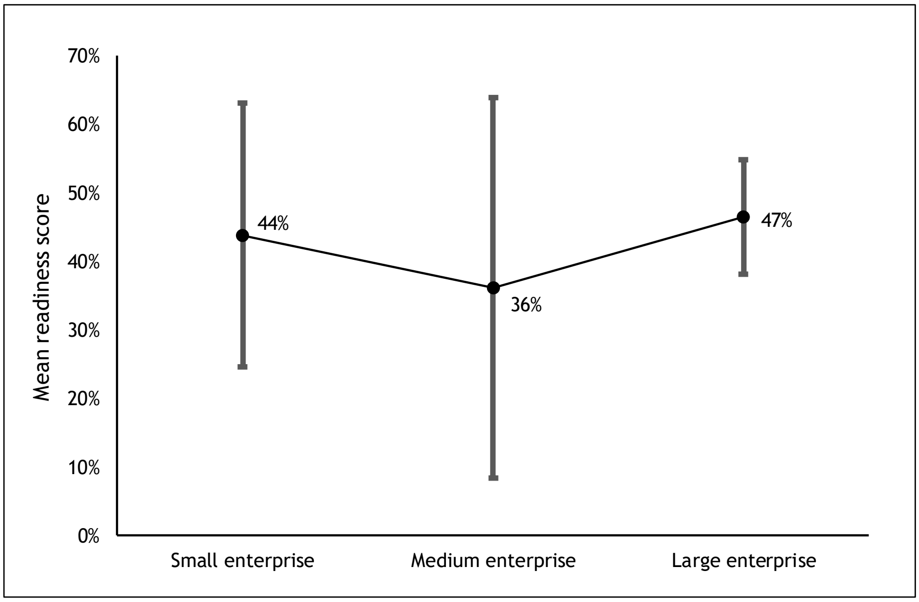

Figure 4: Overall readiness level score means graph (CI: 95%)

4.3.3 ANOVA results

To verify the means graph in Figure 4, an ANOVA test was performed. The results are presented in Table 12, and show that there is no need to perform t-tests.

Table 12: ANOVA analysis results

Test	P-value	Conclusion
ANOVA results	0.394	There is no statistical difference between the organisational sizes' average readiness percentage scores.

4.4 Industry 4.0 readiness by dimension

4.4.1 Readiness dimension means graph

The readiness dimension means graph is presented in Figure 5. The error bars in the means graph overlap, indicating that there is no significant difference between the contribution of any readiness dimensions to the overall readiness level (CI 95 per cent).

4.4.2 ANOVA and t-test analysis results

To verify the means graph findings in Figure 5, a null hypothesis (H_0) and alternative hypothesis (H_A) were formulated and tested using ANOVA and the respective t-test.

H_O: There is no significant statistical difference in contribution to the Industry 4.0 overall readiness level between the six readiness dimensions.

H_A: There is a significant statistical difference in contribution to the Industry 4.0 overall readiness level between the six readiness dimensions.

Table 13 presents the ANOVA results performed on the dimensions' contribution to the overall readiness level. The ANOVA test results show that there is a need to perform a t-test between each pair of the dimensions.

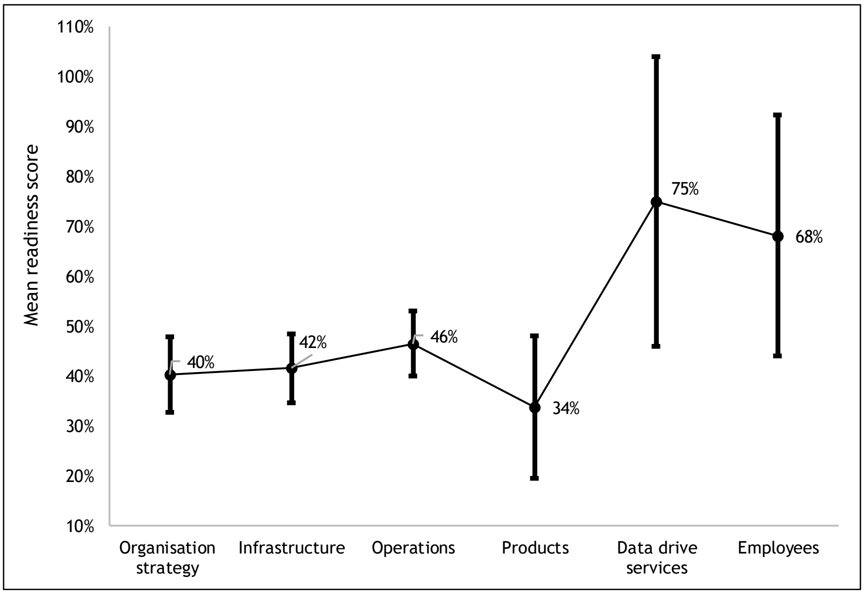

Figure 5: Readiness dimension means graph (CI: 95%)

Table 13: ANOVA analysis results

Test	P-value	Conclusion
ANOVA results	6.2×10^{-14}	There is a statistical difference between at least two dimensions in contributing to overall readiness

Table 14 presents the t-test results. The number in each cell represents the p-value. The results show that there is no significant statistical difference in contributing to the overall readiness level between organisational strategy, infrastructure, operations, and products. On the other hand, no noticeable statistical difference exists between data-driven services and employees in contributing to the overall readiness level.

Table 14: t-test analysis results (p-value)

	Infrastructure	Operations	Products	Employees	Data-driven services
Strategy	0.08	0.11	0.24	$5,3 \times 10^{-6}$	4.9×10^{-7}
Infrastructure		0,29	0,14	$6,3 \times 10^{-6}$	$6,4 \times 10^{-7}$
Operations			0.05	1.3×10^{-4}	1.0×10^{-5}
Products				1.9×10^{-7}	2.4×10^{-8}
Employees					0.29

(dark grey)	No significant difference between the two dimensions
(light grey)	Significant difference between the two dimensions

5 DISCUSSION OF RESULTS

Results from the respondents reveal that, although respondents have different understandings of what Industry 4.0 is, there is agreement on what is involved and why Industry 4.0 should happen. The common understanding is that Industry 4.0 involves huge amounts of data that must be analysed for the purpose of improving processes, systems, and services. A significant number of respondents pointed out that technological advancement is one of the pillars and enablers of Industry 4.0. However, some respondents still have a narrow understanding of Industry 4.0 — an indication that promoting awareness of Industry 4.0 to create common understanding is necessary.

The Industry 4.0 overall readiness level results indicated that 45 per cent of the organisations are at the emerging level. Emerging level organisations comprise 11 per cent of those who have done nothing and have no intention of doing anything. Another 34 per cent are at the beginning stage. The results further indicated that 47 per cent of organisations are at the developing stage, while eight per cent claim to have elements of being established. On average, it is evident that small, medium, and large enterprises are all more-or-less in the same range of readiness for Industry 4.0.

In total, 80 per cent of the respondents pointed out that their organisations were in the emerging category (47 per cent) or developing category (33 per cent) in terms of Industry 4.0 organisational strategy. The organisations in the emerging category either have no existing Industry 4.0 strategy, or they have launched pilot initiatives. This could be interpreted as a lack of commitment to drive Industry 4.0 initiatives in a significant number of organisations in South Africa.

The results indicated that a number of organisations experience significant challenges in areas of equipment infrastructure that support Industry 4.0 requirements. In total, 84 per cent of organisations are in the emerging category (42 per cent) or developing category (42 per cent). These results could be interpreted as a significant number of organisations in South Africa not having equipment infrastructure that supports Industry 4.0 requirements. Further to this, their equipment functionalities might not be upgradable to Industry 4.0 requirements.

Regarding smart operations, 78 per cent of organisations are in the emerging category (28 per cent) or developing category (50 per cent). This could be an indication that a significant number of organisations are not prepared for vertical and horizontal integration of the physical world and virtual worlds. In addition, Industry 4.0 technical requirements for production and production planning might not be fulfilled. Regarding products' readiness for Industry 4.0, 97 per cent of organisations belong to the emerging category (72 per cent) or developing category (25 per cent). The result could be interpreted as organisations' current products not having functionalities that that meet Industry 4.0 requirements.

Contrary to the other four Industry 4.0 readiness dimensions, 51 per cent of the respondents pointed out that their organisations are in the established category (34 per cent) or advanced category (17 per cent) regarding employees' skills requirements. This could be interpreted as Industry 4.0 skills existing in South African, although these might be inadequate. In support of the current literature on the availability status of Industry 4.0 skills, the results could be interpreted as respondents failing to recognise the skills required for Industry 4.0. This is an indication that further study in this area is essential.

In total, 56 per cent of the respondents indicated that their organisations were in the established category (25 per cent) or advanced category (31 per cent). This could be interpreted as a significant number of organisations collecting digital data and analysing it for continuous improvement purposes.

The ANOVA and t-test results proved the point that employee skills requirements and data-driven services differ significantly from the other four dimensions in their contribution to overall readiness for Industry 4.0. Although this could not be generalised beyond the sample used, the statistical results proved the points discussed in this section.

6 CONCLUSION

Knowing one's Industry 4.0 readiness status is fundamental to the successful adoption and embracing of digital transformation. This exploratory study uncovered significant shortfalls in the area of Industry 4.0 strategy in organisations. A noticeable number of organisations do not have an existing strategy, which is the driver of the adoption of Industry 4.0. Although this might not be a full representation of all South African industries, the study revealed that there are noticeable challenges in terms of equipment infrastructure that supports Industry 4.0 and equipment functionalities' upgradability to meet Industry 4.0 requirements. The exploratory study pointed out that Industry 4.0 skills in South Africa exist in pockets. South African industry could be categorised as partially emerging and partially developing in the area of digital transformation, according to this exploratory study. Further study to reveal more detail on Industry 4.0 skills requirements is essential.

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APPENDIX B: ARTICLE 2

sustainability

Article

Factors that Inhibit Sustainable Adoption of Industry 4.0 in the South African Manufacturing Industry

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Abstract: Industry 4.0 (I4.0) adoption in the manufacturing industry is on the rise across the world, resulting in increased empirical research on barriers and drivers to I4.0 adoption in specific country contexts. However, no similar studies are available that focus on the South African manufacturing industry. Our small-scale interview-based qualitative descriptive study aimed at identifying factors that may inhibit sustainable adoption of I4.0 in the country's manufacturing industry. The study probed the views and opinions of 16 managers and specialists in the industry, as well as others in supportive roles. Two themes emerged from the thematic analysis: factors that inhibit sustainable adoption of I4.0 and strategies that promote I4.0 adoption in the South African manufacturing industry. The interviews highlighted cultural construct, structural inequalities, noticeable youth unemployment, fragmented task environment, and deficiencies in the education system as key inhibitors. Key strategies identified to promote sustainable adoption of I4.0 include understanding context and applying relevant technologies, strengthening policy and regulatory space, overhauling the education system, and focusing on primary manufacturing. The study offers direction for broader investigations of the specific inhibitors to sustainable I4.0 adoption in the sub-Saharan African developing countries and the strategies for overcoming them.

Keywords: Industry 4.0; sustainability; manufacturing industry; South Africa; technology adoption drivers; technology adoption barriers; qualitative descriptive study

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1. Introduction

Adoption of Industry 4.0 (I4.0) has been on the rise in developed countries' manufacturing industries, with other developing countries, such as China and India, following suit. The term I4.0 was coined in Germany in 2011, and its principles were adopted to enhance the competitiveness and growth of the national manufacturing industry [1–3]. The subsequent wide-ranging adoption of this approach recognizes it as an enhancer of competitiveness and growth in the manufacturing industry [4,5].

Although acknowledged globally, the adoption of I4.0 in South Africa has not been analyzed in the literature. Its many benefits in the country could include enhancing global competitiveness and boosting productivity and revenue growth of the manufacturing industry [4,5]. The adoption of I4.0 therefore attracts significant interest from sectors related to and supporting the manufacturing industry, including the digital industry, public sector, research and development, and non-governmental organizations (NGOs). However, the adoption of I4.0 also has the potential of widening global inequality among and within countries, and could hinder the achievement of the United Nations 2015 sustainable development goals (SDGs) [6]. In particular, I4.0 could detrimentally affect the achievement of SDG 8 (the promotion of sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all), SDG 9 (inclusive and sustainable industrialization), and SDG 10 (reduction of inequality within and among countries) [7] in developing countries [8].

Industry 4.0 is not a one-size-fits-all framework, and a geographic lens is necessary when exploring relevant barriers and driving factors [9,10]. An increasing number of studies have focused on the drivers and barriers to I4.0 adoption in various developed and developing countries [9,11–13], but none so far in South Africa. This is one of several developing countries moving towards convergence with developed country standards [14], and has the potential of becoming a leader for sustainable adoption of I4.0 in the manufacturing industry sector in sub-Saharan Africa. The country also played an active role in the development of the SDGs, and is committed to the efforts needed to meet these goals [15]. Thus, it could illuminate the benefits of I4.0 adoption and introduce strategies for identifying and mitigating its potential negative impacts on SDGs, thereby acting as a benchmark in the region. Understanding the contextualized barriers in the country, as well as the drivers of sustainable adoption of I4.0, could be the first step towards the achievement of both I4.0 and SDGs.

The South African manufacturing industry has been shrinking over the past two or more decades. Its share of the country's gross domestic product decreased from 19.3% in 1994 to 12% in 2018 [15]. Notably, the industry employs both semi-skilled and low-skilled employees [16]. Adoption of the I4.0 initiative [17–19] could therefore pose significant challenges when balancing the manufacturing industry's attempts both to catch up and keep pace with developed countries and to address the issue of unemployment in its fields of operation [20,21]. In seeking ways to strike this balance, it is important to explore contextual factors that currently inhibit sustainable adoption of I4.0.

South Africa also faces socioeconomic challenges, including non-inclusive economic growth and inequality [15,22,23]. To address them, the South African government launched the national development plan (NDP) in 2012, which aimed at fighting poverty, inequality, and unemployment and at growing an inclusive economy [15,24]. This NDP predated the SDGs, but has a high (74%) correlation to them [15,24]. Both the SDGs and South Africa's NDP feature and emphasize an end to poverty, protection of the environment, and inclusive prosperity [7,15]. Achieving sustainability in the South African manufacturing industry through I4.0, therefore, requires that its adoption aligns with the objectives of the NDP and the SDGs. This challenge can be addressed most effectively if factors that inhibit sustainable adoption of I4.0 in the country are properly understood within the specific national context.

Barriers and drivers pointed out in existing studies [2,4,5,9–13,25,26], such as lack of ICT infrastructure, lack of standards, data security concerns, high investment requirements, skills shortages, lack of regulatory framework, and lack of implementation strategy, could apply to the South Africa manufacturing industry. However, factors unique to the country could inhibit sustainable adoption of I4.0. Public and private sector workshops, seminars, and conferences on I4.0 and the fourth industrial revolution are noticeably on the rise in the country [27]. However, there is a lack of empirical studies focusing on the South African manufacturing industry context [28–31]. To address this gap, we designed a small-scale interview-based exploratory qualitative study to identify factors that could inhibit sustainable adoption of I4.0 in the country's manufacturing sectors. Interviews offered us the opportunity to gather the views of individuals whose work was relevant to I4.0 adoption in these sectors. Participants came from sectors that provide support and have an interest in manufacturing, such as the digital industry, the research and development sector, the public sector, and relevant NGOs. Those taking part provided perspectives from management as well as a content expert perspective. We aimed to obtain a sense of the direction that I4.0 adoption might take in South African manufacturing, and to explore nuances specific to this context that, to date, have not been identified in the academic literature. The study was guided by the research question: what are the factors that inhibit sustainable adoption of I4.0 in the South Africa manufacturing industry?

The remainder of this article is structured as follows: Section 2 presents a theoretical background to sustainable technology adoption in the manufacturing industry and a literature overview on worldwide barriers and drivers to I4.0 adoption; Section 3 presents the empirical setting together with data collection and data analysis; Section 4 presents the study results, which are discussed in Section 5 and lead to the study limitations and direction for future research; Section 6 concludes the study.

2. Theoretical Background and Literature Review

The countries that are signatories to the UN's 2015 Sustainable Development 2030 agenda face the challenge of achieving its 17 goals [7,32]. According to Fu et al. [32], sustainable technology adoption could facilitate their meeting the SDGs, and has attracted interest from both society and academia [32]. However, studies relating to sustainable technology adoption have focused mainly on SDGs related to the environment and economics, and less on its social aspects.

Sustainable technology adoption following the I4.0 framework includes the adoption of technologies such as cyber-physical systems, the internet of things, additive manufacturing, and autonomous robotics [2,3,33]. Sony and Naik [34] pointed out that such adoption is regarded as sustainable if it balances the environmental, economic, and social needs of present and future generations [34], and Müller et al. [12] have stressed the need to balance the environmental, economic, and social aspects of sustainability when adopting I4.0 technologies. These principles also apply to technology adoption in the manufacturing industry [4,35–37].

Müller et al. [12] pointed out that the current literature predominantly investigated the impact of I4.0 from a single technological adoption sustainability aspect [12]. Adoption of I4.0 technologies in manufacturing has significantly focused on economic sustainability, competitiveness, and growth [1–3]. Other studies that focused on environmental sustainability are exemplified by de Sousa Jabbour et al. [38], who pointed out the need for balancing I4.0 adoption and environmental sustainability. Müller et al. [12] addressed the balancing of environmental and economic sustainability in Germany's manufacturing industry. The developing country context of I4.0, however, has not so far been examined from the social sustainability standpoint.

Existing studies have already revealed the societal advantages of technology adoption in developing countries, such as, for example, in the application of big data and big data analytics to mitigate the effects of disease outbreaks [39] to foster informed decision-making in private and public spheres in this area, and to improve predictive capacity when planning for future requirements. Studies are still lacking, however, that investigate I4.0 adoption in manufacturing, taking into account the satisfaction of broader social, economic, and environmental issues that could otherwise undermine sustainability in developing countries. To address this gap, our study sought to gain an understanding of factors that could inhibit I4.0 adoption within the specific context of the South African manufacturing industry in terms of the balance between competitiveness in manufacturing, on the one hand, and societal aspects of such adoption in this developing country, on the other hand, in the light of pervasive inequality and unemployment.

2.1. Barriers and Drivers Relating to Industry 4.0 Adoption

Industry 4.0 was initially conceived with the object of increasing Germany's global technological innovation competitiveness [13,40,41] and optimizing value creation in its manufacturing industry. The strategy is associated with the employment of advanced technologies in manufacturing, and the term is used to describe advances in the application of digitalization, automation, and creation of digital value chains [17–19].

There has been growth in empirical research on barriers and drivers to I4.0 in various country settings, including Romania [11], Hungary [9], Germany [2,12], India [10,13], China [41], and Denmark [25]. The studies presented here (Table 1) were selected for their detailed contributions to the understanding of factors influencing the adoption of I4.0.

Table 1. Barriers and drivers to I4.0 adoption literature overview.

Author(s) Reference	Study Focus and Setting	Key Contributions	Drivers and Barriers
Kumar et al., 2020 [5]	Analyzing the barriers to I4.0 through the best–worst method for Indian industry	Ranking of the barriers to I4.0 adoption using the best–worst method	Barriers: lack of ICT infrastructure, lack of standards, data security concerns, high investment requirements, skills shortages, lack of regulatory framework, unwanted strain, no manpower.
Stentoft et al., 2020 [25]	Drivers and barriers to I4.0 readiness and practice in Danish SME manufacturers	Demonstration of the difficulties faced by SMEs in achieving I4.0 readiness	Drivers: legal requirements, customer requirements, cost reduction, optimized time to market Barriers: lack of standards, shortage of financial resources, lack of skills, awareness challenges
Luthra et al., 2020 [4]	Examining the drivers of I4.0 to diffuse sustainability in supply chains in India	Use of Grey-DEMATEL to define the causal interactions among I4.0 drivers	Driver: competitiveness, improved information sharing system and resource development, adoption of innovative business models, collaboration and transparency
Müller 2019 [2]	Workers' perspective on concerns hampering I4.0 implementation in Germany industrial enterprise	Insights on barriers to I4.0, from workers' point of view, which can be utilized by management	Barriers: lack of competence, employee resistance to change, lack of implementation strategy, unclear benefits to workers, automation taking decisions from humans
Prause 2019 [26]	Examination of the challenges of I4.0 adoption by Japanese SME manufacturing firms	Challenges to I4.0 adoption regression model and use of Cronbach's alpha to test its reliability	Barriers: lack of knowledge, complexity of I4.0, high implementation cost, market uncertainty, security concerns
Türkeș et al., 2019 [11]	Investigation of drivers and barriers to I4.0 implementation in Romanian SMEs	Identified barriers and drivers to I4.0 implementation in Romania SMEs	Drivers: increased efficiency, product quality, global competitiveness Barriers: lack of expertise, regulations and working procedures in developing countries, lack of standards
Raj et al., 2019 [10]	Examining barriers to I4.0 technologies in developed and developing economies in the contexts of India and France	The total degree of influence that barriers to I4.0 implementation have on each other using the Grey-DEMATEL approach	Barriers: high investment cost, insufficient data and information security, lack of infrastructure, inequality, digital skills shortages, lack of standards and regulations, resistance to change
Horváth and Szabó 2019 [9]	Exploring how company executives interpret the driving forces and barriers to I4.0 implementation in Hungary	Comparison of barriers and drivers to I4.0 between SMEs and multinational companies	Drivers: workforce challenges due to aging population in developed countries, raising global competitiveness Barriers: lack of skilled workforce, insufficient data security, organizational resistance

Table 1. *Cont.*

Author(s) Reference	Study Focus and Setting	Key Contributions	Drivers and Barriers
Müller et al., 2018 [12]	Examining I4.0 opportunities and challenges in Germany's manufacturing industry	Categorical ranking of I4.0 adoption challenges/barriers	Drivers: strategic and business model opportunities that maintain and expand competitiveness, enhanced efficiency, timing, flexibility, and quality Barriers: complexity of integrating I4.0 technologies
Kamble et al., 2018 [13]	Analyzing the potential barriers to I4.0 in Indian manufacturing organizations	Establishment of barriers to an I4.0 relationship and dependence power and development of hierarchical relationships of these barriers	Barriers: legal and contractual challenges, employment disruptions, need to enhance skills requirements, lack of ICT infrastructure, insufficient security and privacy, regulatory challenges, implementation cost, lack of awareness

The country-based studies in the literature present drivers and barriers to I4.0 adoption in developed and developing countries, but none examine drivers and barriers to such adoption in sub-Saharan African developing countries. This study seeks to close this gap by investigating factors that inhibit sustainable I4.0 adoption in the South African manufacturing industry.

2.2. Industry 4.0, South Africa's National Development Plan, and the Sustainable Development Goals

The SDGs were crafted and adopted by the United Nations in 2015 [42] to drive development towards balancing the "dimensions of sustainable development: economy, social, and environment" globally [7]. This aligns with the objective of South Africa's NDP "to eliminate poverty and reduce inequality" [7,24].

The emerging of I4.0 has centered on enhancing competitiveness, productivity, and revenue growth [43]. Its value creation capability, therefore, has the potential to contribute to the achievement of SDG goals [42], such as SDG 12 ("ensure sustainable consumption and production patterns") [7], which corresponds to the NDP's Chapter 5 objective of environmental sustainability and resilience [24]. Bonilla et al. [43] pointed out that I4.0 could positively drive SDGs related to environmental sustainability, provided that technology is innovated to meet the country's requirements and supportive policies are put in place [43]. Technological advancement has been recognized for its potential to solve social and economic challenges faced by developing countries [39,44,45]. The adoption of I4.0 in a country, therefore, needs to be underpinned by well-developed and balanced policies to help it achieve both competitiveness and inclusivity.

Adopting I4.0, however, poses significant challenges and risks to aspects of inclusive development and the reduction of inequality outlined in the NDP and the SDGs [8]. Van Niekerk [6] viewed technological advancements as one of the drivers of inequality within and among countries [6]. Thus, I4.0 could potentially hinder the achievement of SDG 10 ("reduce inequality within and among countries") [7,8]. SDG 10 is aligned with the NDP's Chapter 11 (social protection).

With I4.0 comes increased job complexity requiring specialized skills [31,46,47], which makes significant demands on the manufacturing industry's skills requirements. Accordingly, the adoption of I4.0 could result in compromising achieving SDG 8 [8] (promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all) [7], which aligns with NDP Chapter 3 (economy and employment) [24]. Furthermore, developing countries have a less competitive advantage in achieving SDG 9 (inclusive and sustainable industrialization) [7,8], which aligns with NDP Chapter 4 (economic infrastructure) [24].

The literature relating to I4.0, read together with the developing country aims embedded in South Africa's NDP and the UN's SDGs, suggests that I4.0 adoption in the South African manufacturing industry requires customized supportive innovations and policies around technological development. Understanding the factors that could inhibit I4.0 adoption or undermine the broader national aims is therefore important for facilitating, designing, and developing the supportive policies needed for success.

3. Method

The research focused on exploring contextual factors that inhibit the sustainable adoption of I4.0 in the South African manufacturing industry. It followed a qualitative descriptive interview-based approach [48–50] to collect views and opinions from participants who represented different facets of the manufacturing industry about the adoption of I4.0 in this industry in South Africa.

3.1. Research Setting and Participants Sampling

The study was undertaken using semi-structured interviews with participants at management and specialist expert levels in the manufacturing and digital industries in order to obtain rich data. We included further relevant role-players from the research and development sector, public sector, and non-governmental organizations that provide support and have a special interest in manufacturing. The aim was to obtain a relevant interdisciplinary range of views and opinions.

Purposeful sampling, commonly employed in qualitative descriptive studies [51,52], was used to select the study participants based on the following inclusion criteria: practicing within South Africa; involvement in and contribution to I4.0 workshops, conferences, and online I4.0 platforms; and the participant's current position as a decision-maker or expert. The participants from the manufacturing industry came from organizations that had already adopted or were in the process of adopting I4.0, and were selected for their ability to provide informed opinions on factors that affect its sustainable adoption. The participants from the digital industry were working with I4.0 technologies and were involved in assisting manufacturing companies in the adoption journey at consultancy and support levels. These two groups were directly involved in I4.0 adoption decision-making and the design of implementation roadmaps. The public sector, research and development sector, and non-governmental organization participants were selected to provide in-depth views on I4.0 adoption with aspects of sustainable development.

Participants were recruited via e-mail, telephone, and LinkedIn. Thirty potential participants were invited, and sixteen agreed to participate. A one-page summary describing the overall study and an informed consent form to be signed by both the potential participant and the researcher formed part of the invitation. The informed consent document stipulated the research overview, expectations from the participant, risks involved, and how the risks would be minimized, as well as the handling and use of the data collected. Participation was voluntary, and all participants were free to withdraw from the research at any time during or after the interview. The study was conducted under the guidelines and clearance from the researchers' institution's ethical clearance process.

Table 2 shows the participants distribution by industry. The manufacturing and digital industries were represented by about two-thirds of the participants, with the rest representing the other selected relevant interested parties.

Table 2. Participant distribution by industry.

Industry	Number of Participants (%)	Participants [1]
Manufacturing	5 (31)	P3, P4, P8, P9, P16
Digital	5 (31)	P5, P11, P12, P13, P14
Research and development	2 (13)	P1, P6
Public sector	3 (19)	P2, P10, P15
Non-governmental organizations	1 (6)	P7

[1] Participants are referred to as P (participant) followed by an identifying number.

Table 3 shows the participant distribution by type of responsibility. Half were at the managerial level, and the rest were selected for their specialist expertise. A technology agreements facilitator, working in the government department responsible for the manufacturing industry and technology adoption, was included for perspectives relating to liaison between the industry and government.

Table 3. Participant distribution by responsibility.

Responsibility/Position	Number of Participants (%)	Participants
Management level	8 (50)	P1, P3, P4, P5, P8, P10, P12, P15
Specialist/expert level	7 (44)	P6, P7, P9, P11, P13, P14, P16
Other—Technology agreements facilitator	1 (6)	P2

3.2. Data Collection

To collect a rich dataset and participants' broader views [53], the semi-structured interviews focused on obtaining an understanding of factors influencing sustainable adoption of I4.0 in South African manufacturing. They were conducted face-to-face or by telephone, depending on the participant's preference. All were conducted in English, and no language barrier was encountered. They were audio-recorded, and field notes were taken during the course of the interviews as a first step in ensuring data credibility.

Two standard open-ended questions guided each interview: (a) can South Africa adopt I4.0 in the same way as other countries and please elaborate on your answer? and (b) please discuss the factors that you think inhibit the sustainable adoption of I4.0 in the South African manufacturing industry? The interviews lasted about 45 min to one hour, depending on the time taken to answer follow-up questions posed to yield in-depth opinions and explanations from participants. The questions were designed to collect data on the nature of the environment in which the manufacturing industry was operating, contextual factors affecting sustainable adoption of I4.0, and strategies to enhance sustainable adoption of I4.0 in the South African manufacturing industry.

3.3. Data Analysis

The interview recordings were transcribed verbatim, and the accuracy of the transcriptions was checked by subsequently comparing them with the recording and correcting the final versions as necessary.

Thematic analysis was used to identify patterns and themes in the data. This method provides the means to stay close to the data while presenting a sufficient summary of participants' views [48]. To ensure rigor, the data analysis followed the process of data familiarization, initial codes generation, reviewing of codes, searching for themes, theme review, and theme generation [54,55].

The researchers listened to the audio readings during the transcription process and formulated initial thoughts and ideas. Potentially interesting data segments were highlighted, and patterns of meaning underlined. Transcripts were imported into ATLAS.ti, and the researchers carefully read through each script, started to organize the data into meaningful chunks of data [54], and created the initial code lists using open coding in ATLAS.ti [56].

Codes were reviewed by renaming and merging codes while identifying patterns and relationships using links and network functions in ATLAS.ti [56]. This led to the identification of code categories and the generation of descriptive themes. The researchers maintained participants' views in line with the objective of a qualitative descriptive study [49,52,57]. The importance of each theme related to the research questions was generated. A summary of the themes, categories, and codes is presented in Table 4, followed by a detailed representation of participants' views. Furthermore, the co-occurrence table tool in ATLAS.ti was used to identify frequencies and determine noticeable overlaps of codes [56]. This was used for exploratory purposes and for identifying codes that required further analysis.

Table 4. Themes, sub-themes, and codes used.

Theme	Sub-Theme	Associated Codes
Factors that inhibit I4.0 adoption in the South African manufacturing industry	Socioeconomic factors	Resistance to technology, cultural construct, social structural inequalities, noticeable youth unemployment, limited access to information, awareness challenges, I4.0 geared towards competitiveness, slow pace of adoption.
	Task environment factors	Policy constraints, fragmented task environment, lagging industrial development, exponential rate of change, inadequate innovation system, international developments and trends, government support.
	Infrastructure factors	Equipment not supporting I4.0 requirements, inadequate ICT infrastructure, limited access to I4.0 technologies, limited access to reliable electricity supply, limited availability of advanced technologies.
	Human capital factors	Critical skills shortage, inadequate alignment between skills development and skills requirements, skills migration, potential negative impact on low-skilled and semi-skilled jobs.
Strategies to promote I4.0 adoption in the South African manufacturing industry		Understand context and apply relevant technologies, strengthen policy and regulatory space, overhaul education system, create I4.0 awareness, invest in I4.0 infrastructure, ensure collaboration between partners, enhance international relationships, focus on primary manufacturing, select technologies that enhance human capability and productivity.

4. Findings

From our analysis of the 16 interviews, two key themes emerged: factors that inhibit I4.0 adoption and strategies to promote I4.0 adoption in the South African manufacturing industry. Table 4 presents an overview of these themes, associated sub-themes, and the codes that were generated. These are further analyzed in Section 4.1 to Section 4.3. Though it is not a standard practice in a qualitative study, we included graphs that provide an overview of the prevalence of each inhibitor by the number of participants.

4.1. Sustainable Adoption of Industry 4.0 Inhibiting Factors

Factors that, according to our participants, inhibit sustainable adoption of I4.0 are grouped into four sub-themes: socioeconomic factors, task environment factors, infrastructure factors, and human capital factors.

4.1.1. Socioeconomic Factors

All of the participants agreed that socioeconomic factors significantly inhibit the sustainable adoption of I4.0 in the South African manufacturing industry. Figure 1 shows the number of participants who highlighted the presence of each socioeconomic inhibiting factor.

Participants from the manufacturing industry (P3), digital industry (P12), research and development (P1, P6), public sector (P2, P10), and NGO (P7) saw resistance to I4.0 technologies as a key barrier to adoption, and one in particular emphasized that such resistance was strengthened by labor unions' concern that I4.0 could potentially reduce or even eliminate low-skilled and semi-skilled jobs:

> "The other aspect from a social point of view that may be a barrier is [the] acceptance of the technologies. If you look at what the labor unions are talking about at the moment, they are more worried about job losses." (P1)

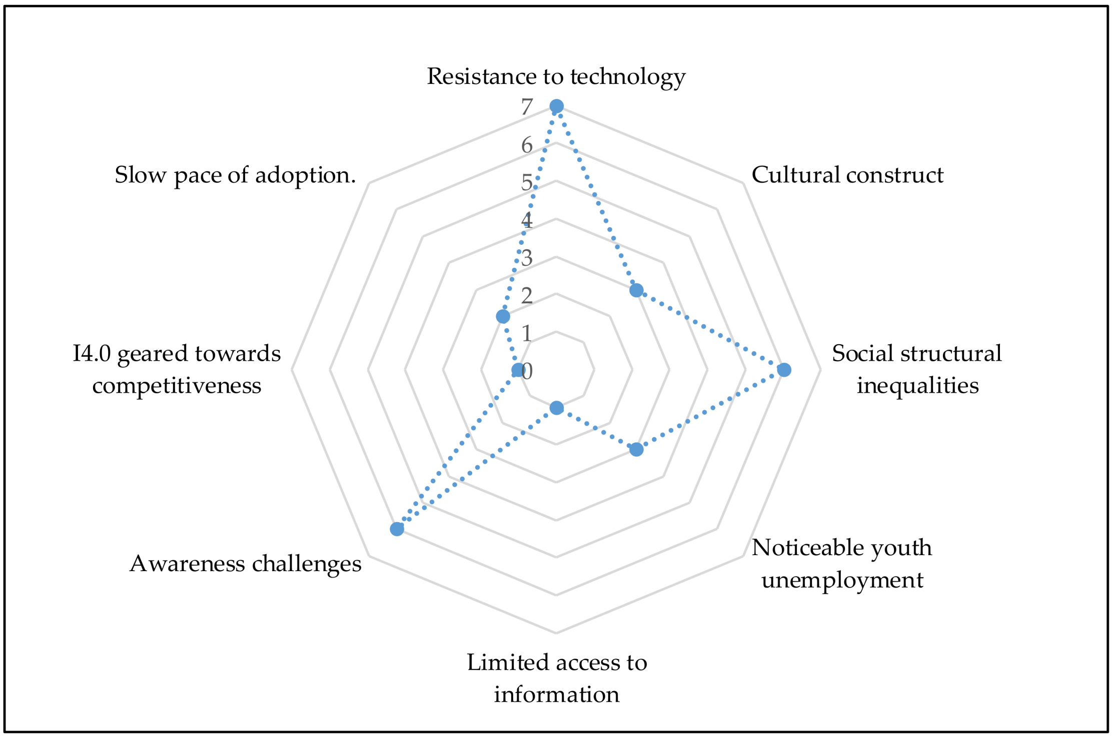

Figure 1. Socioeconomic inhibiting factors versus the number of participants.

There was also agreement from participants at management (P5) and specialist/expert (P9, P13) levels, as well as from the technology agreements facilitator, that youth unemployment deriving from their lack of basic skills greatly adds to the social-economic inhibitors to I4.0 adoption:

> "This country has problems with unemployment among young people, who come out of school and matriculation without a good education and even a very poor ability to read." (P13)

Social structural inequalities and the "the extent to which the society is wired" (P5) in South Africa additionally hinder sustainable adoption of I4.0, as pointed out by six of the participants, at management (P1, P3, P5, P10) and specialist/expert (P13) levels. They stressed the fact that I4.0 adoption in the country must focus on solving both competitiveness and equality challenges:

> ". . . I4.0 in places like Germany is about economic competitiveness. It's about making firms and sectors and the whole Germany economy more competitive in the global landscape . . . I4.0 in South Africa can't only be about competitiveness, it can't only be about firms investing in high tech and upgrading their tech and make more money. It can't just be about competing; it has also to be in some sense competing while addressing the serious issue of inequality in this country." (P10)

Participants at the management level (P3–P5, P12) and specialist/expert level (P6, P7) highlighted the lack of awareness or understanding about I4.0, its impact, and how it can be adopted in their organizations, and saw this as a factor that can restrict successful adoption:

> "I think it's number one, unawareness, overall unawareness . . . So people they hear that there is I4.0, but they don't know where to start, they don't know how [they can go about] implementing it." (P4)

4.1.2. Task Environment Factors

Figure 2 presents the task environment factors versus the number of participants who pointed to them as factors that inhibit sustainable adoption of I4.0 in the South African manufacturing industry.

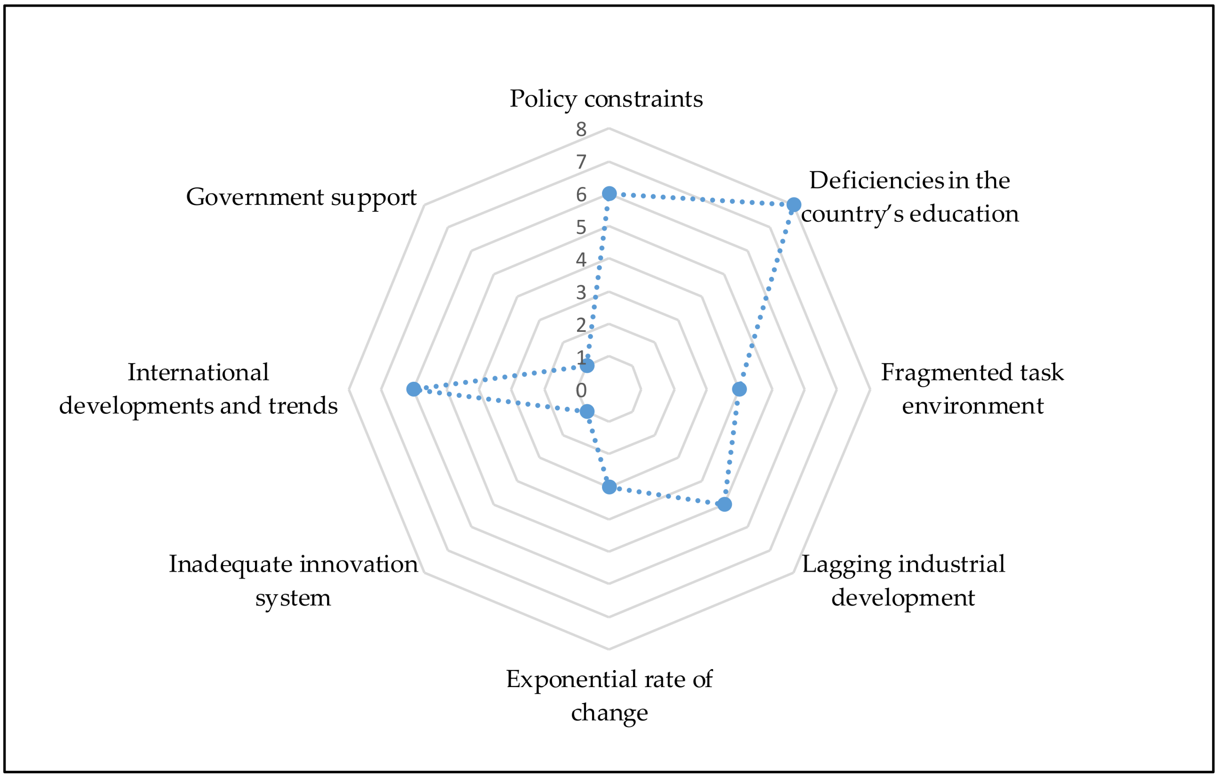

Figure 2. Task environment inhibiting factors versus the number of participants.

Participants from the manufacturing industry (P4, P8), public sector (P2), research and development (P6), and NGOs (P7) were concerned that policy and regulations in South Africa were not supportive of large-scale I4.0 adoption. Furthermore, the country's policy framework, as observed by a public-sector participant, does not support swift adjustment to exponential technological advancements:

> "We do not have government policies in place that will enable [the] business to easily apply all the I4.0 stuff or elements." (P4)

> ". . . we haven't achieved full readiness, so we need to use a mixture of policies to make sure that we adjust, policies that speak to our economic competitiveness in the manufacturing sector . . . microeconomic policies, as well [as] policies around education sector . . . regulations around the digital space are not yet completed, which inhibits I4.0 being rolled out on massive scale in a way that everybody who wants to play in this space can do." (P2)

However, nobody representing the digital industry had similar concerns, perhaps because, as another public-sector participant pointed out, there was currently considerable policy discussion on facilitating I4.0 in the country, even as he acknowledged the challenges in respect to policy and regulation:

> "The public sector in terms of policy I think it is getting uptake and I think there are a lot of policy discussions happening right now about how public sector can facilitate a link towards I4.0." (P10)

Participants from all of the represented groups agreed that the deficiencies in the country's education system have a significant negative impact on sustainable I4.0 adoption. They described the system as being characterized by poor-quality teaching and learning, misalignment in the development of skills required by industry, and underperformance in tertiary education throughput:

> "There is a huge obligation of the government departments that reports within the government, like education, that they must pull up their socks and make sure the quality of qualifications that comes out of matric is up to standard. How can you expect somebody that can only know 33% of the subject matter to be proficient? There is 67% that he does not know that he could not give an answer to or give the correct answer to. So how is that person equipped for the big world out there to come and render a service?" (P4)

The South African manufacturing industry is lagging in terms of industrial revolutions, with some companies still struggling with the second industrial revolution, as pointed out by participants at the management (P1, P4, P5, P8) and specialist/expert (P7) levels:

> "I think that the current system is so flawed in all its ways. I mean we [are] talking the second industrial revolution not even third. It almost needs a complete revamp from the future requirement point of view as opposed to reengineering the current system to support the fourth industrial revolution environment." (P7)

There was also agreement from participants at the management (P3, P4, P5) and specialist/expert (P6, P7) levels, as well as from the technology agreements facilitator (P2), that a significant number of manufacturing organizations in the country react to the trend in technological advancement rather than strategically respond to it.

4.1.3. Infrastructure Factors

The number of participants who pointed out each infrastructure factor that inhibits sustainable adoption of I4.0 in the South African manufacturing industry is presented in Figure 3.

The participants in the manufacturing industry (P3, P4, P8, P9), digital industry (P5, P11, P12), research and development (P10), and public sector (P2, P10) categories all agreed that the country faced considerable infrastructural challenges, including those related to information and communication technology (ICT):

> "We do not necessarily have the ICT infrastructure to facilitate the establishment of cyber-physical systems and IoT [Internet of Things], which are the pillars in I4.0." (P10)

Participants at the management level (P1, P4) and specialist/expert level (P6, P9, P11) concurred that access to advanced technologies is a barrier to inclusive participation in I4.0. "Technologies are expensive" (P1), and "SMEs will not be able to afford" (P4) the necessary I4.0 supporting infrastructure.

The technology agreements facilitator highlighted a lack of reliable electricity supply as a major obstacle to the successful adoption of I4.0:

> ". . . lack of access to reliable electricity, which is a basic infrastructure that we need to run the devices and if you don't have access to alternative source of energy and [you] rely on the public grid for electricity or energy you are obviously going to be limited as you know, recently with blackouts we have been experiencing." (P2)

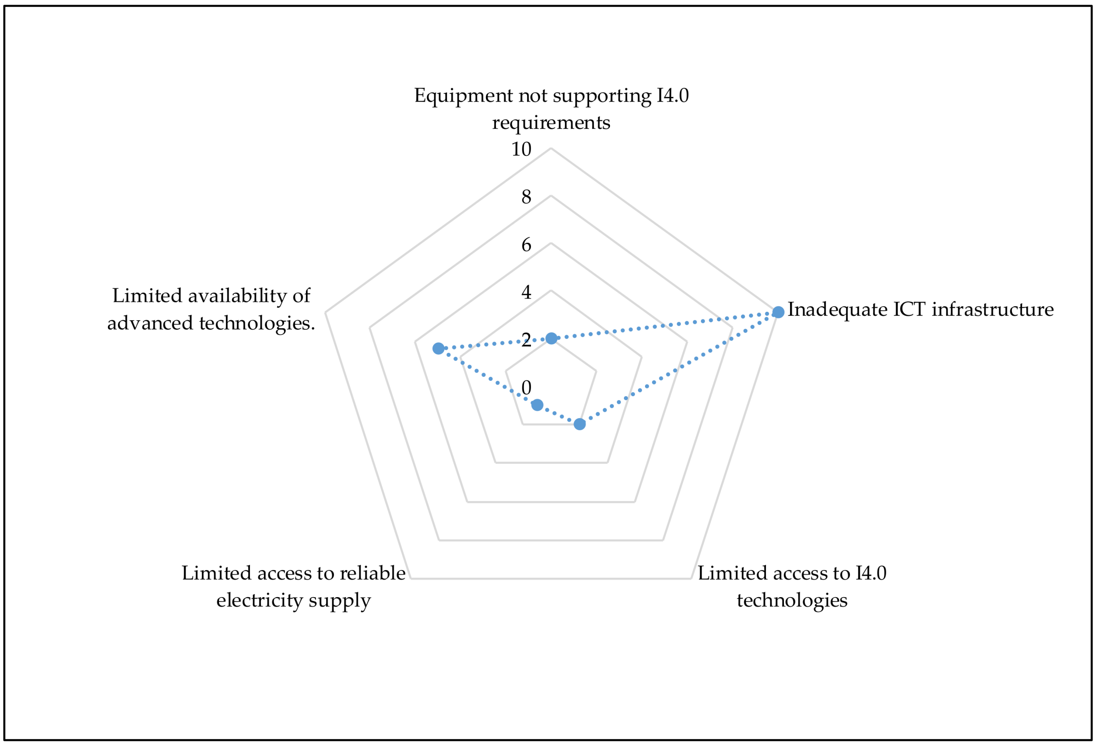

Figure 3. Infrastructure inhibiting factors versus the number of participants.

4.1.4. Human Capital Factors

Figure 4 highlights the human capital factors versus the number of participants who pointed to them as factors that inhibit sustainable adoption of I4.0 in the South African manufacturing industry.

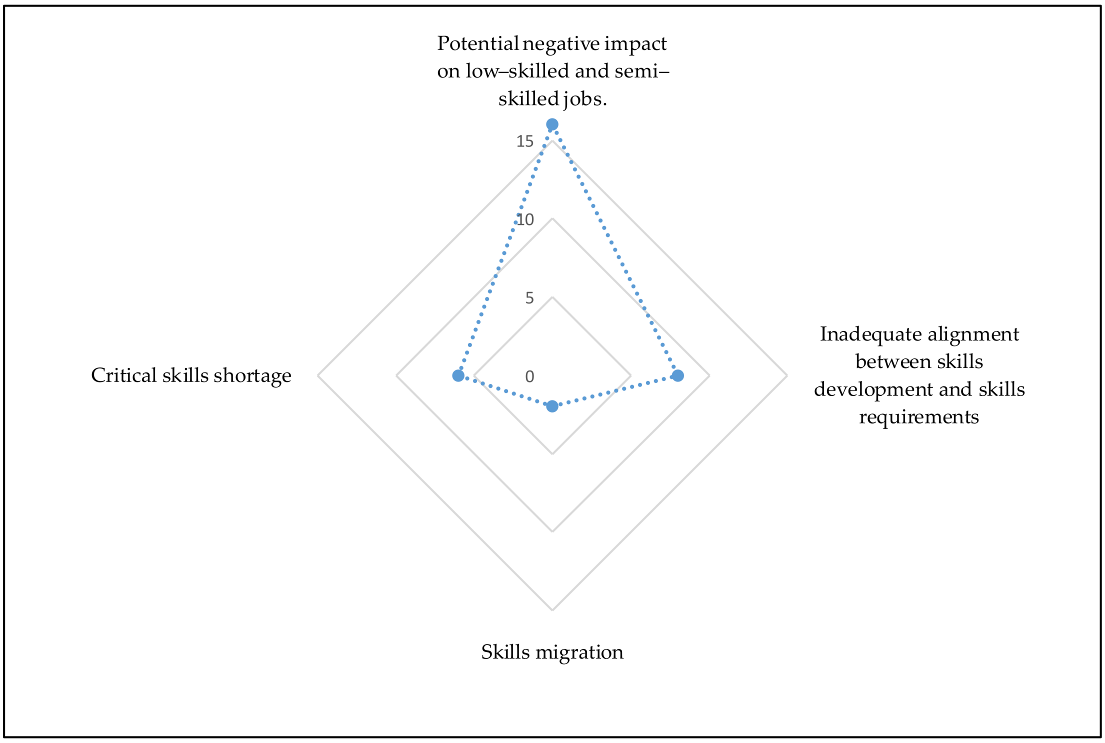

Figure 4. Human capital inhibiting factors versus the number of participants.

Participants at the management level (P1, P3, P4) and specialist/expert level (P6, P11, P13) believed that specialized skills required to participate in I4.0 were lacking due to insufficient development of such skills:

> "I think the whole skills issue is one of the biggest problems that this country faces in trying to get itself ready for the I4.0 . . . But also to produce people with specialized skills required to work in I4.0. That for me is going to be one of the biggest challenges this country faces." (P13)

There was agreement from participants in the manufacturing industry (P8, P9), digital industry (P5, P12, P13), research and development (P6), public sector (P10), and NGO (P7) about the mismatch between the skills required by the industry and I4.0 and the skills being produced by the education system, which results in unemployment or underemployment:

> ". . . the current system is currently defective because about 70% of South Africans ultimately either become unemployed or underemployed. So why do you train people for unemployment?" (P7)

> "The education needs to prepare us for I4.0 because at the moment, I feel and I think we are preparing our students and our people for the second industrial revolution, which is the production line type of thinking . . . whereby you just go to school, get good grade, and go work somewhere else, you know. But I4.0 needs a shift, needs a paradigm shift that talks to the mindset how we do things." (P9)

All of the participants agreed that I4.0 could potentially reduce or even eliminate certain low-skilled and semi-skilled jobs, since technologies in I4.0 are structured around automation, artificial intelligence, and competitiveness; this creates challenges for the country's manufacturing industry, which currently employs a significant number of people in such jobs:

> "It's a big challenge because I4.0 per say is geared towards competitiveness . . . none of that is about inclusiveness. And I personally don't see a clear path with making that inclusive because ultimately I4.0 it's about competitiveness that is driven by automation, and if you are automating there are chances of employing fewer people. You might be employing fewer low-skilled people. You might be paying more money to the high-skilled people. So here is the dynamics of I4.0 that could be seen to run against the principle of inclusiveness." (P10)

> "We have the debates around artificial intelligence, machine learning, robotics being a threat to low-skilled and semi-skilled jobs in our manufacturing industry. So the question is what kind of policy do we assume to ensure that we secure rather than bring instability to those sectors, what alternative source of work do we have [for] them." (P2)

Participants from the manufacturing industry (P8) and digital industry (P11) believed that the migration of people with specialized skills looking for greener pastures in other countries adds to the skills challenge faced in South Africa.

> "South Africans do great things in other countries, especially overseas, you know. We can replicate the same effort in our economy." (P8)

4.2. Strategies to Promote I4.0 Adoption

The number of participants who pointed out each strategy to promote I4.0 adoption in the South African manufacturing industry is presented in Figure 5.

All of the participants agreed that understanding the country's contextual operating environment could assist in adopting specific I4.0 technologies that would help to solve its specific challenges:

> "We have to look into South African context and say . . . what are the kind of the problems we want to solve? What is important to South Africa? Because if you look at things like autonomous drivers, yes, it is important to the problems of

those developed countries, but is it really important here in South Africa? We have got other big challenges that we can solve with I4.0." (P11)

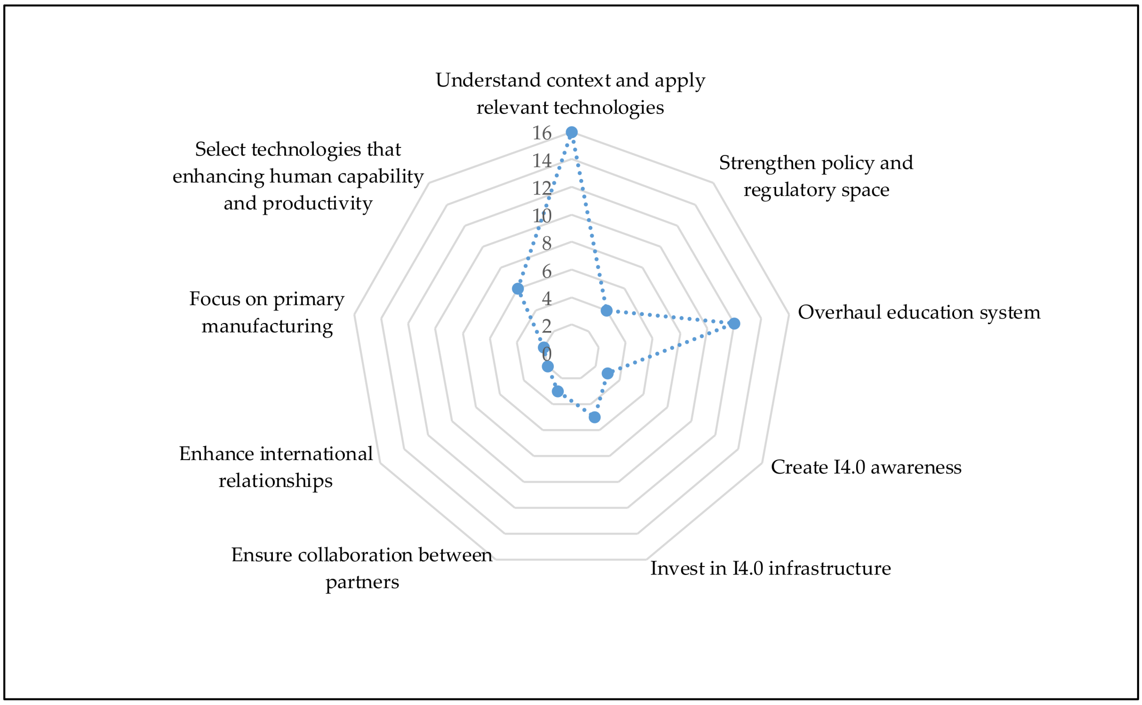

Figure 5. Strategies to promote I4.0 adoption versus the number of participants.

Participants at the management (P1, P4) and specialist/expert (P6, P7, P9, P11) levels believed that manufacturing companies could select I4.0 technologies that augment and enhance human capability and create and enhance jobs as a strategy to promote sustainable adoption of I4.0 in the country:

"So instead of full-blown automation, we need to adopt solutions that do not have adverse impact on the employment scenario because that would then have impact on the social-political kind of human activities." (P11)

"So there is really an opportunity to make it [I4.0 technology] relevant for those people who have been stuck in this element of low-paying jobs and menial labor, and one can make those kind of workers as better and easier and more fun experiences. It really goes down to, it makes the job more interesting if you have wonderful high technologies that can aid you and save you time and save you effort." (P6)

Participants from the manufacturing industry (P3, P4), digital industry (P13), and research and development (P1, P6) thought that various stakeholders' uncertainty about the impact of adopting I4.0 could be addressed by making people aware of "what is I4.0 and what elements can be adopted" (P4) without taking away jobs:

"I think we can support adoption of I4.0 first and foremost by educating people that it's not going to take away jobs. There is a tremendous fear in the government and among the labor unions in South Africa that I4.0 means job losses, job cuts, people on the streets, civil unrest." (P1)

All of the participant categories emphasized the responsibility of the government in creating the policy and regulatory environment that promotes the manufacturing industry to do business and thrive in I4.0:

"So the government must create an environment in which businesses can easily apply and thrive with all the aspect of Industry 4.0." (P4)

Participants at the management (P8, P10, P12) and specialist/expert level (P7, P9, P11, P13) further highlighted the value of revamping the education system to respond to current and future skills requirements as a strategy to support the sustainable adoption of I4.0.

A specialist/expert in the digital industry (P13) emphasized the need for government incentives to companies that are sustainably adopting I4.0 initiatives to stimulate similar investments in the manufacturing industry:

> "South African manufacturing industry can leverage I4.0 if there [is] a way that maybe [the] government can provide incentives in some way for companies to invest in the latest technologies. Is there some way that they could reduce their corporate tax they pay . . . because they have invested a certain amount of money in improving their systems, their processes, the way they do things?" (P13)

Managers (P1, P8) and specialist/expert participants (P6, P7, P13) were optimistic that if companies focused on investing in I4.0 technologies, this would promote achieving successful adoption of I4.0 in the country. They emphasized the importance of understanding the difference between investing in the third industrial revolution and fourth industrial revolution technologies:

> ". . . if we do these investments, we have to invest not for the third industrial revolution, but for the fourth [industrial revolution]. So in other words if [we] go and invest and every company invest, we need to make sure that whatever we create in terms of infrastructure is geared towards the fourth industrial revolution. So I think consider the question what is the difference between investing in third industrial revolution as with the fourth [industrial revolution]. What does that mean?" (P7)

Participants at the management level (P1, P4, P10) and specialist/expert level (P14) suggested that collaboration and strategic partnerships between companies and groups within the country and abroad would promote sustainable adoption of I4.0 and attract international interaction and investment:

> "Strategic partnership. So what I mean by that is companies in South Africa who are working in a specific area like manufacturing in a particular way with particular products within the industry, can they think to have strategic partnership with companies in other countries oversees, where they will benefit from what those companies have learnt and the way those companies overseas have done things. In return, help those overseas companies also doing more business in South Africa. So it works both ways. So if there are partnerships that South African companies can have with maybe a similar or complementary technology company in another country where each can support each other and win business with each other's markets to grow their business." (P13)

4.3. Relationships Diagram of Inhibitors to Sustainble Adoption of I4.0

The inhibitors of sustainable adoption of I4.0 in the South African manufacturing industry were further analyzed to identify their relationships using the links function in ATLAS.ti [56]. Three major ATLAS.ti relationships were employed in the analysis: 'is part of', 'is associated with', and 'is cause of'. Furthermore, 'will intensify', a customized relationship, was used to link other codes. Figure 6 illustrates the established relationships between the theme factors that inhibit sustainable I4.0 adoption (green) and the four sub-themes (blue) with their associated codes (red).

A significant number of inhibitors were identified to be linked with deficiencies in the education system: noticeable youth unemployment, critical skills shortage, inadequate alignment between skills development and skills requirements, and awareness challenges. This will all cause the slow pace of adoption of I4.0 technologies in the manufacturing industry.

Slow pace to the adoption of I4.0 was identified to be caused by the resistance to technology and the cultural constructs within the country. Furthermore, it was associated with the policy environment that does not support quick changes in requirements in the industry.

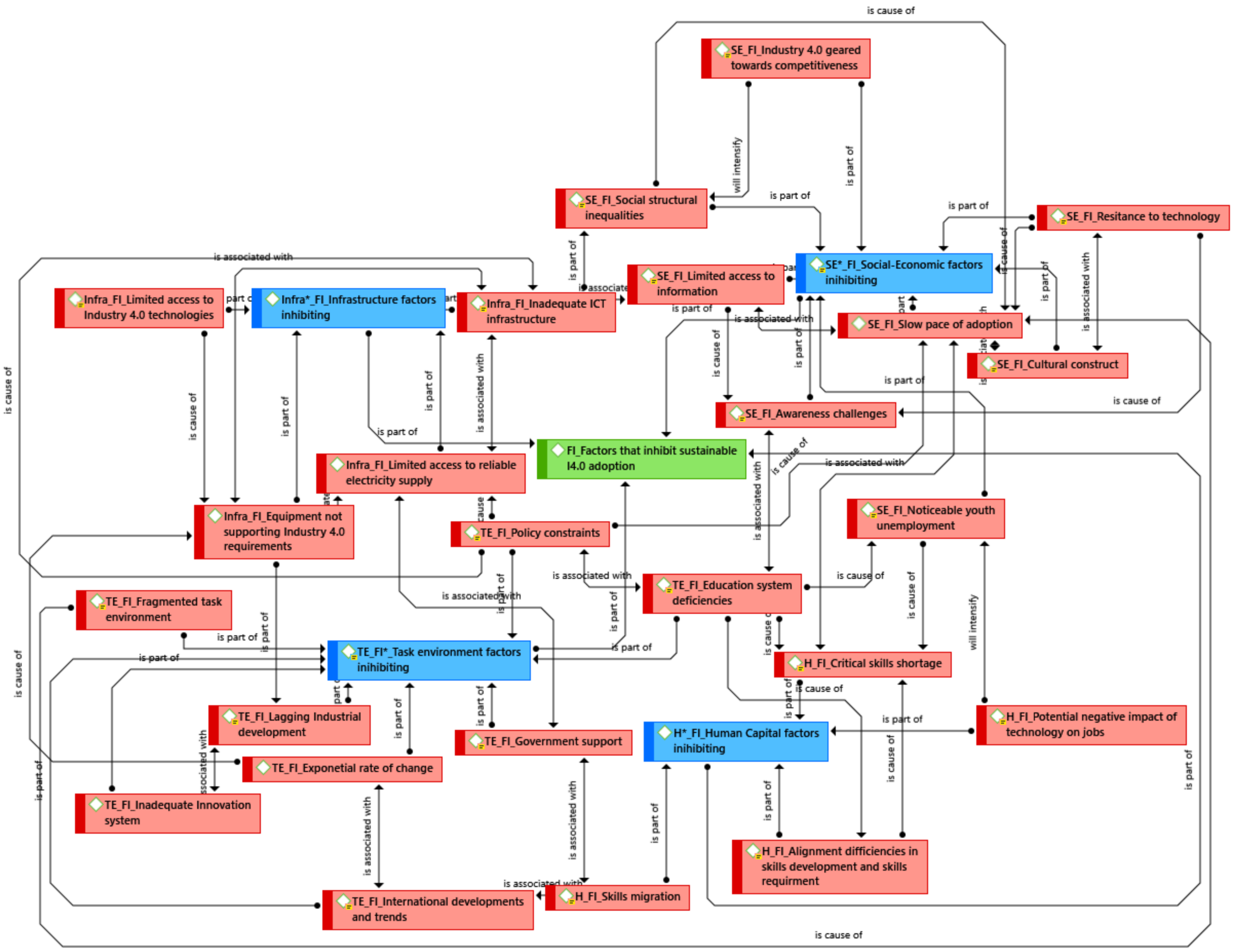

Figure 6. Relationships diagram of inhibitors to sustainable adoption of I4.0.

Policy constraints were linked with causing inhibitors, such as inadequate ICT infrastructure, limited access to reliable electricity, and deficiencies in the education system.

The potential negative impact of technology on jobs was linked with the potential to strengthen noticeable youth unemployment, while the perception that I4.0 is geared towards competitiveness could strengthen social structural inequalities in the country.

The inhibitor of equipment not supporting I4.0 requirements was identified to be caused by the exponential rate of change of technologies and limited access to I4.0 technologies. This inhibitor is associated with limited access to a reliable electricity supply and inadequate ICT infrastructure. Furthermore, equipment not supporting I4.0 requirements is considered as part of lagging industrial developments.

5. Discussion and Recommendations

5.1. Discussion

The current study explored the factors that inhibit sustainable adoption of I4.0 in the South African manufacturing industry. Our research utilized the views of management and experts in the manufacturing and related supporting industries, who pointed out inhibitors specific to the country, including social structural inequalities, resistance to technology, noticeable youth unemployment, a fragmented task environment, and deficiencies in the education system. They also suggested strategies that can enhance sustainable I4.0 adoption in the industry, which relate to South Africa, but that could also apply to other countries in the region.

Because I4.0 adoption could potentially reduce or even remove certain low-skilled and semi-skilled jobs, which stakeholders such as labor unions fear, mitigating action would need to be taken to avoid jeopardizing the achievement of SDGs relating to equality and inclusiveness. In their inter-country comparative study, for example, Raj et al. [10] highlighted inequalities as an inhibitor to the possible results and benefits of I4.0 adoption. Our findings, therefore, support a focus on the skilling and re-skilling of employees in organizations as a way to provide for continuing employability of the existing workforce as I4.0 is adopted. Furthermore, careful selection of technologies that drive inclusiveness and support employment creation would be needed.

Our participants observed that South African manufacturing operates in a fragmented task environment, which could inhibit efforts to establish a unified direction in adopting I4.0. Furthermore, the regulatory and policy framework was not seen to support large-scale adoption of I4.0, and was insufficiently able to address rapid changes related to I4.0 technologies. Our findings suggest that the South African government could learn and adapt for its own purposes lessons from countries such as Germany, whose government supported the 2020 High-Tech Strategy that led to the establishment and implementation of I4.0 [51,52].

Our findings also accentuate the infrastructure challenges—notably ICT—to I4.0 adoption. These are not unique to South Africa [10], but are worsened in this country and others in the region, where basic infrastructural support, such as a reliable electricity supply, is lacking.

Our findings indicated human capital challenges as a further significant inhibitor of sustainable adoption of I4.0 in manufacturing, and are consistent with other studies [9,10,13,31,35,58] that reveal workforce and skills challenges as barriers to such adoption. Although workforce challenges are a common theme in developed as well as developing countries, their causes are often specific to the type of country. For example, developed countries face the challenge of aging populations and justifying their strategy of adopting advance robotics and automation related to I4.0 as a solution [9,11]. In South African manufacturing, by contrast, there are many young job-seekers, but too many of them lack the relevant I4.0 skills because of deficiencies in the education system and misalignment between the industry's skill requirements and actual skill development. The implication, therefore, is that I4.0 solutions in South Africa must focus on enhancing and improving human capacity—as well as the education and skills development system itself—rather than replacing the workforce.

In addition to gaining an understanding of inhibitors to I4.0, the present study revealed potential strategies to promote sustainable adoption of I4.0 in the South African manufacturing industry. The strategies pointed out in this study could assist investors to focus on issues that will increase their chance of acceptance and success in the country and the region.

The findings of this study revealed that I4.0 adoption in the South African manufacturing industry should consider balancing competitiveness aspects and meeting the country's NDP and SDG aspects of inclusiveness and equality. Prevailing socioeconomic challenges, such as social structural inequalities and noticeable youth unemployment, necessitate the manufacturing industry and its supporting industries to innovate I4.0 technologies for successful adoption.

Furthermore, policymakers in the country should develop policies and regulations that support technology acceptance by various stakeholders, which include the workforce, labor unions, and investors. Targeted regulations and policy that require attention could include ICT, skills development, education, and trade and industry policies.

The study suggests that successful adoption of I4.0 significantly depends on people as well as technology. It is people in combination with technology that can change and improve situations. A shortage of I4.0 skill requirements was identified as a global challenge [5,10], and competition for people with relevant skills could intensify. Therefore, South Africa's manufacturing industry must intensify skills development, as well as skills retention, as linked strategies to mitigate skills shortage and skills loss.

5.2. Study Limitations and Future Studies

Although these findings have contributed to our understanding of management and experts' perspectives on the adoption of I4.0, we acknowledge that there are limitations to the study. It is not the first to explore factors that inhibit I4.0 adoption in the manufacturing industry [2,4,5,9–13,25,26], although it is the first to address the issue in the specific country context of South Africa. The small sample size could be regarded as a limitation, although it fits well into the research design and the purpose of the study. Thus, the findings are not generalizable owing to the small sample size and the subjectivity of participants' opinions. Nevertheless, the points they raised offer useful direction for further, broader investigations of specific inhibitors to sustainable I4.0 adoption and strategies for overcoming them, not only in South Africa, but also in the developing countries in the same region.

The research design and methodology in this study was limited to qualitative data. This restricted us only to apply qualitative data analysis techniques, and thus the inhibitors could not be ranked in terms of severity. We, therefore, recommend future studies that could use both qualitative and quantitative methods and apply techniques, such as the analytical hierarchy process (AHP) and Delphi technique, for further analysis of the factors that inhibit sustainable adoption of I4.0 in the manufacturing industry.

This study also opens doors for future research into factors that inhibit I4.0 adoption within specific manufacturing industry sectors where its impact and opportunities could vary.

5.3. Recommendations

Our findings suggest that deficiencies in the education system are significantly linked to other inhibitors, and addressing these could contribute to mitigating factors that are inhibiting sustainable adoption of I4.0. Fixing the deficiency in the education system, coupled with organizations prioritizing up-skilling and re-skilling of employees, could provide solutions to inhibitors, such as the noticeable youth unemployment, critical skills shortage, inadequate alignment between skills development and skills requirements, and awareness challenges. Thus, various stakeholders, including the government departments, such as basic education, higher education, and training, and the department of science and technology, must collaborate with other stakeholders, such as the industry and trade unions, in addressing the deficiencies thereof.

Policy constraints were also linked to a noticeable number of inhibitors, such as inadequate ICT infrastructure, limited access to reliable electricity, and deficiencies in the education system. Since changes in technological development are exponential, it is recommended that the policy framework in the country must be flexible and quick to adopt all necessary changes that foster sustainable development. The suggested targeted regulations and policies that will have a significant impact and require attention could include regulations around ICT, skills development, education, and trade and industry policies.

It is further recommended that the manufacturing industry in the country must not adopt I4.0 for the sake of following global trends. Instead, decision-makers must seek to understand the contextual country requirements and apply relevant technologies that support such. This could include selecting technologies that enhance human capabilities, thus minimizing the possible negative impact of I4.0 technologies on semi-skilled and low-skilled employees.

6. Conclusions

The study aimed to explore factors that inhibit sustainable adoption of I4.0 in the developing country context of the South African manufacturing industry. The present small-scale study offered us the opportunity to gather views from individuals whose work was relevant to I4.0 adoption in the country's manufacturing industry. Although the focus was on factors that inhibit I4.0 adoption, strategies to promote it emerged during data analysis as a strong second theme. These included understanding the context and application of relevant technologies; strengthening the policy and regulatory space;

overhauling the education system; and selecting technologies that enhance human capability and productivity. The findings suggest that successful adoption of I4.0 goes beyond the development of technological capabilities, and needs to also take into consideration aspects of social-economic sustainability. In the context of South African manufacturing, sustainable adoption entails balancing competitiveness with inclusivity in ways that help to achieve the goals embedded in the country's NDP and the UN's SDGs, and that move the industry—and the country—towards stronger economic growth and quality of life for all.

Author Contributions: W.M. was responsible for data collection, data analysis, and preparing the manuscript—the work is based on his PhD studies. L.v.D. and R.C. supervised the study. All authors discussed the results and contributed to the final manuscript. All authors have read and agreed to the published version of the manuscript.

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APPENDIX C: ARTICLE 3

AN INVESTIGATION OF INDUSTRY 4.0 SKILLS REQUIREMENTS

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ABSTRACT

The Industry 4.0 wave is built on technological advancement that is bringing about significant change. The impact of Industry 4.0 is being felt across all industries, including the education sector. During the 2019 State of the Nation address, the President of South Africa pointed out that the government was seeking to respond to the change in skills requirements. In this paper, a systematic literature review will be performed to investigate Industry 4.0 skills requirements in the engineering profession and the role of capability development in meeting Industry 4.0 requirements. An exploration of the impact of Industry 4.0 on technical institutions as opposed to academic institutions will also be discussed. This paper incorporates this exploratory investigation into detailed research on developing a skills development framework that seeks to bridge the gap between Industry 4.0 skills requirements and development in South Africa.

OPSOMMING

Die verskynsel van Industrie 4.0 word gedryf deur tegnologiese vordering wat beduidende verandering teweegbring. Die impak van Industrie 4.0 is oor alle industrieë waarneembaar, insluitend die onderwyssektor. Gedurende die 2019-staatsrede het die President van Suid-Afrika daarop gewys dat die regering poog om die verandering in vereistes vir vaardighede te hanteer. In hierdie artikel word ‘n sistematiese literatuuroorsig uitgevoer om vas te stel wat die vereistes is vir Industrie 4.0-vaardighede in die ingenieursprofessie asook die rol van vaardigheidsontwikkeling om aan Industrie 4.0-vereistes te voldoen. ’n Ondersoek na die impak van Industrie 4.0 op tegniese instellings in teenstelling met akademiese instellings word ook bespreek. Hierdie werkstuk inkorporeer hierdie verkennende ondersoek in gedetailleerde navorsing oor ’n vaardigheidsontwikkelingstruktuur wat ten doel het om die gaping tussen vereistes vir vaardighede vir Industrie 4.0 en ontwikkeling in Suid-Afrika te oorbrug.

1 INTRODUCTION

According to historians, human civilisation has, to date, undergone three industrial revolutions: the first industrial revolution (mechanisation), the second industrial revolution (mass production and electricity), and the third industrial revolution (automation) [1, 2]. These revolutions not only influenced production and business models: they also affected the skills required by future employees in various industries [3]. From one industrial revolution to the next, some jobs disappeared while others were created. More importantly, some skills became redundant while others became valuable. The upcoming fourth industrial revolution is no exception with regard to the replacement of jobs and skills. Industry 4.0, an acknowledged initiative driving the fourth industrial revolution, is characterised by significant technological advancement that requires a specialised and skilled workforce [3].

Industry 4.0 is driving the world into a global, automated, virtual, and flexible environment, which results in a global contest for jobs that demand specialised skills for the digital and sharing economy [4]. The adoption of Industry 4.0 technologies results in people working in a digitised and networked workplace that promotes interaction with algorithms and robotics, as well as operating in a virtual world [5]. These changes result in new job requirements for a unique and specialised skills set [6, 7]. Thus there is bound to be a noticeable change in the skills requirements between the fourth industrial revolution and the previous three industrial revolutions.

The availability of relevant skills and capabilities in a country's workforce will significantly influence the successful adoption of Industry 4.0 at the micro- and macro-level. Moreover, the quality of skills and qualifications of the workforce will play a noticeable role in driving the innovation and competiveness of organisations [3, 8]. Conversely, a lack of the required skills set will result in a noticeable drop in performance and reduced competiveness in organisations. Yet Schallock, Rybski, Jochem, and Kohl [9] state that Industry 4.0 is more than technological advancement; it also has to prioritise human resource development, which involves developing the skills that will be required in the future [9].

Unemployment stands to be one of the biggest outstanding challenges in developing countries, including South Africa. Listed among the factors that contribute to high unemployment are: (a) the mismatch between available skills and skills required in the industry; (b) the high level of unskilled labour; and (c) inadequate education [10-12]. Industry 4.0 offers the prospect of opportunities for quality and productive employment. The problem lies in the fact that Industry 4.0 has the potential to increase unemployment through the loss of manual and repetitive jobs that can easily be automated, unless the subject of skilling and re-skilling for the digital economy is addressed from the onset by enhancing skills development in technical and academic institutions.

Developing countries are faced with a critical shortage of professionals with the required Industry 4.0 skills set [13]. This makes it necessary to investigate closely the essential requirements for the skills in this digital economy, and to determine how these skills can be developed and incorporated into existing educational structures.

Shvetsova and Kuzmina [14] point out that there is an existing gap between the skills required and the skills developed in the Industry 4.0 era. This could be because there is no clear awareness of the skills that meet Industry 4.0 requirements.

The South African National Development Plan prioritises the creation of employment and the improvement of the quality of education and skills development in a way that will bring about inclusive development and fight poverty [15]. In the 2019 State of the Nation address, the President of South Africa pointed out that one of the challenges the nation faces is creating jobs. He further pointed out that the government is seeking to respond to changing skills needs and the skills needs of the future by enhancing training in the education system [16]. This confirms that an investigation into Industry 4.0 skills requirements and a skills development framework are vital.

This paper seeks to investigate Industry 4.0 skills requirements in the engineering profession and skills development through performing a systematic literature review (SLR). An exploration of the impact of Industry 4.0 on technical institutions, as opposed to academic institutions, will be discussed. This paper conducts an exploratory investigation into developing a skills development framework that seeks to bridge the gap between Industry 4.0 skills requirements and development in South Africa.

The paper outline is as follows: Section 2 presents an Industry 4.0 overview, and Section 3 outlines the methodology to investigate skills requirements for Industry 4.0. The SLR results and a discussion of the results are presented in Section 4 and Section 5 respectively. Section 6 outlines the conclusion and future work.

2 INDUSTRY 4.0 OVERVIEW

The rapid transformation of jobs has resulted in a wide mix of skills, attitudes, experiences, and requirements in Industry 4.0 [17-19]. The trend of job complexity has been upward through successive industrial revolutions [20]. Industry 4.0, by virtue of driving the fourth industrial revolution, could pose a significant threat to employment, given the increased complexity of workplace requirements. This effect extends to the skills requirements of jobs and skills development in educational institutes.

Performing a skills requirements study in the Industry 4.0 era is of significance because it informs employment seekers and skills development institutions about what to work towards and what to expect. Adolph, Tisch, and Metternich [21], referring to production environments, point out that technological megatrends will significantly affect the skills and competencies needed. This in turn requires organisations to develop strategies, and skills development institutions to be innovative, in creating the required skills and competencies.

Gudanowska, Alonso, and Törmänen [22] report that, although the competencies required in different fields might differ, there are similarities in the competencies required in different industries. They add that soft skills will be as important as technical skills in the engineer of the future [22]. The future engineer's interaction with intelligent machines will form a symbiotic partnership that requires a firm base of soft skills, such as emotional intelligence, critical thinking, innovation, communication, collaboration, leadership, and teamwork [23]. Intelligent machines cannot apply common-sense reasoning; neither can they show empathy, which humans need to do to increase productivity when working in smart factories [24].

2.1 Engineering professionals in South Africa

Engineering professionals in South Africa are generally categorised into four distinct levels: specified category practitioner, technician, technologist, and engineer, as presented in Table 1, which was formulated using a significant amount of information from the Engineering Council of South Africa website [25]. Identifying Industry 4.0 skills requirements for each engineering professional level is significant in determining how individuals should respond to the new work landscape.

Table 1: Engineering professional categories in South Africa [25]

Expertise layer	Qualification	Institution type	Description
Specified category practitioner	Higher Certificate in Engineering	Technical vocational education and training (TVET)	Vocational with strong industry-oriented focus, simulated work experience, or work-integrated learning.
Technician (NQF 6)	Advanced Certificate in Engineering Practice	Universities of Technology, TVET	The individual has a vocational-orientated qualification; demonstration of focused knowledge and skills in a particular field is essential. Knowledge and skills gained in workplace. Uses the work-integrated learning approach.
	Diploma in Engineering Technology	Universities of Technology, TVET	Vocational or industry-oriented training, prepared to enter a particular role in the industry; does not include work-integrated learning.
	Diploma in Engineering	Universities of Technology, TVET	Vocational orientation, which includes professional, vocational, or industry-specific knowledge. Demonstration of focused knowledge and skills in a particular field.
	Advanced Certificate in Engineering	Universities of Technology	Vocational-industry orientation; demonstrates sound knowledge in a particular field or discipline, and ability to apply knowledge and skills.
Technologist (NQF 7)	Advanced Diploma in Engineering	Universities of Technology and Comprehensive Universities	Industry-oriented, professional and career focus, ability to demonstrate initiative and responsibility in either academic or professional environments, may contain work-integrated learning.
Engineer (NQF 8)	Bachelor of Engineering / Bachelor of Science in Engineering	Universities	Oriented towards imparting firm base in mathematics, natural science, engineering sciences, engineering modelling, engineering design in order to solve problems in the societies in which we live.
	Bachelor of Engineering Technology Honours	Universities	Enhances the application of research and development, expertise in a particular discipline. Graduates must work independently in applying original thought and judgement to technical and risk-based decisions in complex situations.

The universities of technology referred to in Table 1 were formerly known as technikons. Although the institution type that offers a particular qualification is not fixed, Table 1 generalises according to traditional offerings. Figure 1 presents the professional skills level with the skills complexity, skills required, and task frequency at each level. It can be seen that skills complexity and skills required decrease from the level of engineer to the level of specified category practitioner, and vice versa: task frequency decreases from the bottom to the top level.

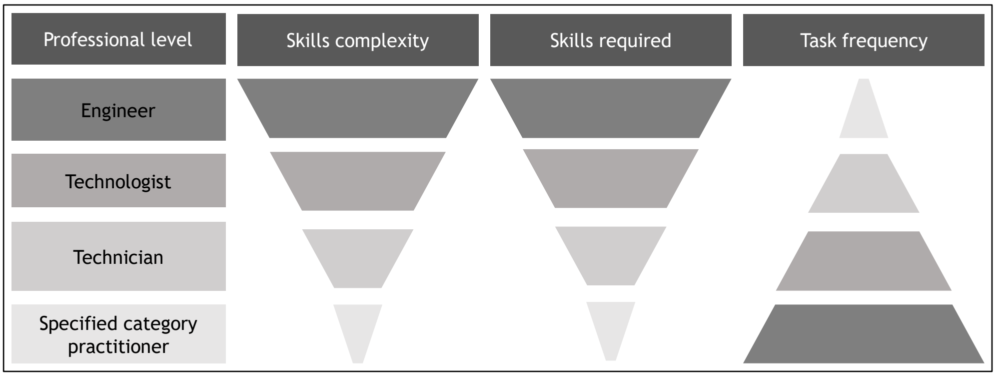

Figure 1: Skills level vs skills complexity, skills required, and task frequency [Own work]

Figure 1 shows that the current set-up of the engineering profession is that the skills required and the skills complexity differ from one engineering professional level to another. Could there be the same expectation in the Industry 4.0 era? Are specific skills expected at each engineering professional level?

2.2 Impact of Industry 4.0 on skills requirements

The best talent is not the machines but [a] combination of both humans and machines [20]

Jaschke [26] points out that successive industrial revolutions noticeably changed the nature of work processes, which resulted in the transformation of employees' roles and required skills. The disruptive nature of Industry 4.0 brings about considerable changes in work processes, which consequently requires a different approach to the way work is performed [27]. Sackey and Bester [28] further highlight that Industry 4.0 will significantly transform employees' work profiles. New skills sets will be required to perform existing and new jobs that will emerge owing to Industry 4.0 technological advances [18]. The future factory will be significantly populated with collaborative robotics that can interact with humans in the workplace. This implies that, although the degree of automation will vary with sectors and types of jobs, its impact will be universally felt [29]. Such an environment requires humans to develop logic, which will be applied by advanced robots [30]. Collaboration of humans and robots will be inevitable for improved productivity [23]. Adopting this view, the authors conclude that Industry 4.0 will result in noticeable changes in the employees' skills requirements.

The literature [17, 18, 20, 31] converges on the view that there will be a rise in automation and advanced robotics replacing routine, repetitive, and middle-income jobs. Technological advancement in Industry 4.0 is significantly diminishing the relevance of existing skills sets and encouraging the creation of new skills sets [18, 19]. Benefits associated with these developments include the elimination of unsafe routine and repetitive jobs, the exclusion of non-stimulating jobs, and the creation of opportunities to develop meaningful and transferable skills.

A significant number of authors [18, 20] state that technical skills must be complemented by strong social and collaborative skills. Big data analytics has proven to be the outstanding skill that engineers must possess to be relevant in Industry 4.0 [18]. To make a noticeable impact, data analytics skills must be coupled with technical skills, business and industry knowledge, and soft skills [17]. Technical commercialising skills will be desirable in Industry 4.0.

Because of Industry 4.0, both technical and academic institutions must strive to supplement theoretical knowledge with practical skills, social skills and responsibility, ethics and values, and entrepreneurship capability, among others [20]. Other countries are moving towards rolling out work-based learning degree programmes that are meant to achieve learning and innovation skills, information technology skills, and life and career skills [32].

Prifti, Knigge, Kienegger, and Krcmar [27] point out that skills for Industry 4.0 will require a certain level of engineering professional training. Advanced Industry 4.0 technologies in the workplace will significantly change the skills profile of engineers and information technology professionals [27]. This can be demonstrated by the use of digital twin skills by engineers in commissioning machines from remote service centres and troubleshooting equipment in remote areas.

Prifti *et al.* [27] explain that the skills requirements for Industry 4.0 differ from previous developments in the industry because, beyond domain knowledge, personal skills prove to play a vital role, and the interaction between the technologies and their virtual nature creates something conceptual. These personal skills can be learned and adopted. Engineering training must not focus only on specific discipline knowledge; behavioural skills must also receive significant consideration. Beyond balancing discipline knowledge and behavioural skills, interdisciplinary understanding must be developed [27]. Industry 4.0 technological developments are in the virtual world; thus our typical behaviours are not effective, stressing the need for interdisciplinary understanding.

Furthermore, the sudden and impactful advances of Industry 4.0 technologies require employees to possess life-long learning capabilities [27]. According to Prifti *et al.* [27], big data and data analytics, combined with other skills, are more important than the technical skills required in individuals working in Industry 4.0. However, the comprehensive work by Prifti *et al.* [27] does not include the identification of skills and competencies for each professional level.

Cotet, Balgiu, and Zaleschi [33] identify soft skills and hard skills in comparison with behavioural skills and domain skills respectively, unlike Prifti *et al.* [27]. In the work of Cotet *et al.*, soft skills are identified as contributing significantly to the success and development of the employee in the Industry 4.0 era [33].

According to Cotet *et al.* [33], the three top soft skills required in an Industry 4.0 era employee are creativity, emotional intelligence, and proactive thinking. The authors' understanding is that those three top skills assist an employee to adapt easily to the incremental changes that are characteristic of the nature of Industry 4.0 technologies.

Adolph *et al.* [21] discuss competencies that include, among others, agility in problem solving, the ability to reshape processes, flexibility, and self-learning as central in driving production environments in Industry 4.0.

2.3 Impact of Industry 4.0 on technical and academic institutions

If young people are making a tube frame chassis for a racing car, suddenly trigonometry becomes very interesting — they see the point of all the measurements and calculations [20].

Over the years, the importance and preference attached to technical institutions has been on a downward trend in academic institutions in a significant number of countries, including South Africa. Industry 4.0 skills requirements demand a reconsideration of the importance that is attached to qualifications obtained from technical and vocational institutions. Technical institutions should be modernised and informed by industry requirements. Industry 4.0 calls for the enhancement of the social status of technical institutions. Technical institutions are relevant in the digital transformation ecosystem, since they are the mainstay of developing a technically skilled workforce [11].

This requires both academic and technical institutions to provide opportunities for lifelong learning. Jaschke [26] highlights that the changing role of employees due to industrial revolutions has changed how the required skills are developed and employees are trained. Sackey and Bester [28] state that the engineering profession is directly linked to changes in technological developments. It can thus be concluded that Industry 4.0 will result in noteworthy changes in skills development and, consequently, in technical and academic institutions.

Technological advancement is happening at a fast pace resulting in new skills requirements and thus raising the need for an agile response in order to develop relevant skills that address the need. The skills development models must capacitate the urgent mitigation of skills challenges [18]. The World

Economic Forum [19] advocates that technology should be embedded in the education system to reveal its importance in Industry 4.0.

Technical institutions must be supported and strengthened, since technical and practical skills remain essential in Industry 4.0 [17]. South Africa's technical institutions must promote the education of engineering professionals at all levels in advanced information technology to ensure that they are ready to meet the demands of Industry 4.0.

To be effective in Industry 4.0, technical and academic institutions must promote novelty in methods of acquiring and using knowledge. Baker [17] puts it like this: "abstract knowledge and reasoning need to be connected with [the] real world through practical applications". Collaboration between industry and institutions of higher learning must be fostered to promote the solving of real world problems. Traditional academic subjects must be blended with technical specialisation and project-based learning. The primary object should be to ensure that students find relevance in what they are studying.

Selamat, Taspir, Puteh, and Alias [20] state that the teaching methods and organisational structures in future higher institutions will change significantly. Interdisciplinary training, massive open learning, and personalised learning will be experienced. Technological advancement is happening fast; thus institutions of learning must adapt to match innovation cycles [20].

Kumar and Gupta [34] observe that, in response to technological advancements, industry has shifted to a new paradigm of knowledge orientation, which is supported by the three pillars of skills, education, and research and development. A significant number of developing countries' tertiary education produces unskilled graduates with a vast amount of theoretical knowledge [34]. Weak research and development, a result of poor collaboration between industry and tertiary institutions, has resulted in developing countries being imitators and users of technological advancement from leading economies [34].

The Industry 4.0 era demands high cognitive abilities, which requires transformation in the higher education system. The open education system is slowly taking over, and this will have a significant impact on higher education academic institutions. Higher education institutions might need to realign their business model to accommodate the open market [35].

Sackey and Bester [28] state that Industry 4.0 could result in changing the knowledge and skills required by industrial engineers. They further suggest that there is a need to transform the curriculum of industrial engineering in South Africa and to focus on big data and human-machine interface skills [28]. Thus it can be concluded that Industry 4.0 will affect the curriculum of both technical and academic institutions. The curriculum should be suitable to address issues and prepare students to be competent in the digital economy.

To meet the demands of Industry 4.0, mobile learning applications that allow students to enter a virtual working environment and allow them to work independently have been suggested by Jaschke [26] for technical training in engineering.

Gudanowska *et al*. [22] argue that skills in the manufacturing industry can be developed in the work environment, whereas formal education cannot achieve this. Although not specifying the mode of learning, Prifti [27] points out that competencies can be taught.

Change in technical and academic institutions is inevitable to achieve alignment between skills requirements and skills development. Shvetsova and Kuzmina [14] point out that there could be a reduction in the need to train for the highest qualifications and an increase in the need for active technological expertise.

Although not specifying the actual type of institutions affected, Shvetsova and Kuzmina [14] point out the changes that are needed in higher education systems [14]: digitalisation of education, training personalisation, integration of professional and academic training, the creation of creative spaces, and the creation of university hubs.

3 METHODOLOGY

A study by Prifti *et al.* [27], which presents a systematic literature review on competencies required in the Industry 4.0 era, is acknowledged. Although the study was detailed and comprehensive, the competencies pointed out were generic, and the authors did not attempt to categorise the skills required for the different engineering professional levels.

Kitchenham [36] defines SLR as "a means of evaluating and interpreting all research relevant to a particular research question or topic area or phenomenon of interest" [36]. Using the points of view of Brereton, Kitchenham, Budgen, Turner and Khalil [37] and Siddaway [38], the researcher conclude that SLR seeks to provide an objective summary of relevant evidence by performing a meticulous and systematic process of finding, evaluating, and making a judgement on the outcome of relevant research output on a specific topic of interest.

In line with what Kitchenham [36] and Siddaway [38] point out about what a good SLR must accomplish, this study is undertaken as an SLR that aims to determine the degree to which existing research output has moved towards clarifying the discrepancy between Industry 4.0 skills requirements in the engineering profession and Industry 4.0 skills development, and to identify gaps that could give direction to future research.

This section is organised as follows: Section 3.1 outlines the research questions, and Section 3.2 gives the inclusion and exclusion criteria used in this study. The SLR method is presented in Section 3.3.

3.1 Research questions

To accomplish the objective of this study, which is to identify Industry 4.0 skills requirements in the engineering profession and skills development in meeting Industry 4.0 requirements, research questions (RQ) 1 to 3 were formulated:

- RQ 1: What Industry 4.0 skills are required in the engineering profession?
- RQ 2: What skills are required for each engineering profession level?
- RQ 3: How can these skills be developed?

3.2 Inclusion and exclusion criteria

Using the work of Liao, Deschamps, Loures, and Ramos and Liao, Loures, Deschamps, Brezinski, and Venancio [39, 40], inclusion and exclusion criteria were formulated to maintain objectivity in the assessment of the collected research papers. Table 2 presents an overview of the inclusion and exclusion criteria used in this study.

Table 2: Inclusion and exclusion criteria [39, 40].

Exclusion/ Inclusion	Criteria	Description
Exclusion	Duplication **(DP)**	The paper appears more than once in the same search criteria
	Language compatibility **(LC)**	The full text of the paper is not in English, except for the title, abstract, and key words
	No full-text **(NF)**	The full text of the paper cannot be accessed
	Non-related **(NR)**	**NR1**: The research paper is not a peer-reviewed academic article **NR2:** The research paper is not related to Industry 4.0 and skills requirements
	Casually applied **(CA)**	**CA1:** The paper uses the terms 'Industry 4.0' and 'skills' and their synonyms loosely **CA2:** The research paper addresses Industry 4.0, but does not focus on skills requirements **CA3:** The research paper addresses skills requirements not related to Industry 4.0
Inclusion	Partially related **(PR)**	**PR:** The research focuses on Industry 4.0 skills and competencies in general, but not specifically on the engineering profession
	Closely related **(CR)**	**CR1:** The research paper explicitly discusses Industry 4.0 skills required in the engineering profession **CR2:** The research paper focuses on Industry 4.0 skills development

3.3 Systematic literature review method

This study is carried out under the guidelines adopted from Kitchenham [36] and Brereton *et al.* [37], in combination with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method used by Moher, Liberati, Tetzlaff, and Altman [41]. Section 3.3.1 presents the search strategy, and the study selection is outlined in Section 3.3.2. Section 3.3.3 and Section 3.3.4 report the data collection and data analysis respectively.

3.3.1 Search strategy

The search terms are selected by identifying key terms from the research questions that can be applied to the issues to be addressed. The key terms chosen for inclusion in the search are 'Industry 4.0' and 'skills'. To accommodate variations in the spellings and the use of synonyms, alternative words were identified, as shown in Table 3.

Table 3: Search term alternative spellings and synonyms

Search term	Alternative search words
'Industry 4.0'	'Fourth Industrial revolution', '4th Industrial revolution', 'I4.0', 'Industry 4.0'
Skills	Competencies, abilities

Aliyu [42] points out that the use of a Boolean search string increases the probability of the search returning relevant research papers. To achieve a thorough collection of research papers, a Boolean search string was constructed using the search terms in Table 3, the Boolean operator AND, which restricts retention to papers with all relevant key terms, and the operator OR to accommodate alternative spelling and synonyms [36, 42]. The search string applied in the study was: ("Industry 4.0" OR "fourth industrial revolution" OR "4th Industrial revolution") AND skill*.

The systematic literature search was conducted on Scopus online databases. The concept of Industry 4.0 was initiated in Germany at the Hanover Fair in 2011 [27]; thus, for this research output, the period from January 2012 to March 2019 was considered.

3.3.2 Study selection

To select the papers to be included in this study, the exclusion and inclusion criteria presented in Table 4 were applied. Figure 2 presents the SLR stages followed using the PRISMA approach.

The first step in selecting the research papers was to remove identified duplicate (DP) papers. The initial screening process excluded all papers that were not in English (LC) (except for the title, abstract, and keywords), and papers to which there was no full access (NF).

Research papers that qualified for inclusion after the initial screening process were further examined to check their eligibility for inclusion. The second screening stage eliminated papers that were not peer-reviewed academic articles (NR1), and those that were not related to Industry 4.0 and skills requirements (NR2). The papers that loosely used the terms Industry 4.0 and skills (CA1), addressed Industry 4.0 but did not focus on skills requirements (CA2), or addressed skills requirements outside the context of Industry 4.0 (CA3) were eliminated at this stage.

The papers that passed the exclusion criteria were deemed eligible and were scrutinised and reviewed in detail. The eligible papers were classified according to three inclusion criteria: papers that focus on Industry 4.0 skills and competencies in general, but not specifically in the engineering profession (PR), papers that explicitly discuss Industry 4.0 skills required in the engineering profession (CR1), and papers that focus on Industry 4.0 skills development (CR2).

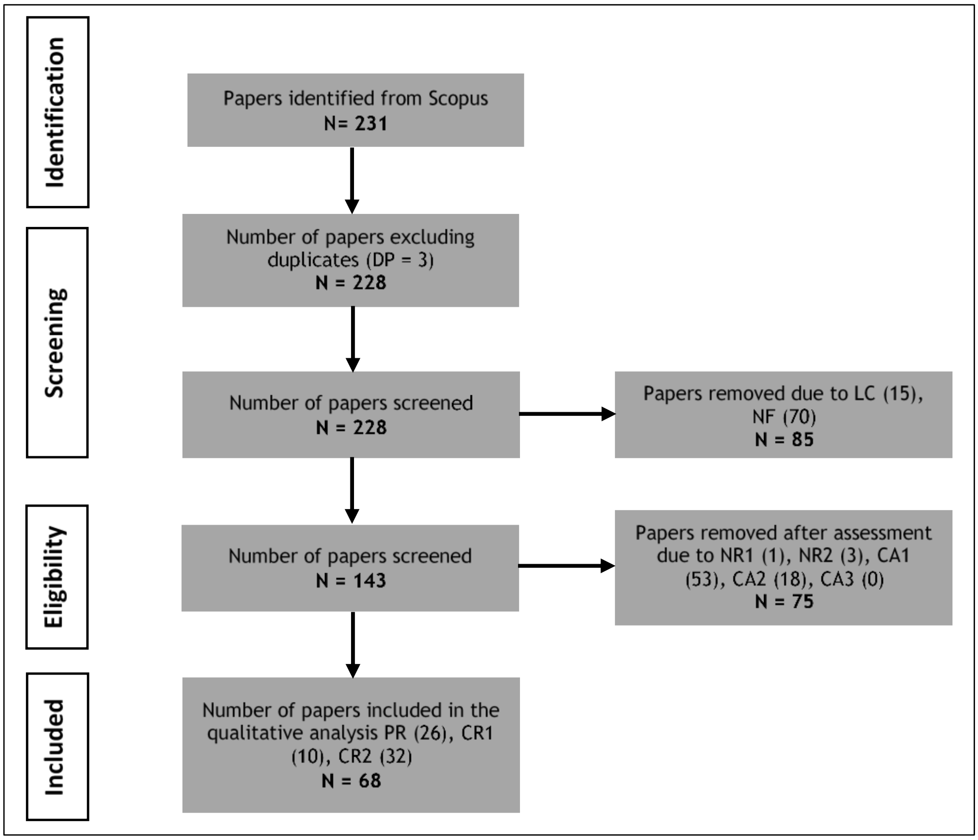

Figure 2: Systematic literature review stages using PRISMA approach [39-41]

3.3.3 Data collection

In response to the research questions presented in section 3.1, the data extracted from the papers that were included incorporate the engineering profession skills required in the Industry 4.0 era, the skills required for each specific engineering professional level, and methods for developing these skills.

3.3.4 Data analysis

The collected data were analysed using the qualitative method by applying descriptive codes. This was done with the objective of identifying the skills required in the engineering profession in the Industry 4.0 era. The analysis sought to identify the specific skills required for each engineering profession category.

4 SYSTEMATIC LITERATURE REVIEW RESULTS

4.1 Industry 4.0 skills requirements SLR results

The essential skills for Industry 4.0, presented in Table 1, were extracted from the research papers that satisfied the eligibility criteria discussed in section 3.3.2. All the skills deemed necessary for Industry 4.0 were considered, thus providing a wide set of skills. Each skills category was divided into sub-categories, which then showed the skills required with the related references.

Table 4: SLR skills requirements results

Skills category	Skills sub-category	Skills set	References
Technical skills	Technological skills	• Designing skills that incorporate virtualising, simulating, interoperability, modularising, decentralising capabilities.	[4, 43, 44]
		• Fault and error recovery skills	[45]
		• Application and use of technological skills	[46]
		• Process digitalisation and understanding	[31, 46, 47]
		• Ability to work with the Internet of Things, autonomous robots, 3D printing, and other advanced technologies • Interaction with modern interfaces	[44]
	Programming skills	• Computational skills	[48]
		• Simulation skills	[44]
		• Coding	[31, 45, 47, 48]
		• Computer and software programming skills • Software development	[4, 46-51]
	Digital skills	• Data analytics/data processing	[4, 43, 44, 46, 47, 49-54]
		• IT/data/cyber security	[31, 43, 45-47, 50, 53]
		• Cloud computing skills	[43]
		• IT knowledge and abilities	[43, 47, 55, 56]
		• Artificial intelligence skills	[43]
		• Digital content creation skills	[46]
Non-technical skills/soft skills	Thinking skills	• Creativity, innovation, practical ingenuity	[4, 6, 33, 43, 46, 48-50, 54, 57-65]
		• Critical and logical thinking	[41] [46, 48, 52-54, 60, 61, 64, 65]
		• Flexibility	[31, 43-45, 49, 52, 54, 62, 65]
		• Complex problem solving, trouble-shooting	[4, 6, 43, 45, 46, 48-50, 52-54, 60, 61, 63-66]
		• Analytical thinking skills	[4, 49, 53]
		• Technical and literate communication	[4, 6, 31, 33, 43, 44, 46, 47, 49-51, 53-57, 64, 66, 67]
		• Collaboration (including machine-human)	[45, 46, 48, 50, 52, 54, 55, 66-68]
		• Interdisciplinary skills	[45, 47, 49, 51, 53]
	Social skills	• Teamwork	[4, 6, 31, 33, 43, 44, 46, 47, 49, 52, 57, 64]
		• Perspective-taking	[42]
		• Professional ethics	[43, 57]
		• Understanding of diversity	[43]
		• Self-awareness, self-organisation	[6, 45, 47, 56]
		• Interpersonal skills	[43] [52, 66, 68]
		• Intercultural skills	[31, 55]
	Personal skills	• Social responsibility and accountability	[43] [47]
		• Lifelong learning skills	[33, 47, 49, 50, 53, 63, 64]
		• Leadership skills/people management	[4, 31, 33, 44, 46, 51, 54, 64, 65]
		• Emotional intelligence	[46, 54, 55, 63, 65]
		• Negotiation skills	[46, 55, 63, 65, 68]
		• Entrepreneurship	[62-64]
		• Adaptability	[44, 47, 50, 54]

4.2 Skills development SLR results

Table 5 presents the skills development approaches that were identified from the papers that satisfied inclusion criterion CR2 presented in Table 2. Each skills development approach is coupled with a summary of the findings and the related references.

Table 5: SLR skills development approach

Skills development approach	Summary	References
Apply artificial intelligence in education	• To develop AI skills in engineers, the authors advocated for intelligent tutoring systems, automated teaching assistants, and the use of educational data mining and learning analytics	[69]
Learning factories/teaching factory	• Learning factories using virtual factory-based training to develop problem-solving skills • Incorporation of augmented reality and virtual reality in learning factories to develop technical skills in robotics, cybernetics, and data analysis • Linking industry and educational institutions in developing Industry 4.0 skills requirements • Developing both technical and non-technical skills essential for Industry 4.0 • Virtual training using advanced technologies of the factory of the future in knowledge and skills transfer • Promoting interdisciplinary training • Learning factories depicting real learning environments, with emphasis on hands-on training and the development of social skills	[9, 32, 47, 70-79]
Smart education	• Using smart education to develop critical Industry 4.0 skills in engineers	[80]
Education 4.0	• Learning and skills development in both real and virtual worlds using augmented reality and virtual reality • Integrating the Internet of Things and augmented reality technologies in educational institutions' laboratories to develop skills required in Industry 4.0 • Use of Information and Communication Technology and massive open online courses facilitates non-discriminatory participation in developing skills required for Industry 4.0 • Using cyber physical education for developing skills and building competencies. E-learning and e-training	[71, 73, 74, 81-83]
Apprenticeship degrees	• Pointing to the need for degree apprenticeships to develop knowledge and impart industrial experience, and practical hands-on skills to reduce skills gap and skills mismatch • Increasing collaboration between industry and institutions of higher learning	[32]
Interdisciplinary training/ multidisciplinary training	• Teaching content focuses on multidisciplinary knowledge to develop industry skills • Multi-literacies approach facilitates development of three critical skills in Industry 4.0: critical thinking, technological competencies, and teamwork	[84-87] [47]
Hi-tech FABlabs	• Use of hands-on laboratories integrated with class instruction to develop Information Technology and Operations Technology required to design, secure, implement, and maintain systems	[84, 85]
Gaming	• Advocates use of gaming to develop Industry 4.0 skills requirements • Caters for Generation Y and Millennials by using digital gaming-based learning in developing Industry 4.0	[88, 89]

5 DISCUSSION

5.1 Discussion of SLR

The findings of the SLR pointed out that non-technical skills, also referred to as 'soft' skills, are increasingly required in engineers in the Industry 4.0 era. Thus, to be competent and remain relevant, it is necessary to balance technical and non-technical skills in the employees of the future.

A considerable number of soft skills cannot easily be automated; thus they will remain significant in Industry 4.0.

Because of the rapid change in technological advances that demand relatively new skills sets, lifelong learning abilities become essential in the workforce of the future, which must constantly upgrade its skills in response to the demand for new skills.

Industry 4.0 advanced technologies and automated systems are increasing the level of skills complexity required in the workforce of the future. This can be seen, for example, in piloting an aeroplane or monitoring nuclear power plants. Increasing use of artificial intelligence demands strong man-machine interaction to achieve improved productivity. This interaction demands strong non-technical skills, such as emotional intelligence, critical thinking, creativity, innovation communication, collaboration, leadership, and teamwork.

Technical skills will significantly important in the engineers of the future. Technological skills, programming skills, and digital skills are relevant in Industry 4.0. Digital skills that were pointed out as outstandingly significant include data analytics and cyber security skills. The use of learning factories was identified as having the capability of balancing the skills required in the workforce of the future.

A strong partnership between industry and educational institutions is required to reshape Industry 4.0 skills requirements. Learning factories, also referred to as 'teaching factories', could possibly provide a link between industry and educational institutions. It was noted that education is slowly adopting 'Education 4.0', a term coined after Industry 4.0.

The incorporation of interdisciplinary and multidisciplinary approaches in skills development could generate the skills required for Industry 4.0. A significant number of authors point out that multidisciplinary knowledge is required in the workforce of the future.

The SLR revealed that, although a noticeable number of research papers discussed Industry 4.0, there was little discussion of the skills required for each engineering profession level. Daling, Schroder, Haberstroh, and Hees [49] classified skills for managers and workers in the production environment. Mourtzis [73] categorised competencies for Industry 4.0, and ranked their importance for different roles in production enterprises. He argued that technical competencies and methodological competencies are of significant importance to the technical workforce. It was highlighted that non-technical competencies are also clearly important to the technical workforce, production engineers, and executives [73].

5.2 Impact on technical vs academic institutions

Perhaps the most important question to ask is how this study could promote change in academic and technical institutions. One of the approaches that could be followed is to evaluate the existing curricula of BEng and BEng.Tech degrees to see how well they satisfy the recommended criteria in Table 4. This could also highlight both institution-specific and overall deficiencies that need attention.

One of the often-overlooked elements is the students themselves. Understanding their current skill levels and incorporating their inputs could prove meaningful in designing a comprehensive strategy to help institutions to adapt and flourish in Industry 4.0.

5.3 South African context

Because of the social and economic issues facing South Africa and the need for cultural unity, a true solution to the skills challenges will have to include cross-pollination and collaboration between technical and academic institutes. An appreciation of the role and value that each engineering professional expertise level can contribute is vital.

Funding mechanisms such as Technology and Human Resources for Industry Programme (THRIP) THRIP already suggest this type of collaboration by requiring institutions from differing social and academic backgrounds to work together on initiatives and proposals. They also require strong collaboration with industry, with both technical and academic graduates, and with workplace placements.

6 CONCLUSION

The SLR review answered research questions 1 and 3, which ask which Industry 4.0 skills are required in the engineering profession and how these can be developed. The study pointed out that non-technical skills are as important as technical skills in the engineering profession in the Industry 4.0 era.

Advanced technologies are not intended to replace humans for improved productivity; rather, there must be tight human-machine collaboration. Technical and academic institutions must open lines for lifelong learning to meet the challenge of the rapid change in skills requirements in Industry 4.0. Interdisciplinary skills development could be necessary in Industry 4.0 to ascertain the effectiveness of employees in the engineering profession.

The SLR exposed a gap in the literature on the specific skills required for different engineering profession levels. There is also a deficiency in the literature discussing specific Industry 4.0 skills in South Africa. In this regard, future work will focus on developing a model detailing conceptual skills requirements for different engineering professional levels. Detailed research on a skills development framework that seeks to bridge the gap between relevant Industry 4.0 skills requirements and development in South Africa will be undertaken.

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APPENDIX D: ARTICLE 4

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Industry 4.0 skills: A perspective of the South African manufacturing industry

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Orientation: Industry 4.0 (I4.0) is causing significant changes in the manufacturing industry, and its adoption is unavoidable for competitiveness and productivity.

Research purpose: This study investigated I4.0 skills using the views of professionals in the manufacturing industry and experts in digital transformation practising in South Africa.

Motivation for the study: I4.0 was coined originally for the manufacturing industry, and skills availability significantly influences its successful adoption. Furthermore, I4.0 is relatively new in the South African manufacturing industry, and there is still limited empirical research on the subject.

Research approach/design and method: A qualitative descriptive research design was used, and participants were enrolled using purposeful sampling via email, telephone and LinkedIn. Twenty semi-structured interviews were conducted face-to-face or telephonically, and thematic analysis was used to analyse the data.

Main findings: This study found that I4.0 demands higher skills than in conventional manufacturing, and companies should take the lead in facilitating upskilling and reskilling of their employees to preserve jobs. Experiential training could enhance I4.0 skills development in the manufacturing industry.

Practical/managerial implications: Agile changes in I4.0 require constant re-alignment of employees' skills in the manufacturing industry. This requires companies to make the human resource (HR) management function an integral part of business strategy.

Contribution/value-add: The study can help HR practitioners and manufacturing professionals in strategising and innovate technology to manage the evolving I4.0 skills requirements and preserve jobs. The study also asserts a foundation for further investigation of I4.0 skills competencies' development in the South African manufacturing industry.

Keywords: Industry 4.0; industrial revolution; manufacturing industry; skills sets; competencies; experiential training; human resource management; South Africa.

Introduction

The progression in industrial revolution has resulted in an incremental change in job complexity and skills requirements (Selamat, Alias, Hikmi, Puteh, & Tapsi, 2017). Industry 4.0 (I4.0), a Fourth Industrial Revolution initiative, is transforming the manufacturing industry into a more competitive environment in various ways that include the skills mix, attitudes and experiences required in the workforce (Baker, 2016; Gehrke et al., 2015; World Economic Forum, 2016). Skills requirements and skills development are amongst the factors that significantly influence successful adoption of I4.0 (Hartmann & Bovenschulte, 2013; Maisiri & Van Dyk, 2019). Thus, human resources (HR) and its management become vital in manufacturing companies (Paine, 2009).

The South African manufacturing industry makes a noticeable contribution to the country's economy (Republic of South Africa, 2018a, 2018b), and the adoption of I4.0 principles and technologies is unavoidable for survival and competitiveness. The South African manufacturing industry is currently characterised by significant numbers of unskilled and semi-skilled workers (MerSETA, 2018). Thus, the impact of I4.0 on skills requirements cannot be ignored and calls for an investigation.

In a recent study, Dhanpat, Buthelezi, Joe, Maphela and Shongwe (2020) considered HR professionals' roles in I4.0. Their study presented the skills required by HR professionals in I4.0 using the views of practising HR professionals (Dhanpat et al., 2020). This study complements the work of Dhanpat et al. (2020) by focusing on I4.0 skills requirements in the manufacturing industry using the views of manufacturing professionals and digital experts. The findings of this study could enhance the role of HR professionals in I4.0.

Purpose

A systematic literature review aimed at exploring I4.0 skills requirements (Maisiri, Darwish, & Van Dyk, 2019) revealed a lack of empirical studies on this subject in the South African manufacturing industry, and thus the issue is poorly understood. Dhanpat et al. (2020) emphasised the lack of scientific empirical research on I4.0 in South Africa 'although there are workshops and seminars in the field' (Dhanpat et al., 2020, p. 1). Therefore, this article seeks empirical evidence of I4.0 skills requirements in the manufacturing industry using the views of professionals and experts practising in South Africa.

Guided by the work of Kim et al. (2017), as well as Sandelowski (2000), the following research questions are set:

1. What is the impact of I4.0 on jobs and skills requirements in the manufacturing industry in South Africa?
2. Which skills are regarded as critical for I4.0 in the South African manufacturing industry?
3. What are the strategies organisations are implementing to mitigate the impact of I4.0 on jobs and skills requirements?

Literature review

Industry 4.0: a manufacturing industry initiative

I4.0 was coined in 2011 in Germany in a context in which ways were sought to maintain the competitiveness of Germany's manufacturing industry and its leadership in technology innovation (Kang et al., 2016; Lu, 2017; Müller, Buliga, & Voigt, 2018; Ślusarczyk, 2018). Today, the impact of I4.0 on the manufacturing industry is being experienced all over the globe.

Although there are variations in the definitions of I4.0 used by various authors, as presented by Müller et al. (2018), it is evident that it is an initiative that focuses on improving competitiveness in the manufacturing industry. Manufacturers consulted by Ślusarczyk (2018) emphasised that I4.0 will apply significantly to the manufacturing industry.

The global community has responded by developing initiatives that support the manufacturing industry in line with I4.0, for example, EU initiative Factories of the Future to maintain sustainability and boost production (Müller et al., 2018), Made in China 2025 (Internet Plus) to enable state-of-the-art manufacturing (Bartodziej, 2016) and Manufacturing Innovation 3.0 in South Korea (Kang et al., 2016). These initiatives support the concept that I4.0 is a manufacturing initiative that is driving the Fourth Industrial Revolution.

In response to the global adoption of I4.0, the South African Department of Trade and Industry has launched the new Intsimbi Future Production Technologies initiative to build capacity to meet I4.0 requirements (INSTIMBI, 2019; Republic of South Africa, 2018c).

The manufacturing industry in South Africa

The manufacturing industry is the fourth largest industry in South Africa. It comprises 10 sectors (Republic of South Africa, 2018b), including the metals sector, the automotive sector and the plastic manufacturing sector (MerSETA, 2018). The manufacturing industry contributes approximately 14% to the South African gross domestic product (Republic of South Africa, 2018a): a significant input to the countries' economy.

The manufacturing industry further provides a considerable number of jobs (MerSETA, 2018) and contributes approximately 1 in every 10 employees to the country's workforce (Republic of South Africa, 2018b). A general decline in the total number of employees has been noticed as follows: 1.44, 1.19 and 1.1 million in the years 2005, 2014 and 2019, respectively (Plastic & Chemical Trading, 2019).

The manufacturing industry is identified as an employment generator (Kleynhans & Sekhobela, 2008). It has the potential of employing 1.7 million people (Republic of South Africa, 2018a) if the country's installed capacity is fully utilised as opposed to the current 81% capacity utilisation (Plastic & Chemical Trading, 2019). The partial capacity utilisation has been attributed to a lack of skills, amongst other factors (Plastic & Chemical Trading, 2019). I4.0 adoption has the potential of worsening the skills challenge in the manufacturing industry. This emphasises the need to investigate I4.0 skills requirements in the South African manufacturing industry.

Industry 4.0 and the workforce

'People are the true authors of the digital story' (Accenture Consulting, 2017, p. 2). Talent and skills are identified as the drivers of successful adoption of I4.0. The vision of advanced manufacturing can be realised through a skilled and prepared workforce. I4.0 success not only depends on technology but also on people (Accenture Consulting, 2017).

According to Selamat et al. (2017), an upward trend of increasing job complexity has been observed during the progression of industrial revolution. A significant change in the competencies' requirements, employee motivation and unemployment rates will be noted in the manufacturing industry with the adoption of I4.0 (Accenture Consulting, 2017; Calitz, Poisat, & Cullen, 2017; Maisiri et al., 2019). However, none of the studies cited ventured into examining the subject of I4.0 skills in the South African manufacturing industry.

The changes in the job requirements because of the increased complexity of the workplace has the potential of threatening semi-skilled and unskilled jobs (Maisiri et al., 2019) in the manufacturing industry because of the replacement of manual and standard repetitive tasks with automation.

Workforce digital capability and skillset is at the core of successful adoption of I4.0 in manufacturing industries and other hybrid industries (Accenture Consulting, 2017). Further to this, Accenture Consulting (2017, p. 10) highlighted that 'people are at the centre of technological change, and their willingness and readiness to support digital transformation is key to success'. This is supported by Selamat et al. (2017) when stating that the best talent is achieved through the collaboration of machines and humans. Hence, an investigation of the I4.0 skills requirements in the South African manufacturing industry is essential.

Research design

The purpose of this article is to scrutinise the subject of I4.0 skills in the manufacturing industry, using the views of manufacturing industry professionals and digital transformation experts practising in South Africa. Qualitative descriptive research has been 'identified as important and appropriate for research questions focused on discovering the who, what, and where of events or experiences' (Kim, Sefcik, & Bradway, 2017, p. 23), and in collecting data from participants 'regarding a poorly understood phenomenon' (Kim et al., 2017, p. 23).

Research approach

This study followed a qualitative descriptive research approach in investigating the issue of I4.0 skills in the South African manufacturing industry. The descriptive research approach was used instead of other qualitative research approaches because it seeks to explore and provide comprehension and guidance for future studies (Magilvy & Thomas, 2009). 'straight description and comprehensive summary' (Kim et al., 2017, p. 27) and maintained low-inference interpretation during data analysis (Sandelowski, 2010).

Research method

The research method section discusses the following: research setting, entrée and establishing researcher roles, research participants and sampling methods, data collection methods, data recording, strategies employed to ensure data quality and integrity, data analysis and reporting style.

Research setting

This study was undertaken in South Africa through semi-structured interviews with manufacturing industry professionals and digital transformation experts practising in the country. The participants in the semi-structured interviews were mainly from the manufacturing industry.

Entrée and establishing researcher roles

A request for an appointment with prospective participants was communicated via email, telephone and LinkedIn. The invitation was accompanied by a one-page introduction to the study and an informed consent document. Potential participants were not coerced or persuaded to take part in the study, and participation was solely voluntary. The researcher, as the instrument of the study (Magilvy & Thomas, 2009), facilitated the study by arranging, conducting and recording the semi-structured interviews, transcribing the recorded interviews and conducting the data analysis.

Research participants and sampling methods

Manufacturing industry professionals and digital transformation experts were picked to participate in this study using purposeful sampling (Etikan, Musa, & Alkassim, 2016; Neergaard, Olesen, Andersen, & Sondergaard, 2009). Thirty-nine potential participants were contacted to take part in the study, but only 20 participants (Kim et al., 2017; Magilvy & Thomas, 2009) participated in the semistructured interviews, giving a total response rate of 51%. Most participants were from the manufacturing sector (Table 1).

Data collection methods

Semi-structured interviews, commonly used in a qualitative descriptive research approach (Magilvy & Thomas, 2009), were used as the data collection instrument. The semi-structured interviews were conducted by the researcher using face-to-face or telephonic interaction. Semi-structured interviews were chosen because they allow for flexibility by both the researcher and the participant (Miguel, 2011) whilst providing a guide to the issue being investigated.

Data recording

With consent from the participants, the semi-structured interviews were audio-recorded, and the researcher took field

TABLE 1: Participants' industry and responsibilities.

Participant	Industry	Responsibility/position
P1	Research innovation	Research and development manager
P2	Science technology	Technology agreements facilitator
P3	Manufacturing	IT strategist
P4	Manufacturing	Manufacturing execution executive
P5	Manufacturing	Digital factory expert
P6	Technology innovation	Research specialist
P7	Non-governmental organisation	Digital energy solutions expert
P8	Manufacturing	Business transformation and 4IR support consultant
P9	Manufacturing	Advanced technologies expert
P10	Industry and trade	Skills development
P11	Skills development	Fourth Industrial Revolution skills expert
P12	Emerging digital services consultancy	Executive product manager – IoT and digital services
P13	Digital services consultancy	Digital transformation expert
P14	Digital transformation consultancy	Digital solutions specialist
P15	Telecommunications	Information society evaluation and impact assessment deputy director
P16	Manufacturing	Digital factory expert
P17	Manufacturing	Technical trainer and skills facilitator
P18	Manufacturing	Digital control
P19	Manufacturing	Manufacturing execution
P20	Manufacturing consultancy	Innovation executive

IoT, Internet of Things, 4IR, Fourth Industrial Revolution.

notes during participant observation. Only one participant (P5) did not permit the interview to be recorded, and field notes were used to represent this participant's views.

Strategies used to ensure data quality and integrity

Measures were taken to ensure credibility and integrity of the study findings during the data collection, data analysis and reporting (Golafshani, 2003; Neergaard et al., 2009). The semi-structured interviews were audio-recorded and transcribed verbatim to avoid distortion of the participants' views (Braun & Clarke, 2006). Transcription accuracy was enhanced by reading the transcription and comparing it with the audio recording. Any detected discrepancy was immediately corrected.

A systematic method of data analysis was used to ensure that the rigour of the study findings was upheld (Braun & Clarke, 2006). This was enhanced by using ATLAS.ti to minimise the chances of bias in the analysis. In line with the nature of a qualitative descriptive study, the researcher maintained low-inference interpretation during data analysis (Neergaard et al., 2009; Sandelowski, 2000, 2010).

The integrity of the study was further ensured by minimising the researcher's subjectivity and by maintaining neutrality in the data analysis (Neergaard et al., 2009). The participants' opinions were emphasised by the researcher maintaining a passive voice.

Data analysis

In a qualitative descriptive study, the researcher must stick close to the data and provide a comprehensive summary of the issue under study (Sandelowski, 2000, 2010). Therefore, thematic analysis, as commonly used in the descriptive research approach (Sandelowski, 2010), was adopted in this study instead of other data analysis approaches because it provides the researcher with an opportunity to stay close to the data, 'with minimal transformation during analysis' (Kim et al., 2017, p. 24) and with minimum inference (Sandelowski, 2000).

A data analysis process was followed of listening to audio recordings, transcribing, reading and re-reading the transcriptions and field notes, identifying codes and classifying them into categories and themes (Magilvy & Thomas, 2009).

Braun and Clarke's (2006) six-step data analysis framework, as applied by Maguire and Delahunt (2017) and Coetzee, Jonker, Van der Merwe, and Van Dyk (2019), was used in this study (Coetzee et al., 2019; Maguire & Delahunt, 2017). The analysis followed the process of data familiarisation, initial codes' generation, reviewing the codes, searching for categories, reviewing of categories and themes' generation.

The researcher familiarised himself with the data by listening to the audio transcription and generating preliminary concepts and ideas. Interesting quotations were noted, and patterns of meaning identified at a semantic level.

Semi-structured interview transcripts were imported into ATLAS.ti, and the researcher read through the transcripts, and an initial code list was generated. The researcher used both open coding and *in vivo* coding to maintain the views of the participants. The codes were reviewed by renaming, merging and splitting, where necessary, until patterns in the data could be identified.

The relationship between codes was established by using the function links and networks in ATLAS.ti (Friese, 2019). Patterns and similarities were identified, and categories were formulated. The categories were reviewed, and themes established from the identified patterns. The themes' relevance to the research questions was ascertained at this stage.

Reporting style

In line with the objective of this study, and the research approach followed, straight descriptions of the participants' views (Sandelowski, 2000) on I4.0 skills will be presented. A table summarising the themes, sub-themes and related codes is presented followed by comprehensive description summaries (Kim et al., 2017; Neergaard et al., 2009; Sandelowski, 2000) of the themes and their related sub-themes and codes. The participants' exact words were quoted so that the researcher could stay as close to the data as possible.

Study findings

Three themes emerged from the data analysis: I4.0 impact, skills requirements and skills development (Table 2). The themes are further described using the participants' views.

TABLE 2: Emerging themes, categories and associated codes.

Theme	Category	Example of associated codes
I4.0 impact	Working practices	Agile methodologies, ecosystem of skills, working in networks, absorbing more content
	Employees' opportunities	Enhancing job experience and productivity, making jobs more meaningful and interesting, requiring mindset change
	Jobs and skills	Higher skills level, job opportunities and task replacement
Skills requirements	Digital skills	Advanced digital skills, basic digital skills, application of technology, integration of ICT, transition skills
	Soft skills	Social skills, thinking skills and personal skills
	Domain skills	Engineering skills and digital skills
	Entrepreneurial skills	-
Skills development	Workplace learning	Upskilling, reskilling, on-the-job training, attitude towards change
	Experiential training	Work-integrated learning, apprenticeships, experiential training, internships, learn a trade, practical training
	Teaching and learning strategy	Creating a platform for people to learn, mentorship, micro-credentialling and use of technology
	Education system	Alignment between skills requirement and skills development, education quality, curriculum change and industry demand driven

ICT, information, communication and technology.

Industry 4.0 impact

The theme of I4.0 impact comprised three categories: working practices, employees' opportunities, and jobs and skills. Rapid changes in I4.0 technologies require companies, teams and individuals 'to adopt agile methodologies which entail agile business models, agile teams and agile decision-making' (P3). This requires that employees have the 'ability to work in an agile way' (P8).

I4.0 requires a new working practice of establishing an ecosystem of skills and working in networks. Some companies are viewing I4.0 as an 'enabler to take on more work content and volume without reducing or increasing headcount' (P18). This is achieved through localising certain components and bringing some of the previously outsourced jobs on board.

The augmentation of humans and technology enhances employees' experience by 'taking away the safety issue of a job, or the risk of a job' (P1), 'taking more thinking away from operators but ensuring more consistency and quality' (P18) and increases their 'productivity and efficiency' (P7, P9).

Participants pointed out that I4.0 makes jobs more meaningful and interesting by enabling 'lower-skilled people to do higher-skilled jobs' (P6) using technologies such as augmented reality and virtual reality. I4.0 technologies enable employees 'who have been stuck in low paying jobs and menial labour' (P7) to be more relevant and perform higher functions in their companies. Employees become more visible:

> '[*A*]s decision-makers and not just as somebody who presses the button but [*somebody who is*] actually in charge of a machine, ensuring that the machine provides the correct kind of data.' (P7)

A significant number of participants emphasised that technology could 'create more opportunities for us' (P9) by 'not taking away jobs' (P1) and companies will 'still need more people, but it will be more on a different skill level' (P18). Some companies are automating routine functions 'not in order to reduce the workforce and take away peoples' work, but to [*enable employees*] … to innovate and come up with new ideas to solve problems.' (P3).

It was noticed that:

> '[*Y*]oungsters or the new people that are coming to the new workplace are expected to be on a higher level in terms of the information technology (IT) understanding, [*and*] understanding how [*the*] Internet of Things (IoT) is going to affect them.' (PP17)

There will be significant job transitioning and task replacement with the adoption of I4.0 technologies, but this does 'not mean replacing the person doing the job' (P1). Other participants pointed out that 'I4.0 does not have [*a*] negative impact on employee headcount' (P18) in their companies. However, 'if they're gonna be no change in the skills development system, in the next 3 to 4 years, we gonna have massive retrenchment coming up for South Africa, massive retrenchments' (P17).

Skills requirements

Participants emphasised that 'soft skills alongside technical skills are even more important than technical skills alone in I4.0' (P20) and 'those soft skills we find lacking' (P3); 'those softer skills are missing' (P13) in the employees. The soft skills were grouped into thinking skills, social skills and personal skills.

Thinking skills such as 'problem-solving' (P2–P4, P9, P12–P14, P17, P18, P20), 'critical thinking' (P3, P4, P9, P11, P13, P20), 'creativity and innovation' (P1, P3, P8, P9, P11, P14), 'application of knowledge' (P4) and 'agile decision-making and accountability' (P3, P7–P9, P13, P18) were indicated to be critical in I4.0.

Social skills such as 'collaboration' (P1–P3, P7–P9, P12, P14), 'communication' (P3, P4, P7, P9, P20), 'cross-cultural ability' (P20) and teamwork (P1, P7, P8, P20) were seen as essential to participate in I4.0 meaningfully.

Participants emphasised the importance of personal skills such as 'ability to quickly adjust to change and act' (P1, P3, P4, P8, P13, P18), 'emotional intelligence' (P9, P17), 'lifelong learning' (P2–P4, P6–P7, P13, P17–P18, P20), 'multi-skilling' (P1–P2, P6, P8–P9, P18) 'prioritisation' (P3), 'self-directedness and less taking [*of*] orders' (P8, P18) and 'personal evaluation' (P3–P4) in I4.0. Other companies are 'trying to implement that every day you have to teach something new to someone else or every day you have to learn something new' (P3) so that employees become aware of the ongoing trends and 'continuously keep up to skills' (P3).

Advanced digital skills related to big data analytics, advanced robotics, artificial intelligence, augmented reality and machine learning, amongst others, were pointed out to be vital in I4.0 (P1–P4, P7–P8, P11–P12, P14, P17).

'So skills in big data analytics, augmented reality, more use of the cloud, better use of the industrial Internet of Things, … and robotics as well; if we are able to implement those things in the manufacturing industry, then it will, of course, benefit the country in all sort[*s*] of way[*s*] because those companies will reduce their cost' (P14).

Digitals skills such as coding skills, data analytics, human–machine interaction and understanding information technology were regarded as basic skills in the sense that they will be commonly required in the manufacturing industry by employees (P1–P2, P7–P8, P12–P13, P17, P19). These skills will be needed as 'part and parcel of the adjustment, and people with these transitional skills are those you need basically' (P2).

Regarding information, communication and technology (ICT), it was pointed out that 'any formal skilling needs to, in one way or the other, have ICT at the centre' (P2). The question will be 'whether or not you are properly skilled in digitalisation and ICT' (P2).

There will be a difference between an 'artisan versus a skilled I4.0 artisan, a technician versus a skilled I4.0 technician, a technologist versus a skilled I4.0 technologist and an engineer versus an I4.0 engineer' (P4) regardless of the engineering focus, be it mechanical, industrial, electrical or electronic.

Employers need to 'start a lot more of entrepreneurship skilling' (P20) to strengthen their employees' entrepreneurial skills, which will empower them to deal with possible unemployment that can arise from the impact of I4.0.

Skills development

Participants emphasised that the possible negative impact of I4.0 on jobs and skills requires a significant implementation of skills development both in the workplace and skills development institutions. Workplace training, which includes 'reskilling' (P1–P3, P6, P17–P19), 'upskilling' (P1–P4, P17–P19) and 'on job training' (P2, P4, P19), was identified as critical in developing relevant I4.0 skills. Companies should take the lead in facilitating the upskilling and reskilling of their employees:

> 'So, what we have found as an organisation as well is, we need now to upskill our own people now. We have embarked on creating small programs where we introduce these new technologies to our workforce, and we are creating a lot of training programs so that our workforce understands what's coming and how I4.0 will also impact them.' (P17)

Participants observed that 'generally people themselves are not keen or eager to spend out of their own time and money to upskill themselves for the future' (PP19) and this attitude varied with 'older age group, let's say above 35 years … [*who*] don't want change to take place in the workplace because their normal working day is gonna be upset.' (P17).

Participants emphasised that I4.0 skills will be a significant requirement and hence educational institutions must promote experiential training (P1, P4) in the form of 'practical training' (P8, P13, P17–P18), 'internships, apprenticeships' (P1–P2) and 'work-integrated learning' (P5–P7). Skills will be recognised more than abstract knowledge because 'that is the only way we can create more jobs, and [*it is an*] economic enabler for us to move ahead' (P17).

Companies should 'create opportunities for people to learn' (P19) and 'give people access whether it can be free internet access and free access to information because accessibility is a challenge' (P3). 'Innovation centres, technology stations' (P7), 'D labs' (P6) and 'learning factories' (P1) were regarded as instruments for making information available.

Both workplace training and institutional training should adopt I4.0 technologies such as 'augmented reality and virtual reality' (P6–P7, P9) to 'accelerate training' (P6) and skills development. Conducting such training could considerably improve skills development turnaround in terms of time and quality:

> 'And in some cases what we have seen as well, which can be a good example again, on the other hand, is with the manufacturing of spare parts for equipment, … we have seen that … augmented reality glasses and virtual reality glasses have been effectively used in accelerating training.' (P7)

Micro-credentialling (P3–P4, P6, P13, P17), short courses (P2, P4, P17–P18) and mentorships (P4, P19) were identified as other essential strategies that can be used to enhance the development of I4.0 skills in the South African manufacturing industry.

Shortage of I4.0 skills in the South African manufacturing industry was attributed to a significant lack of alignment between skills requirements and skills development (P2–P3, P7–P8, P11, P13–P14, P17). P9 stated that 'we are preparing our students and our people for the first, second and third industrial revolution'. Participants emphasised that 'the quality of teaching and learning is not great and is intensified by organised labour in the education sector that is largely resistant to change' (P6) and that this lack of quality widens the skills challenge in the country.

Curricular alignment to I4.0 skills requirements, from early childhood training to tertiary education, was recommended as an urgent action in the country (P1–P3, P11–P14, P17, P20). The curriculum must be 'industry skills demand-driven' (P11) and must offer broad assessment criteria (P9):

> 'So, if you look at automotive manufacturers how they predict the cars and how the cars get introduced, I mean they work on a plus or minus 12-year cycle. So, in a 12-year cycle, they know exactly what technology they need 12 years from now. So, if industry get much closer to education and they say guys in 12 years.' (P17)
>
> 'time, this is what we think that gonna come in order for these youngsters to be able to work at a certain level they need.' (P17)

Discussion

Outline of the findings

The findings of this study accentuate that the adoption of I4.0 in the South African manufacturing industry is essential, thus confirming findings in other studies (Calitz et al., 2017). Some South African manufacturing companies are adopting I4.0 without affecting their workforce headcount, and learning from this experience is paramount. These companies are innovating technology in such a way that jobs are saved. This is achieved by implementing various strategies, such as automating routine functions to provide employees with opportunity and time for innovation and problem-solving; absorbing more content and bringing in previously outsourced functions by leveraging the capability of I4.0 technologies; focusing on technologies that simultaneously augment humans and enhance competitiveness and productivity; and in-house reskilling and upskilling.

This study points out that the impact of I4.0 on jobs and skills depends significantly on the individual company's innovativeness and its strategy towards employees' well-being. Technology innovation to save jobs requires joint efforts from manufacturing professionals, digital experts and HR practitioners who are change agents and strategic partners (Paine, 2009).

Incremental learning, where employees are encouraged to learn something small and new every day or teach someone something new every day, is being adopted by other manufacturing companies in South Africa. Employees are given sufficient time to learn through experimentation and are given opportunities to make mistakes and rectify them promptly. This shortens employees' learning cycle, thus increasing their relevance to the organisation. In the process, jobs are preserved, and this is of significance to South Africa, which faces notable unemployment challenges (Rambe, 2018).

The findings of this study intimate that I4.0 demands higher skills levels in the workforce than conventional manufacturing. The South African manufacturing industry is characterised by a significant percentage of the low-skilled workforce (MerSETA, 2018). Workplace training has the potential of achieving higher workforce productivity levels (Van Zyl, 2017) and could assist in mitigating I4.0 skills challenges in the South African manufacturing industry. To this end, HR practitioners need to align their training strategies towards the facilitation and promotion of reskilling and upskilling of the workforce in meeting I4.0 skills requirements (Dhanpat et al., 2020).

The education system has a notable contribution to minimising I4.0 skills challenges in the manufacturing industry. The potential lies in aligning skills development with industry requirements. Such alignment was pointed out to be missing in the South African education system. The alignment can be achieved when the education system and other skills development institutions are industry-driven. In the same respect, there was an emphasis on strengthening the development of workplace employability skills. This supports the relevance of work-integrated learning (Rambe, 2018) and other practical models that are relevant in developing I4.0 skills for the manufacturing industry.

The study confirms the importance of soft skills such as problem-solving, critical thinking, collaboration, communication, cross-cultural ability, teamwork, emotional intelligence, lifelong learning and multi-skilling in I4.0 (Carter, 2017; Kazancoglu & Ozkan-Ozen, 2018; Krot, Mazgajczyk, Rusińska, & Woźna, 2018; Maisiri et al., 2019). Soft skills such as agile decision-making and accountability, ability to quickly adjust to change and act, self-directedness and a reduced taking of orders, which were identified in this study, are rarely found in the literature.

Mindset change in the workforce was identified to significantly contribute to the successful adoption of I4.0 in the manufacturing industry. To manage the change process, the workforce requires transitional skills, such as coding skills, data analytics, human–machine interaction and understanding of information technology. The strategic role of HR practitioners (Davis, 2017; Rimanoczy & Pearson, 2010) in collaborating with manufacturing professionals becomes important in ensuring that employees acquire the needed transitional skills.

Practical implications

The quick changes in the use of technologies in the manufacturing industry require constant alignment of employees' skills and demand that companies make the HR management function an integral part of their business strategy.

This study provides information on I4.0 skills that can be used by both manufacturing professionals and HR practitioners in strategising on future employment practices in their companies.

The study further provides practical solutions to ensuring the competitiveness of the manufacturing industry through the successful adoption of I4.0, facilitated by skills availability and skills development. The findings of this study could enhance strategies to develop I4.0 skills for both workplace training and institutional training.

Limitations and recommendations

The study focused on the broad subject of I4.0 skills in the South African manufacturing industry and did not venture into distinguishing between disrupted environment-specific skills and generic permanent skills. Further to this, the study only focused on skills and not on the whole subject of competencies (skills, knowledge and personal attitudes) of employees in I4.0 (Rambe, 2018). Thus, the study lays a foundation for further investigation into the subject of I4.0 competencies' requirements and development. A comprehensive study on an I4.0 competency maturity model is suggested.

A sample size of 20 participants may be identified as a limitation towards getting broader views on the subject investigated. However, the study design minimised the possible effect of small sample size by purposefully selecting participants regarded as experts in this subject. Although there might be variations in how I4.0 impact on various sectors in the manufacturing industry, the study did not focus on a particular manufacturing industry sector in South Africa. Although this could be sufficient for this study, future studies should consider looking at how I4.0 is impacting on skills in different manufacturing industry sectors in South Africa.

Conclusion

The study investigated the subject of I4.0 skills in the South African manufacturing industry, and the findings reveal that I4.0 has a potential to have a negative impact on jobs if no action is taken to align workforce skills with industry skills requirements. However, a notable number of South African manufacturing companies are innovating the technologies they use and implementing strategies that minimise or even eliminate workforce headcount reduction. It can be concluded that the role of HR practitioners in collaborating with manufacturing professionals becomes increasingly relevant in managing the evolving I4.0 skills' requirements and preservation of jobs.

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Competing interests

The authors declare that they have no competing interest that may have inappropriately influenced them in writing this article.

Authors' contributions

W.M. was responsible for data collection, data analysis and preparing the manuscript – the work is based on his PhD studies. L.V.D. supervised the study. All authors discussed the findings and contributed to the final manuscript.

Ethical consideration

In compliance with North-West University's ethical clearance process, participants were enrolled voluntarily, and no participants were persuaded or coerced to participate. This was achieved by providing the prospective participants with an informed consent document, which they had to sign before participating in the research. The research overview, expectations from the participants, risks involved and how the risks would be minimised, as well as the handling and use of the data collected, were stated in the informed consent document. Participants were offered the liberty to withdraw from the study during or after the interview. The researcher adhered to the statements contained in the informed consent document at all stages of the study.

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Data availability statement

Data sharing does not apply to this article, as no new data were created or analysed in this study.

Disclaimer

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APPENDIX E: ARTICLE 5

Industry 4.0 Competence Maturity Model Design Requirements: A Systematic Mapping Review

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***Abstract*—The impact of Industry 4.0 (I4.0) on the manufacturing industry's systems and processes extends to employees' competency requirements. This consequently requires a response in the preparation of graduates who will be ready to practice engineering with professional level technical know-how and soft skills in I4.0. The study focused on developing a conceptual I4.0 competency maturity model (I4.0CMM) and illustrating it using industrial engineering capability functions. Using the systematic mapping review approach, a gap analysis was conducted of design requirements for I4.0 competency models and frameworks in the literature as measured against predefined design requirements of an I4.0CMM. A total of 303 relevant research papers from Scopus, Web of Science online databases, and grey literature were retrieved. Twenty-five papers and documents were included in the study. The results of the review indicated that the predefined design requirements for an I4.0CMM were not all satisfied in literature. Thus, a conceptual I4.0CMM that is aligned to industrial engineering capability functions was developed and is illustrated. The I4.0CMM could be a solution in providing a comprehensive competency assessment framework for industrial engineering practice and education.**

Keywords—Industry 4.0, competency, maturity model, systematic mapping review, industrial engineering

I. Background to the Study

Workforce competencies significantly influence the successful adoption of Industry 4.0 (I4.0) in organizations [1]. The background of I4.0 and its application in the manufacturing industry [2, 3] require that engineers considerably drive its successful adoption. Accordingly, the engineering education role of "preparing the graduates to practice engineering with competent technical know-how and soft skills at professional level" [4] becomes particularly important.

Industry 4.0 demands higher competency levels and requires employees with substantial skills and qualifications [1, 5, 6]. Thus, the alignment of engineering education in producing graduate attributes that meet I4.0 competency requirements cannot be avoided [5].

A study by Acerbi et al. [7] pointed out that there was a lack of comprehensive I4.0 competency assessment models and tools in literature. To assess this gap in literature, design requirements for a conceptual Industry 4.0 competency maturity model (I4.0CCM) were generated while guided by literature [8, 9]. This was followed by a systematic mapping review to identify I4.0 competency models and frameworks existing in literature. A design requirements gap analysis measured against the predefined design requirements for an I4.0CMM was then conducted.

A conceptual I4.0CMM that aligns with the industrial engineering domain was developed and is presented in this paper. As I4.0 has the potential to significantly impact on the knowledge and skills of industrial engineers [10], the conceptual I4.0CMM is illustrated using industrial engineering capability functions.

II. Study Purpose

The purpose of this study was to develop a conceptual I4.0CMM and illustrate it by using industrial engineering capability functions. The study was guided by three research questions:

1) Which I4.0 competency models and frameworks exist in literature?

2) Do the existing I4.0 competency models and frameworks satisfy all the predefined design requirements for an I4.0CMM?

3) What are the domains and dimensions that could be used to formulate the conceptual I4.0CMM?

III. Industry 4.0 Competency Maturity Model (I4.0CMM) Design Requirements

The People Capability Maturity Model (PCMM) [11, 12] was developed to assist organizations in enhancing their workforce capabilities. Application of PCMM enables organizations to mature their "capability for attracting, developing, and retaining the talent" [11] needed.

Management of employees' competencies from graduate level to professional level is crucial for organizations' success [13]. Thus, continuous alignment of employees' competencies with "business objectives, performance and changing needs" [11] is essential for business success.

Maturity models can serve a descriptive purpose if they are applied for assessing the "as-is" capability by comparing the "capabilities of the entity under investigation with respect to given criteria" [8, 9, 14]. On the other hand, maturity models can serve a prescriptive purpose when it is used to show how to find a desirable maturity level and stipulate guidelines to achieve a better state [8, 9, 14].

The design requirements for an I4.0CMM were generated based on serving both descriptive and prescriptive purposes. Table I presents I4.0CMM design requirements which were generated guided by the maturity model design principles framework of Pöppelbuß and Röglinger [8] and as applied by Van Dyk [9].

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TABLE I. I4.0CMM CONCEPTUAL DESIGN REQUIREMENTS

Category	Design requirements (DR)
Application domain	**DR1:** The I4.0CMM must outline engineering profession competency requirements for the manufacturing industry that must also be adaptable to other engineering industries.
Purpose of use	**DR2:** The I4.0CMM must provide a set of knowledge, technical and soft skills required to perform specific engineering capability functions. **DR3:** The I4.0CMM must support and guide engineering professionals' practice and continuous professional development. **DR4:** The I4.0CMM must provide competence reference standards for engineering education and quality assessment of engineering processionals along the career continuum. **DR5:** The I4.0CMM must be useful to assess employees' competency measured against the industrial revolutions and future requirements.
Target group	**DR6:** The I4.0CMM must be easily understood and useful for researchers, academics in engineering education, manufacturing professionals, and human resources practitioners.
Class of entities under investigation	**DR7:** The I4.0CMM must be adaptive and flexible in identifying skills for the future and must not only be confined to I4.0 applications and technologies.
Maturity and dimensions of maturity	**DR8:** The I4.0CMM must include a competency domain, a capability functions domain, and a distinct maturity levels domain. **DR9:** The I4.0CMM competency statements must be clearly defined and easy to interpret.
Maturity levels and maturation paths	**DR10:** The competency statements must clearly differentiate between maturity levels.

IV. METHODOLOGY

According to Grant and Booth [15], systematic mapping review is among the fourteen reviews that have been used in a significant number of studies to identify research gaps in existing literature [16-22]. Peters and Wood [16] attest that systematic mapping review is "a review method of choice when a focused area of inquiry is in early scientific development" [16].

To accomplish the purpose of this study, both peer reviewed research papers and grey literature [23] were considered in the systematic mapping review [18].

The systematic mapping review was defined and accomplished in three steps [16, 17]: gathering data using a predefined search procedure, selecting the relevant data using predefined inclusion and exclusion procedures, and extracting relevant information from the literature.

A. Search Procedure

A predefined search strategy was developed to minimize bias during the search for relevant literature to be used in this study. The study used three key search terms: I4.0, competencies, and model. The systematic mapping research method utilized a Boolean search string [24] with the following alternative search words: fourth industrial revolution, skills, and framework. The literature search was conducted on Scopus and Web of Science online databases and included searching grey literature on key consulting organization websites and expanding the data source by a dedicated search of reference lists [18].

B. Inclusion and Exclusion Criteria

Iterative inclusion and exclusion criteria [18, 24] were used to select relevant studies published between 2011 and 2020. This was because the I4.0 concept was coined in 2011 [2]. Studies that focused on I4.0 competency models or frameworks were included. Five iterative steps for excluding studies were followed: exclusion by duplication; exclusion by language compatibility; exclusion by full paper text not accessible; exclusion by paper using the terms competencies and skills loosely in relation to I4.0 competency models; and exclusion by inadequate evidence of a model or framework.

C. Data Analysis

The data analysis focused on identifying design requirement gaps in the included systematic mapping review literature as measured against the predefined design requirements for an I4.0CMM presented in Table I.

V. RESULTS

This section presents the systematic mapping review results and the gap analysis results.

A. Systematic Mapping Review Results

Twenty-five papers were included in the systematic mapping review (Fig. 1). A significant number of papers used the search terms casually and hence were excluded from further analysis.

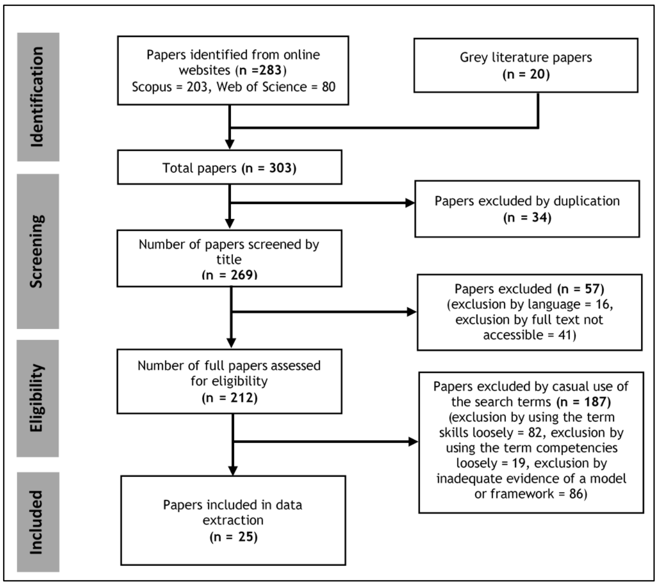

Fig. 1 Systematic mapping review results

B. Gap Analysis Results

Table II maps the gaps between design requirements for the I4.0 competency models and frameworks in literature and the predefined design requirements for an I4.0CMM. The analysis revealed that I4.0 competency models and frameworks in literature satisfied some but not all of the predefined design requirements for an I4.0CMM.

DR1, DR3 and DR4 were fully satisfied by a significant number of studies which provided sufficient information on I4.0 skills and knowledge that could guide the engineering profession's skills development and practice.

Some studies partially satisfied DR2, for example Sakuneka et al. [25] focused on the skills and knowledge of a control engineer. Only Accenture Consulting [26] fully satisfied DR2 by presenting a set of skills and knowledge required for various engineering roles in I4.0.

None of the reviewed studies satisfied DR5, DR7 and DR8 in any way. All studies were confined to I4.0 competency with no flexibility in looking beyond I4.0 requirements.

DR9 was partially satisfied by a few studies, such as the study of Acerbi et al. [7] that provided general competency statements for different maturity levels. Only Accenture Consulting [26] fully satisfied DR9 by presenting capability statements for various skills in different engineering roles.

The work of Acerbi et al. [7] satisfied DR10 by suggesting five distinct competency maturity levels: basic level, aware level, practiced level, competent level, and proficient level.

TABLE II. GAP ANALYSIS RESULTS

No	Paper Title & Reference	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10
1	A methodology to assess the skills for an Industry 4.0 factory [7]	✓	×	✓	×	×	✓	×	×	×	✓
2	Estimating Industry 4.0 impact on job profiles and skills using text mining [27]	×	×	×	✓	×	✓	×	×	×	×
3	Emerging learning environments in engineering education [28]	✓	×	✓	×	×	✓	×	×	×	×
4	Skills in European higher education mobility programs: Outlining a conceptual framework [29]	×	×	✓	✓	×	✓	×	×	×	×
5	A summary of adapting Industry 4.0 vision into engineering education in Azerbaijan [30]	✓	×	×	×	×	✓	×	×	×	×
6	An investigation of Industry 4.0 skills requirements [24]	✓	×	✓	✓	×	✓	×	×	×	×
7	Industry 4.0 competencies for a control systems engineer [25]	✓	×	✓	✓	×	✓	×	×	×	×
8	Smart Education in the context of Industry 4.0 [31]	×	×	✓	✓	×	✓	×	×	×	×
9	Challenges and requirements for employee qualification in the context of human-robot-collaboration [32]	✓	×	✓	✓	×	✓	×	×	×	×
10	Smart industry and the pathways to HRM 4.0: Implications for SCM [33]	✓	×	×	✓	×	✓	×	×	×	×
11	Conceptual framework for the development of 4IR skills for engineering graduates [34]	✓	×	✓	✓	×	✓	×	×	×	×
12	Analyzing Workforce 4.0 in the Fourth Industrial Revolution and proposing a road map from operations management perspective with fuzzy DEMATEL [35]	✓	×	✓	✓	×	✓	×	×	×	×
13	Model of competency management in the network of production enterprises in Industry 4.0: Assumptions [36]	✓	×	✓	✓	×	✓	×	×	×	×
14	Toward a data driven competency management platform for Industry 4.0 [37]	✓	×	×	✓	×	✓	×	×	×	×
15	Tangible Industry 4.0: A scenario-based approach to learning for the future of production [38]	✓	×	✓	✓	×	✓	×	×	×	×
16	Conceptual key competency model for smart factories in production processes [39]	✓	×	✓	✓	×	✓	×	×	×	×
17	Text mining of Industry 4.0 job advertisements [40]	✓	×	✓	✓	×	✓	×	×	×	×
18	Makerspace for skills development in the Industry 4.0 era [41]	✓	×	✓	✓	×	✓	×	×	×	×
19	The Industry 4.0 induced agility and new skills in clusters [42]	✓	×	×	✓	×	✓	×	×	×	×
20	Integration of 3D printing and Industry 4.0 into engineering teaching [43]	✓	×	×	✓	×	✓	×	×	×	×
21	Skill development for Industry 4.0 [44]	✓	×	✓	✓	×	✓	×	×	×	×
22	A competency model for "Industrie 4.0" employees [45]	✓	×	✓	✓	×	✓	×	×	×	×
23	Preparing tomorrow's workforce for the Fourth Industrial Revolution for business: A framework for action [46]	✓	×	✓	✓	×	✓	×	×	×	×
24	Preparing for Industry 4.0: Will digital skills be enough? [47]	✓	×	✓	✓	×	✓	×	×	×	×
25	Manning the mission for Advanced Manufacturing [26]	✓	✓	✓	✓	×	✓	×	×	✓	×

Key: ✓ - Fully satisfied the relevant design requirement × - Did not satisfy the relevant design requirement or only partially satisfied it

VI. DISCUSSION

A significant number of I4.0 competency models and frameworks reviewed in this study focused on skills requirements in I4.0. There is a lack of comprehensive I4.0 competency assessment tools that address the skills and knowledge requirements for specific capability functions in engineering. The reviewed models seldomly provided a comparative scale to gauge employees' competency with reference to the industrial revolutions. A model that could assist in assessing employees' current competency levels and point out higher level requirements could be of significance to decision makers. There is a noticeable shortage of studies that predicted skills requirements beyond I4.0. Development of an I4.0 competency assessment tool that presents competency requirements for specific capability functions in engineering is therefore necessary.

VII. A CONCEPTUAL INDUSTRY 4.0 COMPETENCY MATURITY MODEL

A. I4.0CMM structure

The conceptual I4.0CMM is illustrated in Fig. 2 using the industrial engineering domain. The proposed I4.0CMM conceptual model comprises three domains: a competency domain, a capability functions domain, and a maturity levels domain.

The competency domain has two dimensions: skills (technical and soft) and knowledge requirements.

The capability functions domain has ten dimensions related to industrial engineering [10, 48]. Though these are not exhaustive, the capability functions that were adopted are aligned with industrial engineering roles' requirements.

The proposed I4.0CMM conceptual model assumes the five maturity levels to be in line with industrial revolutions:

level 1 (1st industrial revolution), level 2 (2nd industrial revolution), level 3 (3rd industrial revolution), level 4 (4th industrial revolution), and level 5 (Future requirements).

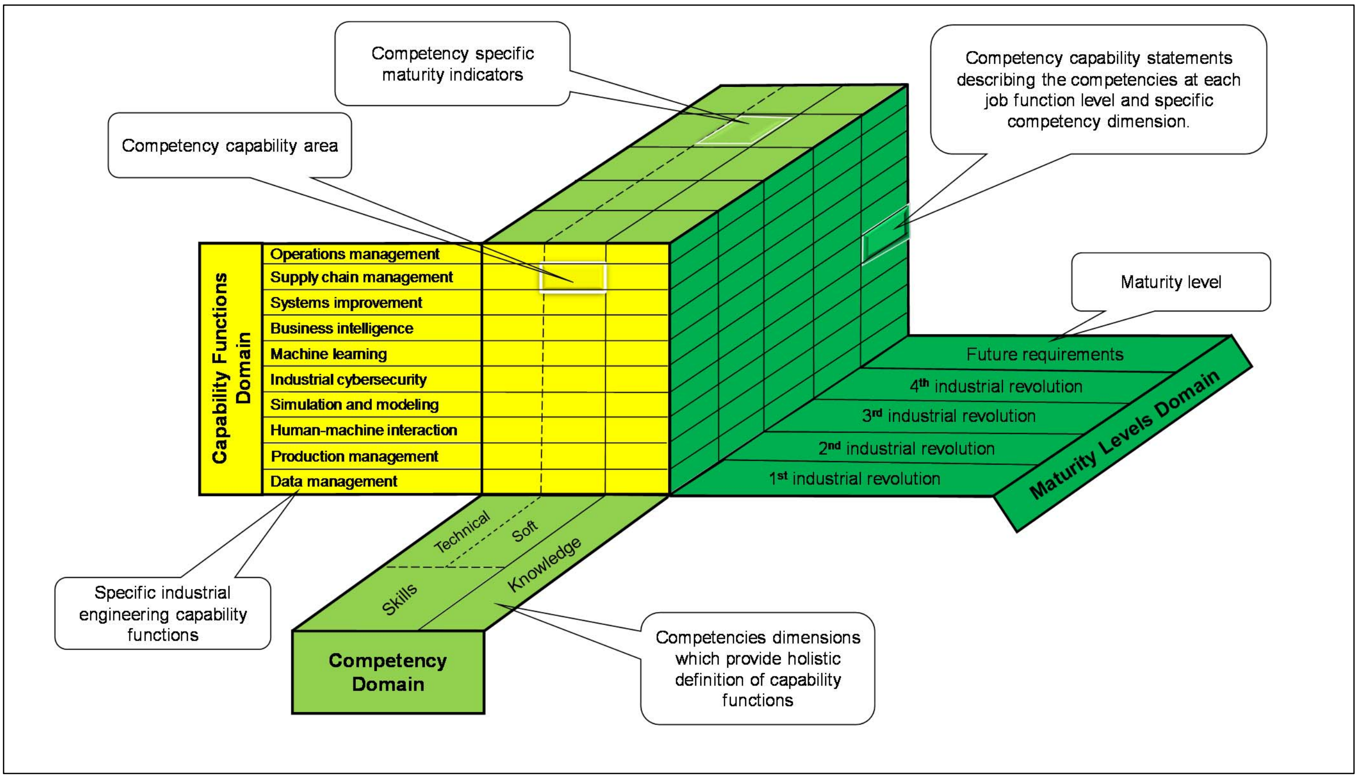

Fig. 2 I4.0CMM conceptual model

B. I4.0CMM Illustration

The I4.0CMM will be used to assess employees' current competency in terms of skills (technical and soft) and knowledge requirements to satisfy a specific industrial engineering capability function. Table III and Table IV illustrate the assessment of the data management and human-machine interaction capability functions, respectively. Technical skills, soft skills and knowledge capability statements at each maturity level are presented. The upskilling requirements depend on the currently determined level of the employee. For example, if the data analysis capability matches level 3 (3rd industrial revolution) requirements, then the industrial engineer needs to upskill to level 4 (4th industrial revolution) requirements. The capability statements presented in Table III and Table IV are not exhaustive and are only used for the purpose of illustrating how the I4.0CMM model would work in practice. Further development is required in this respect.

TABLE III. ILLUSTRATION ON HOW TO USE I4.0CMM – DATA MANAGEMENT CAPABILITY FUNCTION

CAPABILITY FUNCTION	Data management – collection, handling, and analysis of data		
MATURITY LEVELS	**COMPETENCY DOMAIN**		
	Technical Skills	**Soft Skills**	**Knowledge**
Future requirements	Using algorithms and statistical programming languages to analyze real-time data. Handling, analyzing, and interpreting complex digital data.	Proactive learning, future thinking, innovation, and creativity.	Data analytics technologies, real data science development.
4th Industrial Revolution	Identifying patterns and extracting actionable insights and information from data. Corroborating data from multiple sources; accessing data on mobile devices and computers; identifying trends in data and detecting problems; visualizing data; data cleaning [26].	Critical thinking, agile problem identification and problem solving, open minded thinking, communication skills.	Programming knowledge in Scala, Python, R and PySpark. Data optimization, coding, big data analytics
3rd Industrial Revolution	Retrieving, handling and querying data using Structured Query Language (SQL) and NoSQL from rational and irrational databases [49, 50]. Analyzing numeric data using tools such as advanced Microsoft Excel.	Communications skills (verbal and written), analytical mind, attention to details.	Statistical knowledge, SQL knowledge, strong Microsoft Excel skills, advanced mathematical knowledge
2nd Industrial revolution	Recording data on punch cards using keypunches and systematically processing the data using a tabulating machine and its improved versions [49].	Persistent mind, attention to details, communication skills.	Mathematical knowledge, statistics knowledge.
1st Industrial revolution	Manually collecting, preparing, and analyzing data using statistics and mathematics [49].	Accuracy, communications skills.	Mathematical knowledge, statistics knowledge.

TABLE IV. ILLUSTRATION ON HOW TO USE I4.0CMM – HUMAN-MACHINE INTERACTION CAPABILITY FUNCTION

CAPABILITY FUNCTION: Human-machine interaction			
MATURITY LEVELS	**COMPETENCY DOMAIN**		
	Technical	**Soft**	**Knowledge**
Future requirements	Interacting and sharing workload with cognitive and autonomous robots and machines. Executing decision and monitoring processes for a multitude of different production complexes on-site, and off-site [51].	Ability to collaborate and not compete with autonomous robots. Emotional intelligence.	Autonomous robots, artificial intelligence, human factors modeling, and human-machine interaction.
4th industrial revolution	Performing multimodal interaction with machines – touchscreen, dialogue-driven voice control and gesture recognition [51, 52]. Interacting with cognitive and autonomous and self-organizing machines. Using augmented reality and virtual reality as mediating interface in Cyber-physical systems. [52].	Ability to collaborate with machines. Emotional intelligence and agile adaptability to a quick changing environment.	Cyber-physical systems, application of virtual reality and augmented reality, Internet of Things, Smart manufacturing, emotional intelligence
3rd industrial revolution	Humans as machine supervisors – monitoring machines as they perform automated tasks [52]. Interacting with machines in unimodal interactions, i.e. commanding machines through mechanical input, such as a keyboard [51].	Flexibility and ability to interact with machines.	Robotics, automation, control systems, human-machine interaction.
2nd industrial revolution	Humans as controllers of machines – controlling machines in a mass production environment [52].	Multi-skilling, paying attention to details.	Controlling systems and machine display interfaces.
1st industrial revolution	Routine, more-physical-effort tasks to operate the machine – ability to use the machine and making machine adjustments.	Physical ability and individual attitude.	Operation of steam engines, mechanical machines.

VIII. CONCLUSION

This study presents a gap analysis of design requirements for I4.0 competency models and frameworks in literature measured against predefined I4.0CMM design requirements. The analysis points out that the predefined design requirements for an I4.0CMM have seldomly been satisfied in literature. A conceptual I4.0CMM was developed and illustrated in this study using industrial engineering capability functions. The fully developed I4.0CMM, in line with the recommendations (section IX), could close the competency assessment framework gap in the literature. The I4.0CMM has the potential of adding value in assessing and aligning workforce competency requirements in I4.0 and beyond within the manufacturing industry. The I4.0CMM could provide a framework that aligns industrial engineering competency development to industry competency demand. The I4.0CMM will guide engineering education in developing graduate attributes that will meaningfully contribute to the adoption of I4.0 in the manufacturing industry.

IX. RECOMMANDATIONS

This study provides a foundation for further development of an I4.0CMM as a competency assessment tool in the manufacturing industry. The I4.0CMM model was illustrated using industrial engineering capability functions. The recommended next step in this work is to refine the presented I4.0CMM conceptual model by performing an iterative design process to ascertain the validity of model domains and dimensions. This will be followed by the development of capability statements for the specific capability functions. The capability statements should include all the competency dimensions at each maturity level. A structured interview with manufacturing industry representatives and engineering education academics will be conducted to test the validity and functioning of the I4.0CMM.

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APPENDIX F: ARTICLE 6

Development of an Industry 4.0 Competency Maturity Model

Whisper Maisiri, Liezl van Dyk, and Rojanette Coetzee

Abstract—**Industry 4.0 (I4.0) transformations in manufacturing industries impact technology, systems, and processes and extend to employees' competency requirements and, consequently, the preparation of graduates who will be ready to practice engineering with professional-level technical know-how and non-technical skills in I4.0. An I4.0 Competency Maturity Model (I4.0CMM) could be used as a tool to assess and guide the development of I4.0 and future skills requirements. This study applied the Delphi technique to evaluate the I4.0CMM's validity and utility, and the improvement thereof, using experts' opinions in two successive rounds. Purposeful sampling was employed to enroll 35 participants. Nineteen experts participated in round one survey, out of which 17 experts participate in round two of the survey. The study used a central tendency statistical tool (the mean) to evaluate expert consensus (mean score ≥ 75%) and used means graphs to present the data. The study results demonstrated the sufficiency and relevance of an I4.0CMM to both academic and industry practitioners. The I4.0CMM could provide a comprehensive competency assessment framework that guides the development of graduate attributes that align with the I4.0 competency requirements in the industry.**

Index Terms—**competency, Delphi technique, graduate attributes, industrial revolutions, Industry 4.0, maturity model**

I. Introduction

Workforce competencies significantly influence the successful adoption of Industry 4.0 (I4.0) in organizations [1]. The evolution of all engineering professions – but particularly the industrial engineering profession – is interwoven with the progression from the initial to the fourth and further industrial revolutions (IR) [2, 3] as depicted by Fig. 1 [3]. Industry 4.0 and its application in the manufacturing industry [4, 5] magnify the role of engineers in driving its successful adoption. Therefore, the engineering education role of "preparing the graduates to practice engineering with competent technical know-how and soft [non-technical] skills at [a] professional level" [6] becomes critical.

Industry 4.0 demands high competency levels and requires broad skills and qualifications [1, 7-9]. The broad skills include professional skills [10], such as effective teamwork [10–13], people skills, such as creativity, empathy, and flexibility [9, 10, 12, 13], and technological skills [10, 11] such as "ability to work with the Internet of Things, autonomous robots, 3D printing, and other advanced technologies" [11, 12]. In addition, new qualifications will be about enhancing interdisciplinary knowledge and skills [9, 11, 14]. Thus, the alignment of engineering education in producing graduate attributes (GAs) that meet I4.0 competency requirements cannot be avoided [7].

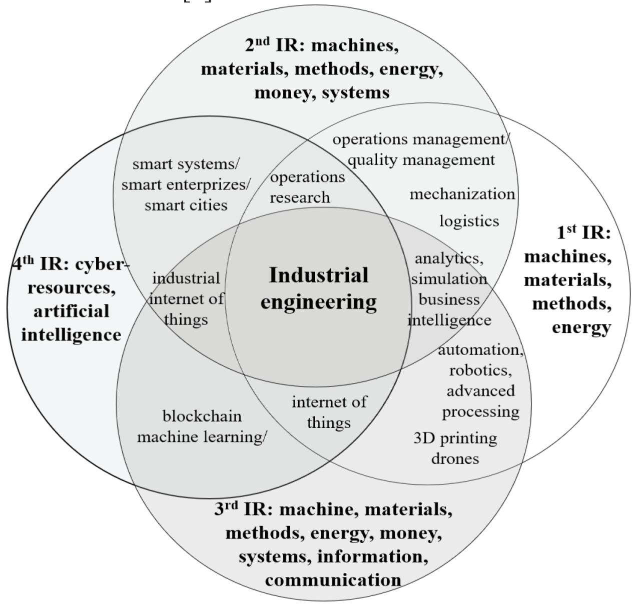

Fig. 1. Relation of Industrial Engineering to the Industrial Revolutions [3]

Literature [15, 16] stresses the significant transformation of the human capital role in I4.0, and thus innovative competency assessment models could assist in the development and assessment of the required competencies. Acerbi *et al*. [17] argued that there was a lack of comprehensive competency assessment models that focus on I4.0, leading Maisiri and van Dyk [18] to assess this gap by conducting a systematic mapping review of existing I4.0 competency models and frameworks in literature. The gap assessment was measured against predefined design requirements guided by literature [19, 20]. The systematic mapping review gap [18] suggested a lack of comprehensive I4.0 competency models and frameworks to assess and align workforce competency requirements in I4.0

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Based on "Industry 4.0 Competence Maturity Model design requirements: A systematic mapping review" by Whisper Maisiri and Liezl van Dyk which appeared in the Proceedings of 2020 IFEES World Engineering Education Forum - Global Engineering Deans Council (WEEF-GEDC), virtual conference, 16 - 19 November 2020.

and future requirements. This led to the conceptualization and presentation of the I4.0CMM in the 2020 IFEES World Engineering Education Forum – Global Engineering Deans Council (WEEF-GEDC) conference paper [18].

Du Preez and Pintelon [21] stated that "industry and industrial engineering are in a continuous process of improvement…" [21]. The industrial engineering profession matured alongside the industrial revolutions [21, 22] and must be ready for continuous changes in "scientific, economic, social, environmental and technological levels" [2] to maintain its relevance. Sackey and Bester [16] argued that I4.0 could significantly impact the knowledge and skills of industrial engineers. On the other hand, the knowledge and role of industrial engineers regarding "[the] systems engineering approach, information technology, manufacturing technology and integration of system components" [21] position them to be role players in the adoption of I4.0. Therefore, the I4.0CMM capability functions domain presented by Maisiri and an Dyk [18] and discussed in this article aligns with industrial engineering functions. However, there is a possibility of adapting the model to other professions' functional domains. The study recorded in this article used the Delphi technique to validate the research problem, the usefulness of the model, as well as the improvement thereof, using expert views.

II. Study Purpose

This study stems from a paper presented by Maisiri and van Dyk [18]. It seeks to prove the validity of the research problem and the sufficiency of the design requirements and verify the compliance of a conceptual I4.0CMM structure against design requirements and the improvement thereof. The study seeks to answer three questions:

1) To what extent does the I4.0CMM contribute to assessing and aligning engineering competency requirements in I4.0 and future requirements?

2) Which design requirements could direct the development of the I4.0CMM in order to be useful for both industry and academics?

3) What are the dimensions required to construct the I4.0CMM?

III. The development of an Industry 4.0 competency maturity model (I4.0CMM)

A capability maturity model (CMM) is a framework with five maturity levels (initial, repeatable, defined, managed, and optimizing) used to assist organizations in adopting best practices in a targeted domain [23-25]. Best practices develop from ad hoc, chaotic processes to become mature, disciplined processes [25]. Maturity models can serve a descriptive purpose if applied for assessing the "as-is" capability by comparing the entity's capabilities under investigation against given criteria [19, 20, 26]. On the other hand, maturity models can serve a prescriptive purpose if used to show how to find a desirable maturity level and stipulate guidelines to achieve a better state [19, 20, 26].

The People Capability Maturity Model (PCMM) is a maturity model that targets human capital management processes [23, 24]. PCMM was developed to assist organizations in enhancing their human capital capabilities. Application of the PCMM enables organizations to mature their "capability for attracting, developing and retaining the talent" [24] needed.

The disruptive nature of I4.0 on competency requirements [15, 16] requires continuous alignment of human capital competencies to meet current requirements. Thus, Maisiri and van Dyk [18] initiated the development of an I4.0CMM, which adopts the principles of maturity models and PCMM. The I4.0CMM could contribute to managing human capital competencies from a graduate-level to a professional level, which is a crucial ingredient for organizations' success [27].

The development of an I4.0CMM started with the generation of design requirements. The design requirements were to direct the development of a model which serves both descriptive and prescriptive purposes [19, 20, 26]. The framework of maturity model design principles of Pöppelbuß and Röglinger [19], as applied by van Dyk [20], guided the initial set of the design requirements [18]. These design requirements were refined and validated in this study (see Section VI of this article) using expert opinions and input.

Consequently, these design requirements guided the conceptualization of the I4.0CMM preliminary structure. The I4.0CMM, as presented by Maisiri and van Dyk [18], comprises three domains: a competency domain, a capability functions domain, and a maturity levels domain. Furthermore, Maisiri and van Dyk [18] illustrated the model using data management and human-machine interaction capability functions [18]. The next stage in the development of the model was to seek expert views to verify the rigor of the I4.0CMM preliminary structure and further refinement thereof.

IV. I4.0CMM significance to the Engineering Education

According to the International Engineering Alliance [28], the "fundamental purpose of engineering education is to build a knowledge base and attributes to enable the graduate to continue learning and to proceed to formative development that will develop the competencies required for independent practice." After entering the workplace, the engineering graduate develops professional competencies leading to professional registration [28].

The I4.0 era requires cross-functional competencies that combine technological advancements and manufacturing knowledge [9, 14, 29]. These competency requirements are created faster than the development of engineering qualifications, therefore widening the misalignment between industry professional competency requirements and engineering education [30]. The I4.0CMM could assist engineering education and workplace human resource development providers in aligning GAs and professional competencies.

In addition, the assessment of GAs, a complex task, can be simplified by using competency models [31]. Competency models provide a framework that facilitates self-evaluation by students and educators in the attainment of GAs. The I4.0CMM could aid students and employees to self-evaluate and selfregulate the achievement of I4.0 skills and future requirements compared to past revolution requirements.

V. Methodology

The current study utilized the Delphi technique to validate the I4.0CMM design requirements and verify the sufficiency of the I4.0CMM structure using expert consensus. The Delphi technique is a continuous iteration process of gathering data from experts until reaching an acceptable consensus level [32]. It suited this study as it has many applications, including validating studies that involve the development of various instruments and models that require expert knowledge and input [33, 34].

Four principles guide the Delphi technique: participants anonymity, an iterative process, controlled feedback, and quantitative data analysis and interpretation, as discussed by Hsu and Sandford [32] and Skulmoski *et al*. [35]. Correctly employing the Delphi method contributes to reaching justifiable, valid, and credible input from experts. Thus, to ensure the credibility and validity of this study, the study was conducted and reported in line with the guidelines of "Conducting and Reporting Delphi Studies" [36, 37].

A. Sampling and participant enrolment

Purposeful sampling, a sampling technique appropriated for establishing an expert panel [37] and commonly used in the Delphi technique [35, 38, 39], was employed to enroll 35 potential experts who meet the following inclusion criteria [35]:

- A minimum of five years known and demonstrated experience in the industrial engineering environment;
- A demonstrated understanding of I4.0 competency requirements;
- The capacity and willingness to participate; and
- Effective communication skills.

Potential participants who meet inclusion criteria were initially identified via LinkedIn profiles. Furthermore, the authors' LinkedIn profiles included an open invitation to participate in the Delphi study. The identified potential participants received a formal invitation via e-mail specifying the study's purpose and explaining the study process. The questionnaire included a compulsory prerequisite check section to ensure only eligible participants completed the survey.

To minimize bias and maintain the validity of the study, potential participants were excluded from the study if:

- there was an existing power relationship with the researchers; and/or
- the potential participants could benefit directly from the study.

B. Data collection

Data were collected between April and May 2021, with a gap of three weeks between each round: two weeks for data collection, and one week for the data analysis. Questionnaires were administered via a Google form questionnaire link sent to the participants in an e-mail and in a message via LinkedIn.

In this study, expert opinions were collected in two consecutive rounds using a questionnaire survey with a five-point Likert scale [37, 40]. In addition, the questionnaire included a single open-ended question at the end of every section to solicit expert comments and recommendations.

Guided by previous studies [37, 40, 41], one author developed the introduction to the study, the questionnaire survey, and participation instructions. These were piloted among the other two authors before sending them to the participants [37].

The participants rated compulsory statements (Appendix – Table V) in round one to validate the research problem and the I4.0CMM design requirements presented in the conference paper by Maisiri and van Dyk [18]. Furthermore, the participants verified the adherence of the I4.0CMM structure [18] to the design requirements. Finally, participants had the opportunity to comment and offer improvement suggestions regarding the design requirements and the I4.0CMM structure.

The outcome of the first-round data analysis was used to develop the second-round questionnaire. The round-two questionnaires omitted round-one statements that achieved expert consensus. The second-round questionnaire statements were designed to rate the refinements and improvements on areas of non-consensus in round-one [36] and additional aspects according to expert comments and suggestions [42]. The first-round data analysis results, aggregated suggestions, and recommendations accompanied the second-round questionnaire that was sent to the participants.

C. Data analysis

The study utilized descriptive analysis [37, 43] to evaluate expert consensus and agreement on various aspects assessed on a five-point Likert scale (1 - strongly disagree, 2 - disagree, 3 - do not know, 4 - agree, 5 - strongly agree). Though the definition of consensus could be subject to interpretation in a Delphi process [32], this study considered an average rating of 3.75 (75% on a five-point Likert scale) as the consensus for any particular question [32, 37, 40, 42, 44]. The study used a central tendency statistical tool (the mean) [34] and presented the data using means graphs [32, 43].

D. Ethical consideration

The study was conducted according to the guidelines of and approved by the North-West University Engineering Research Ethics Committee (NWU-ENGREC) – ethics clearance number NWU-00284-19-A1.

VI. Results Analysis

Nineteen experts participated in the round-one survey, out of which 17 experts participated in the round-two survey. Fig. 2 shows the distribution of round-one and round-two participants according to their years of experience in the industrial engineering environment.

The study results are presented as follows: Section A – round-one results analysis, Section B – refinements and improvements made to the design requirements and I4.0CMM structure, and Section C – round-two results.

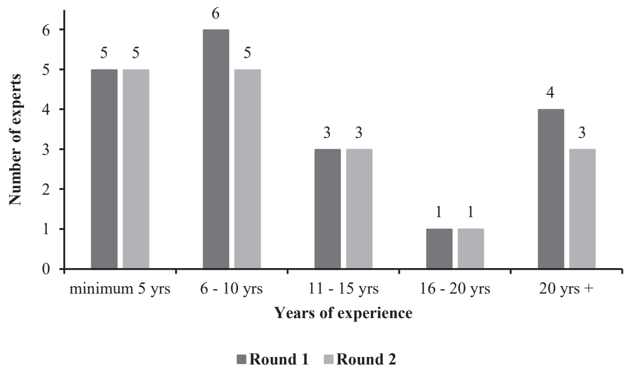

Fig. 2. Participants' Distribution by Years of Experience

A. First-round results

Fig. 3 presents the responses of experts to first-round research problem validation statements (Q1 to Q4 in Table V) in the form of a means graph. There was expert consensus (all means >3.75) for each research problem validation statement. Therefore, the research problem was considered valid. Consequently, the second-round questionnaire excluded research problem validation statements

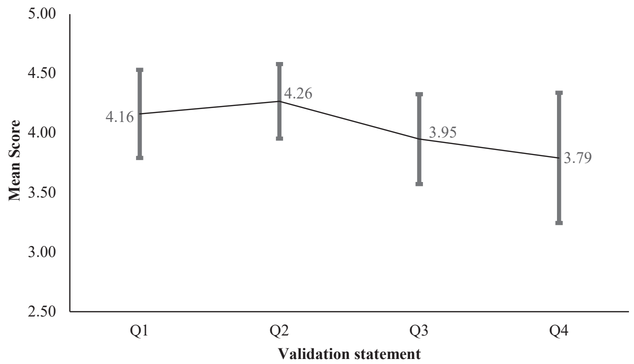

Fig. 3. Problem validation means graph (CI: 95%).

Fig. 4 shows the means graph of the responses of experts to the first-round design requirements validating statements (Q5 to Q7 in Table V). Expert consensus was not achieved (all means < 3.75) for any design requirements validation statement. Therefore, the design requirements presented by Maisiri and van Dyk [18] were not sufficient to direct the development of an I4.0CMM. As a result, the design requirements required improvements and re-testing for validity in the second-round survey.

Fig. 5 presents the means graph of the responses of experts to the I4.0CMM structure verification statements (Q8 to Q12 in Table V). Experts did not reach a consensus (all means < 3.75) on the sufficiency of the I4.0CMM structure as presented by Maisiri and van Dyk [18]. Consequently, the I4.0CMM required improvements and re-testing for compliance with the improved design requirements

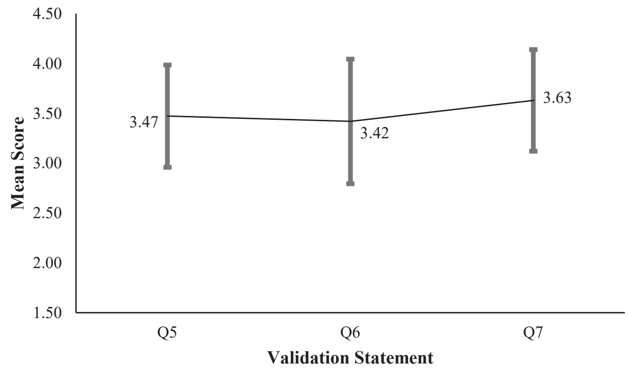

Fig. 4. Design requirements validation means graph.

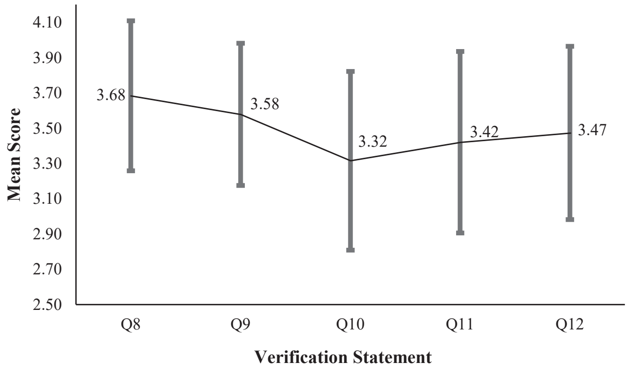

Fig. 5. I4.0CMM structure verification against design requirements

B. Design requirements and I4.0CMM structure improvements

Round-one results showed a lack of expert consensus on the sufficiency of the design requirements and compliance of a conceptual I4.0CMM structure as assessed against design requirements. Improvements were based on the feedback and suggestions from round-one's expert inputs to open-ended questions.

Table VI (see Appendix) presents the improved design requirements compared to the initial design requirements [18] rated in round-one.

In response to the open-ended questions, the experts pointed to the need for a self-assessment function in the I4.0CMM. Thus, Table VI includes an additional design requirement, "DR6: The I4.0CMM must have a self-assessment function against which users can gauge their level of competency."

Refinement of design requirement DR2 captured the whole meaning of competency: knowledge, skills, attitudes, values, and self-concepts. Design requirements rated in round-one only included knowledge and skills.

Design requirement DR6 [18], now DR7 in Table VI, limited the use of the model to manufacturing professionals, which experts raised concerns over. Therefore, the usefulness of the model was generalized to practicing professionals. The term "distinct maturity levels domain" in design requirement DR8, now DR9 in Table VI, was changed to "progressive maturity levels domain." The change revealed the essence of progression from the first IR to the fourth IR and for future requirements. Consequently, design requirement DR10, now DR11 in Table VI, was changed from "The competency statements must clearly differentiate between maturity levels" to "The competency statements must differentiate competency requirements progression through the different industrial revolutions."

Round-one question Q10's ("The competencies dimensions are sufficient and relevant") mean analysis result (mean = 3.32) showed notable divergence from expert consensus on the matter. This result suggests that the I4.0CMM structure presented by Maisiri and van Dyk [18] and rated in round-one had a noticeable deficiency in the competency domain. Participant 17 commented, "Competencies is where the real lack comes into the model. I would propose the Propensity Towards Success model that asks five critical questions: I Head, I Am, I Know, I Can, I Fit. You have worked with the I Know (Knowledge) and I Can (Skill)…". Participant 15 added, "The competence domain needs a bit of work in my mind; the skills maturity (can be renamed knowledge maturity) can perhaps be studied here so that things start out as skills and develop to competencies?"

The current I4.0CMM model in Fig. 6 presents incremental improvements on the model structure when compared with the initial I4.0CMM structure presented in the conference paper by Maisiri and van Dyk [18]. The improvements guided by literature [23, 24, 27, 45-49] and expert inputs include an improved capability functions domain and competency level domain.

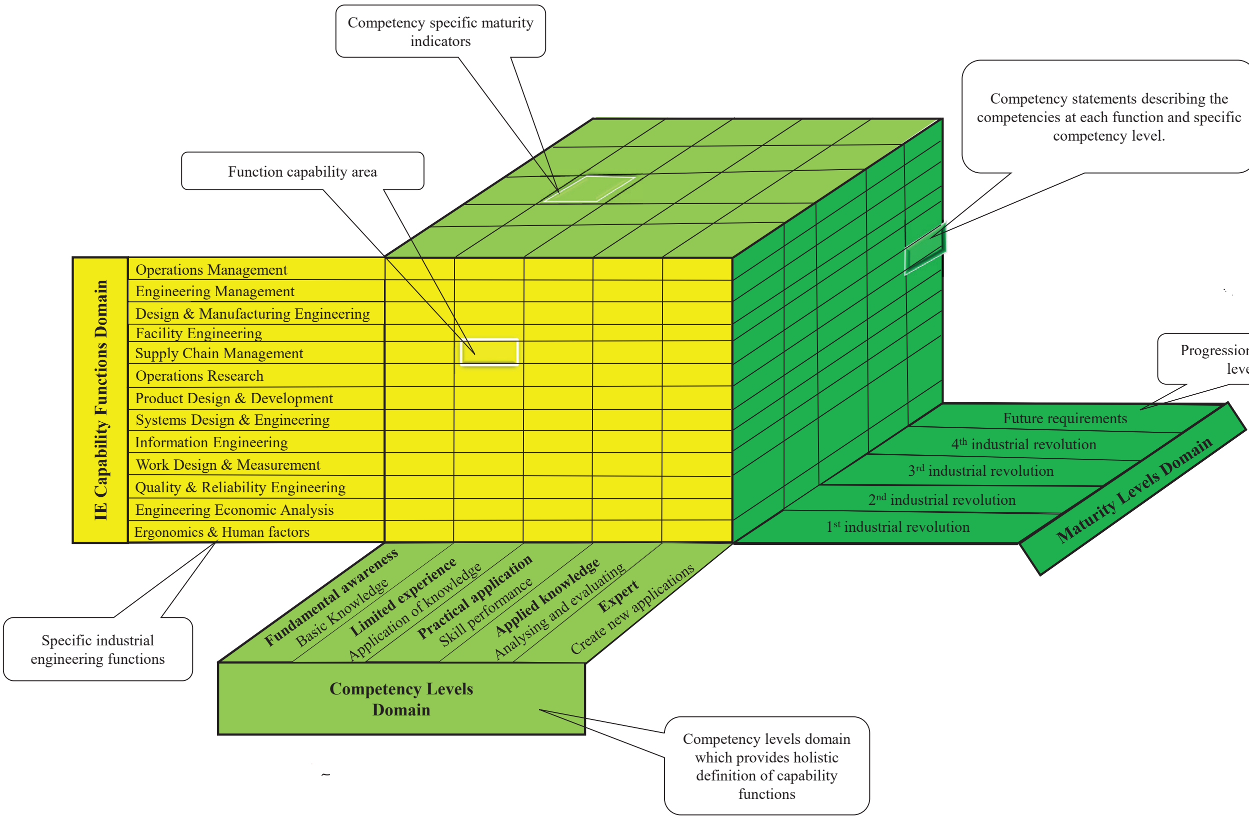

Fig. 6. I4.0CMM structure verification against design requirements

The capability functions domain was demonstrated using industrial engineering functions and was refined to give a better representation of the industrial engineering profession.

The maturity level domain shows the progression maturity of each capability function through the IRs. The illustration in Fig. 1 relates to the intercepts between the IR maturity level and the capability functions domain presented in Fig. 6.

The competency domain changed to competency level domain. The I4.0CMM assumes five competency levels [23, 24, 27, 48]: fundamental awareness, limited experience, practical application, applied knowledge, and expert levels. The competency levels assess an individual's ability to demonstrate a competency [48] in a specific function and progression maturity level. The competency level domain descriptors are adapted from Bloom's taxonomy's six dimensions for the intended outcome of learning [49].

The Fundamental level concerns individual learning [48] and corresponds to Bloom's taxonomy's 'remembering and understanding' dimensions [49]. At this level, an individual has a conceptual comprehension of techniques and concepts.

The Limited experience level is a novice level where an individual has limited experience through the practical application of knowledge and experience attained through the learning process [48] and corresponds to the 'apply' dimension in Bloom's taxonomy [49]. Limited experience can come from on-the-job training.

The Practical level is an intermediate level at which an individual can perform a skill without or with minimal supervision [48]. This level also corresponds to the 'apply' level in Bloom's taxonomy [49]. However, the application is aimed at practical and real-life problem-solving. At this level, the individual focuses on enhancing their skills.

The applied knowledge level is when an individual can perform a specific functional task by applying knowledge. The level corresponds to the 'analyzing and evaluating' dimension in Bloom's taxonomy [49]. On this level an individual can consistently apply knowledge and implement improvements related to functional tasks [48]. Moreover, the individual has gained experience to coach others in performing similar tasks.

The expert level corresponds to the 'create' dimension in Bloom's taxonomy [49], where an individual can create a new application in functional area competencies.

C. Round-two results

In round-two, the experts rated the improved design requirements in Table VI and the improved I4.0CMM in Fig. 6. The participants rated the importance of each design requirement in Table VI in developing the I4.0CMM. The mean scores rating results (Table I) show expert consensus (all means > 3.75) on the importance of all the design requirements

TABLE I:
INDIVIDUAL DESIGN REQUIREMENTS EXPERTS' VALIDATION MEAN SCORES

Design requirement	Mean score
DR1	4.71
DR2	4.71
DR3	4.47
DR4	4.29
DR5	4.35
DR6	4.32
DR7	4.47
DR8	4.06
DR9	4.24
DR10	4.65
DR11	4.47

Table II compares round-one Q5 to Q7 mean scores on design requirements validating statements against second-round mean scores. Experts reached a consensus (all means > 3.75) on each design requirements validation statement in round-two. Therefore, the improved design requirements in Table VI are sufficient to direct the development of the I4.0CMM, consequently answering study question 2 presented in Section II.

TABLE II:
DESIGN REQUIREMENTS VALIDATION: ROUND-ONE VERSUS ROUND-TWO

Question	Mean scores	
	First round	Second round
Q5	3.47	3.76
Q6	3.42	4.12
Q7	3.63	4.12

Table III compares round-one Q8 to Q12 mean scores on the I4.0CMM structure verification statements against round-two mean scores. Experts reached a consensus (all means > 3.75) on the sufficiency of the improved I4.0CMM structure presented in Fig. 6. Thus, the dimensions in the three domains of Fig. 6. can direct the development of an I4.0CMM and this addresses study question 3 presented in Section II.

TABLE III:
I4.0CMM STRUCTURE VERIFICATION AGAINST DESIGN REQUIREMENTS: ROUND-ONE VERSUS ROUND-TWO

Question	Mean scores	
	First round	Second round
Q8	3.68	3.94
Q9	3.58	4.12
Q10	3.32	4.29
Q11	3.42	4.18
Q12	3.47	4.24

VII. UNITS

The current study focused on validating the need for the I4.0CMM, proving the sufficiency of the design requirements, and verifying the compliance of the I4.0CMM structure against the design requirements, using expert opinions. Table IV maps the research questions presented in Section II against the research instrument. In this study, expert consensus was achieved in the second round of the Delphi technique, similar to other studies that used the same technique [37, 38].

Experts agreed that there are challenges around the I4.0 skills requirements and development, consistent with findings in other studies [50-52]. Furthermore, there was consensus on the need for an I4.0CMM to assess and align human capital competency requirements in I4.0 and for future requirements. In support of the need for I4.0CMM, Participant 2 commented that "A CMM tool can help identify the gap between where we want to go and where we are now. I4.0 maturity assessment tools can help with how we can get there." Participant 14 highlighted that "I4.0 skills requirements in the engineering profession need to be clearly defined for use in the South African manufacturing industry".

The development of I4.0CMM adopted PCMM principles, different from other I4.0 competency models presented in the literature [13, 15, 53, 54]. Thus, in response to study question 1 presented in Section II, the I4.0CMM could significantly contribute to assessing and aligning engineering competency requirements in I4.0 and future requirements.

It could be expected that expert consensus would start to form in the second round of the Delphi technique [37, 38]. In this study's first round, experts did not reach consensus on the sufficiency of the design requirements and the structure of the I4.0CMM presented by Maisiri and van Dyk [18]. However, a consensus on the design requirements (Table VI) was reached in the second round after refining the areas of disagreement using expert views from the first round. Thus, the design requirements are sufficient to direct the development of an I4.0CMM, answering study question 2. The I4.0CMM dimensions presented in Fig 6. were verified against the design requirements, thus addressing study question 3.

The contribution by Kamaruzaman *et al*. [54] shows the importance of developing frameworks and models to enhance competencies development of engineering graduates. Furthermore, competency models significantly contribute to the development and assessment of GAs [31]. Thus, the I4.0CMM presented in this study could potentially assist engineering education and workplace human resource development providers in aligning GAs and professional competencies.

VIII. CONCLUSION

This This study extended the work presented by Maisiri and van Dyk [18] by seeking the views of experts to prove the validity of the research problem, prove the design requirements' sufficiency, and verify the I4.0CMM structure against design requirements. Experts reached a consensus that I4.0 skills development and availability are a challenge that can be solved through developing an I4.0 competency assessment model.

The study presented an I4.0CMM comprising three domains: capability functions, competency level and maturity domain. Though the competency level domain and maturity level domain are generic to any engineering field, the current study used industrial engineering to demonstrate the capability function domain. For the model to be usable in different engineering domains, we recommend that the capability functions domain be adapted to suit the dimensions for a specific engineering domain. Future work could include collaborating with other engineering domain experts to illustrate the use of the model in other engineering function domains.

The I4.0CMM adapted Blooms' taxonomy in the competency level domain to enhance the function of self-assessment to demonstrate a competency on a specific capability function and progression maturity level. Thus, increasing the relevance of the model to students and graduates' self-evaluation and professional development mapping.

Though expert consensus was reached for the aspects addressed in this study, some limitations of the study should be mentioned. First, the small number of participants (19), although similar to other studies [37, 40], could be regarded as insufficient to generalize the results of the study. However, the study employed purposeful sampling to ensure the enrolling of only experts who met the inclusion criteria.

Second, the current study did not include the model capability statements and illustration of how the model functions. Thus, the recommended next step in this work is to generate the capability statements for the specific capability functions. Then, testing the model in the real working environment could follow.

This maturity model can be used by engineering education and workplace human resources development providers as a benchmark framework for aligning GAs, and required professional competencies, and for identifying improvement points required to match curriculum provisions to the current and future industry requirements resulting from the fourth – and further – industrial revolutions. Furthermore, it can aid students and graduates in self-evaluating and self-regulating their achievement of I4.0 skills requirements and planning their professional development

APPENDIX

TABLE IV:
STUDY QUESTIONS MAP

Study question	Related survey questions	Answers provided in this study
To what extent does the I4.0CMM contribute to assessing and aligning engineering competency requirements in I4.0 and future requirements?	Questions Q1 to Q4 in Table V	The validation of the I4.0 skills challenge and the need for the I4.0 competency assessment model show that the I4.0CMM could significantly contribute to the assessing and aligning of engineering competency requirements.
Which design requirements could direct the development of the I4.0CMM in order to be useful for both industry and academics?	Questions Q5 to Q7 in Table V	A list of design requirements (Table V) proven for validity through a Delphi study.
What are the dimensions required to construct the I4.0CMM?	Questions Q8 to Q12 in Table V	Dimensions for the three domains, capability functions, competency level and maturity domain (Fig. 6), were established and validated through a Delphi study.

TABLE V:
QUESTIONNAIRE SURVEY SECTIONS

Sections	Validation statements
Problem validation	**Q1** There is a misalignment between Industry 4.0 skills requirement in industry and skills development in the education system. **Q2** Industry 4.0 skills definition in the manufacturing industry is not clear. **Q3** There is a lack of I4.0 competency assessment models to assess and align workforce competency requirements in Industry 4.0 and future requirements. **Q4** There is a need for an I4.0CMM to assess and guide I4.0 competency requirements and development.
Design requirements validation	**Q5** The design requirements are specific and easy to interpret.
	Q6 The design requirements are sufficient to direct the development of an I4.0 competency model useful for both industry and academics.
	Q7 The design requirements are sufficient to direct the development of an I4.0CMM that assesses and guides I4.0 competency requirements and development.
I4.0CMM structure verification	**Q8** The conceptual model structure is simple.
	Q9 The conceptual model dimensions are sufficient and relevant.
	Q10 The competencies dimensions are sufficient and relevant.
	Q11 The functional capability areas are an accurate representation of the industrial engineering practice functional areas.
	Q12 The maturity level dimensions are sufficient and relevant.

TABLE VI:
I4.0CMM DESIGN REQUIREMENTS

Categories	Design requirements (DR)
Application domain	**DR1:** The I4.0CMM must outline engineering profession competency requirements for the manufacturing industry and must be adaptable to other industries.
Purpose of use	**DR2:** The I4.0CMM must provide a set of knowledge, skills, attitudes, values, and self-concepts required to perform specific capability functions. **DR3:** The I4.0CMM must support and guide engineering professionals' practice and continuous professional development. **DR4:** The I4.0CMM must provide competency reference standards for engineering education and quality assessment of engineering professionals along the career continuum. **DR5:** The I4.0CMM must be helpful to assess employees' competencies measured against the

	industrial revolutions and future requirements. **DR6:** The I4.0CMM must have a self-assessment function against which users can gauge their level of competency.
Target group	**DR7:** The I4.0CMM must be easily understood and be useful for researchers, academics, practicing professionals, and human resources practitioners.
Class of entities under investigation	**DR8:** The I4.0CMM must have a function to identify future competency requirements beyond I4.0 applications and technologies.
Maturity and dimensions of maturity	**DR9:** The I4.0CMM must include a competency levels domain, a capability functions domain, and a progressive maturity levels domain. **DR10:** The I4.0CMM competency statements must be clearly defined and easy to interpret.
Maturity levels and maturation paths	**DR11:** The competency statements must differentiate competency requirements progression through the different industrial revolutions.

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Whisper Maisiri received MEng in Mechanical Engineering from the North-West University, Potchefstroom, South Africa, and a BEng (Honours) in Industrial and Manufacturing Engineering from the National University of Science and Technology, Bulawayo Zimbabwe. He is pursuing a Doctor of Philosophy degree in Industrial Engineering at North-West University, South Africa.

From 2017 to 2019, he was a Lecturer with Walter Sisulu University, Butterworth, South Africa. He is currently a Lecturer in the School of Industrial Engineering at North-West University, Potchefstroom, South Africa. His research interest is on technology, innovation, and society, currently focusing on sustainable adoption of the Fourth Industrial Revolution and Industry 4.0.

Liezl van Dyk was awarded a PhD in Industrial Engineering by Stellenbosch University (2013), an MSc in Manufacturing Systems Engineering by the University of Warwick (2000) and a Bachelors of Engineering degree from University of Pretoria (1996).

She is the Executive Dean of the North-West University Faculty of Engineering and is rated by the National Research Foundation of South Africa as an established researcher focusing on ICT-supported service systems.

Prof van Dyk was awarded a lifelong honorary fellowship in 2020 by the South African Institute for Industrial Engineering

Rojanette Coetzee was awarded a Doctoral degree in Industrial Engineering, a Masters degree in Engineering Management and a Bachelors of Mechanical Engineering by the Northwest University, Potchefstroom, South Africa.

She is currently a Senior Lecturer at the School of Industrial Engineering and a Research Director of the Faculty of Engineering at the North-West University. Her research focus is on lean manufacturing and human factors engineering.

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APPENDIX G: READINESS ASSESSMENT QUESTIONNAIRE

Industry 4.0 readiness assessment

My name is Whisper Maisiri (Student Number - 25727265) a registered Industrial Engineering PhD student at North-West University (NWU). I am conducting a research on Industry 4.0 (I4.0) readiness level of the South African Industry.

I would appreciate you taking time to complete this questionnaire and note that it takes approximately 15 to 20 minutes to complete all the questions.

The purpose of this questionnaire is to evaluate the readiness level of South African Industry for I4.0 (the 4th industrial revolution). A holistic picture of I4.0 readiness requires consideration of six aspects namely: organizational strategy, infrastructure, smart operations , smart products, data driven services and employees.

* Required

Statement of confidentiality

Before completing this survey, the researcher assures you that this interview is confidential and completely voluntary. No personal names and company names are collected during this survey. If you come to any question you are not comfortable to answer, move to the next question. All information will be used for academic purposes only, according to the strict ethical and confidential guidelines provided by the NWU.

If you have any questions or concerns in regards to this survey, please feel free to contact Whisper Maisiri on: wmaisiri@wsu.ac.za; wmlisper27@gmail.com, +27(0)47 401 6215, +27 (0)73 049 7536, +27(0)82 525 3757.

Acknowledgement

The researcher would want to acknowledge IMPULS Foundation of German Engineering Federation (VDMA) for permission to use their questions from the online self-check for businesses. Few changes have been done to the questions to suit the purpose of this research.

Section 1: General questions

1. In which province is your organisation situated? *

Mark only one oval.

- ⬭ Eastern Cape
- ⬭ Free State
- ⬭ Gauteng
- ⬭ KwaZulu-Natal
- ⬭ Limpopo
- ⬭ Mpumalanga
- ⬭ North West
- ⬭ Northern Cape
- ⬭ Western Cape

2. In which industry category does your organisation belong? *

Mark only one oval.

- ⬭ Manufacturing
- ⬭ Processing
- ⬭ Mining
- ⬭ Chemical
- ⬭ Aerospace
- ⬭ Other: ______________________

3. Estimate the size of employees in your organisation.

Mark only one oval.

- < 50 employees
- 50 to 99 empoyees
- 100 to 149
- 150 to 199
- > 200

4. What is your role within your organisation?

____

5. According to your understanding, how would describe Industry 4.0 ?

____

____

____

____

____

Section 2: Organisational strategy

Industry 4.0 (I4.0) offer opportunity to develop new business models and to accomplish this requires an implementation strategy. Organisational I4.0 strategy can be used to measure the organisation readiness for the fourth industrial revolution.

6. How would you describe the implementation status of your Industry 4.0 strategy?

Mark only one oval.

- ( ) No existing strategy
- ( ) Pilot initiatives launched
- ( ) Strategy in development
- ( ) Strategy formulated
- ( ) Strategy in implementation
- ( ) Strategy implemented

7. How compatible is Industry 4.0 with your organisational strategies?

Mark only one oval.

- ( ) Not compatible
- ( ) Not sure
- ( ) Compatible

8. Has your organisation invested or have plans to invest in the implementation of Industry 4.0 in of the following divisions?

Check all that apply.

- [ ] Research and development
- [ ] Production/manufacturing
- [ ] Purchasing
- [ ] Logistics
- [ ] Sales
- [ ] Service
- [ ] IT

Other: [ ] ______________________

9. In which areas does your company have systematic technology and innovation management?

Check all that apply.

- [ ] IT
- [ ] Production technology
- [ ] Product development
- [ ] Services
- [ ] Centralised, in integrative management
- [ ] Do not have

10. Indicate technologies you use in your organisation.

Check all that apply.

- [ ] Sensor technology
- [ ] Mobile end devices
- [ ] Radio-frequency identification (RFID)
- [ ] Real-time location systems (RTLS)
- [ ] Cyber security
- [ ] Machine to Machine (M2M) communications
- [ ] Big data to store and evaluate real-time data
- [ ] Simulations
- [ ] Virtualization technologies
- [ ] Cloud technologies as scalable IT infrastructure
- [ ] Additive manufacturing
- [ ] Embedded IT systems
- [ ] Adaptive robotics
- [ ] Augmented reality
- [ ] Digital twin

Other: [ ] ____________________

Section 3: Infrastructure

Industry 4.0 (I4.0) paradigm enables production environment where the production systems and logistics systems are significantly automatic and does not require human involvement. This is achieved through cyber-physical systems (CPS), which link the physical and virtual worlds by communicating through an IT infrastructure, the Internet of Things. I4.0 also involves digital modelling through the smart collection, storage, and processing of data. In this way, the smart factory concept ensures that information is delivered and resources are used more efficiently. This requires the real-time, cross-enterprise collaboration between production systems, information systems, and people.

11. How would you evaluate your equipment infrastructure when it comes to the following functionalities?

Mark only one oval per row.

	No	Not available	Yes, to some extend	Yes completely
Machines/systems can be controlled through IT	◯	◯	◯	◯
M2M: machine-to-machine communications	◯	◯	◯	◯
Interoperability: integration and collaboration with other machines/systems possible	◯	◯	◯	◯

12. How would you evaluate the adaptability of your equipment infrastructure when it comes to the following functionalities?

Mark only one oval per row.

	Not relevant	Relevant but not upgradable	Upgradable	High because functionality already available
M2M: machine-to-machine communications	◯	◯	◯	◯
Interoperability: integration and collaboration with other machines/systems possible	◯	◯	◯	◯

13. The digitisation of factories makes it possible to create a digital model of the factory. Are you already collecting machine and process data during production?

Mark only one oval.

◯ Yes, all

◯ Yes, some

◯ No

14. Which of the following systems do you use in your organisation and which one have an interface to the leading system?

Check all that apply.

	In use	With interface to the leading system
MOM – manufacturing operations management (MES, QMS, LIMS)	☐	☐
ERP – enterprise resource planning	☐	☐
PLM – product lifecycle management	☐	☐
PDM – product data management	☐	☐
PPS – production planning system	☐	☐
PDA – production data acquisition	☐	☐
MDC – machine data collection	☐	☐
CAD – computer-aided design	☐	☐
SCM – supply chain management	☐	☐
PLM - plant lifecycle management	☐	☐
APS - Advanced production systems	☐	☐

Section 4: Operations

Industry 4.0 (I4.0) features the concept of vertical and horizontal integration which is the enterprise-wide (internal) and cross-enterprise (external) integration of physical and virtual worlds. I4.0 has brought significant changes to production and planning systems (PPS) and supply chain management (SCM). Smart operations enable technical requirements in production and production planning to self-control. Thus the vision of I4.0 is to achieve a workpiece that guides itself automatically through production.

15. Where have you integrated cross-departmental information sharing into your system?

Check all that apply.

	Internal	External (with customers and/ suppliers)
Production/manufacturing	☐	☐
Research and development	☐	☐
Purchasing	☐	☐
Logistics	☐	☐
Sales	☐	☐
Finance/accounting	☐	☐
Service	☐	☐
IT	☐	☐
Human resources	☐	☐
Nowhere	☐	☐

16. Does your company already have cases in which the workpiece guides itself autonomously through production?

Mark only one oval.

- Yes, cross-enterprise
- Yes, but only in selected areas
- Yes, but only in the test and pilot phase
- NO

17. Does your company have production processes that respond autonomously/automatically in real time to changes in production conditions?

Mark only one oval.

- Yes, cross-enterprise
- Yes, but only in selected areas
- Yes, but only in the test and pilot phase
- No

18. How is your IT organised?

Mark only one oval.

- No in-house IT department (service provider used)
- Central IT department
- Local IT departments in each area (production, product development, etc.)
- IT experts attached to each department

19. How far along are you with your IT security solutions?

Mark only one oval per row.

	Solution implemented	Solution in progress	Solution planned	Not relevant for us
Security in internal data storage				
Security of data through cloud services				
Security of communications for in-house data exchange				
Security of communications for data exchange with business partners				

20. Are you already using cloud services?

Mark only one oval per row.

	Yes	No, but we are planning to	No
Cloud-based software	◯	◯	◯
For data analysis	◯	◯	◯
For data storage	◯	◯	◯

Section 5: Products

Smart products are a vital component of a unified “smart factory” concept facilitating automated, flexible, efficient production. Physical products are equipped with ICT components (sensors, RFID, communications interface, etc.) to collect data on their environment and their own status. Only when products gather data, know their way through production, and communicate with the higher-level systems can production processes be improved and guided autonomously and in real time. It also becomes possible to monitor and optimise the status of the individual products. This has potential applications beyond production alone. Using smart products during the usage phase makes new services possible in the first place – through communications between customers and manufacturers, for example.

21. Does your company offer products equipped with the following add-on functionalities based on information and communications technology?

Check all that apply.

- [ ] Product memory
- [ ] Self-reporting
- [ ] Integration
- [ ] Localisation
- [ ] Assistance systems
- [ ] Monitoring
- [ ] Object information
- [ ] Automatic identification

Other: [ ] ______________________

Section 6: Data driven services

The objective of data-driven services is to align future business models and enhance the benefit to the customer. The after-sales and services business will be based more and more on the evaluation and analysis of collected data and rely on enterprise-wide integration. The physical products themselves must be equipped with physical IT so they can send, receive, or process the information needed for the operational processes. This means they have a physical and digital component, which in turn are the basis for digitized services in the usage phase of the products.

22. The process data gathered in production and in the usage phase enable new services. Do you offer such services?

Mark only one oval.

- Yes, and we are integrated with our customers
- Yes, but without integration with our customers
- No

23. Do you collect data from the usage phase and analyze the data for continual improvement purposes?

Mark only one oval.

- Yes
- No, we collect the data but do not analyze it
- No, we do not collect data in the usage phase

Section 7: Employees

Employees help companies realise their digital transformation and are the ones most affected by the changes of the digital workplace. Their direct working environment is altered, requiring them to acquire new skills and qualifications. This makes it more and more critical that companies prepare their employees for these changes through appropriate training and continuing education.

24. How do you assess the skills of your employees when it comes to the future requirements under Industry 4.0?

Mark only one oval per row.

	Not relevant	No-existant	Existant but inadequate	Adequate
IT infrastructure	⬭	⬭	⬭	⬭
Automation technology	⬭	⬭	⬭	⬭
Data analytics	⬭	⬭	⬭	⬭
Data security / communications security	⬭	⬭	⬭	⬭
Development or application of assistance systems	⬭	⬭	⬭	⬭
Collaboration software	⬭	⬭	⬭	⬭
Non-technical skills such as systems thinking and process understanding	⬭	⬭	⬭	⬭
Complex problem solving	⬭	⬭	⬭	⬭
Critical thinking	⬭	⬭	⬭	⬭

APPENDIX H: DELPHI STUDY PARTICIPANTS INVITATION LETTER

Dear XXXX

I am writing this letter to invite you to participate in the Delphi study aimed at developing and validating and Industry 4.0 competence maturity model which seeks to add value in assessing and aligning workforce competency requirements in Industry 4.0 and beyond. The Delphi technique solicitate experts' options in an iterative process with a minimum of two rounds. This study involves questioning you on three separate occasions. In each round, you will be provided with a questionnaire that requires you to rate various statements on a five-point scale and provide comments where you feel it's necessary to do so. Each round will take approximately 15 to 20 minutes of your time and the rounds are spaced 3 weeks from each depending on the participants response.

The Delphi method sorely depends on the experts opinions and you are regarded an expert because you meet the following criteria:

a. the participants must have a minimum of 5 years known and demonstrate experience in the industrial engineering environment;

b. demonstrate an understanding of I4.0 competency requirements;

c. capacity and willingness to participate;

d. available to provide feedback in more than three rounds of questionnaires/interviews.

On accepting this invitation, I will schedule an optional 10 to 15 minutes Zoom meeting to give you more details of the I4.0CMM and discuss anything you might need to know before.

Kind regards

Whisper Maisiri

25727265@nwu.ac.za

O730497536

APPENDIX I: DELPHI STUDY ROUND 1 QUESTIONNAIRE

Round 1_Development of an Industry 4.0 competence maturity model (I4.0CMM)_Delphi process

Thank you for taking the time to participate in this questionnaire. The questionnaire will approximately take 15 to 20 minutes to complete.

The purpose of this questionnaire survey is to solicit input from experts in the development, verification and validation of an I4.0CMM.

Once we have received responses from all participants in round 1, we will analyse and summarise the results and formulate a brief second questionnaire for round 2.

* Required

Informed consent statement

Before participating in this research, the researcher assures you that all information gathered will be treated as confidential, and participation is entirely voluntary.

All information will be used for academic purposes only and may be quoted in the thesis, conference presentation and published papers, according to the strict ethical and confidential guidelines provided by the NWU research ethics certificates for this study (Ethics clearance no: NWU-00284-19-A1).

You can contact Whisper Maisiri at 0730497536 or 25727265@nwu.ac.za if you have any further questions regarding the survey.

You can also contact the North-West University Engineering Research Ethics Committee: Prof Hein Neomagus at Hein.Neomagus@nwu.ac.za if you have any concerns that were not answered about the research or if you have complaints about the research.

By completing this survey you give informed consent to participate in this study.

General questions

You are kindly requested to provide your information below. All information will be kept confidential and will not be shared. The information is only to identify participants for subsequent rounds of the survey.

1. E-mail address *

2. Name and Surname *

3. How many years have you been working in the industrial egineering environment? *

Check all that apply.

- [ ] 0 - 5 years
- [ ] 6 -10 years
- [ ] 11 - 15 years
- [ ] 16 - 20 years
- [ ] 20 years +

Research problem validation questions

The research problem states: Industry 4.0 (I4.0) skills requirements in the engineering profession are not clearly defined, and its investigation in the South African manufacturing industry context is limited. Furthermore, there is a lack of I4.0 competency assessment models and tools to assess and align workforce competence requirements in I4.0 and future requirements

The research aim states: to develop an I4.0 competency maturity model (I4.0CMM) that can be used to assess and guide I4.0 competency requirements and development using industrial engineering capability functions.

4. The questions in this section are aimed to validate the research problem and the research aim. Kindly indicate the level of your agreement with the following statements: *

Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
There is a misalignment between Industry 4.0 skills requirement in industry and skills development in the education system?					
Industry 4.0 skills definition in the manufacturing industry is not clear?					
There is a lack of I4.0 competency assessment models to assess and align workforce competence requirements in Industry 4.0 and future requirements?					
There is need of an I4.0 competency maturity model (I4.0CMM) that can be used to assess and guide I4.0 competency requirements and development using industrial engineering capability functions					

5. Comments on research problem and research aim (Optional)

Design requirements validation questions

You are kindly requested to browse through the design requirements to develop an Industry 4.0 comptence maturity model (I4.0CMM) and answer the following questions:

Design requirements

Category	Design requirements (DR)
Application domain	**DR1:** The I4.0CMM must outline engineering profession competency requirements for the manufacturing industry that must also be adaptable to other engineering industries.
Purpose of use	**DR2:** The I4.0CMM must provide a set of knowledge, technical and soft skills required to perform specific engineering capability functions. **DR3:** The I4.0CMM must support and guide engineering professionals' practice and continuous professional development. **DR4:** The I4.0CMM must provide competence reference standards for engineering education and quality assessment of engineering processionals along the career continuum. **DR5:** The I4.0CMM must be useful to assess employees' competency measured against the industrial revolutions and future requirements.
Target group	**DR6:** The I4.0CMM must be easily understood and useful for researchers, academics in engineering education, manufacturing professionals, and human resources practitioners.
Class of entities under investigation	**DR7:** The I4.0CMM must be adaptive and flexible in identifying skills for the future and must not only be confined to I4.0 applications and technologies.
Maturity and dimensions of maturity	**DR8:** The I4.0CMM must include a competency domain, a capability functions domain, and a distinct maturity levels domain. **DR9:** The I4.0CMM competency statements must be clearly defined and easy to interpret.
Maturity levels and maturation paths	**DR10:** The competency statements must clearly differentiate between maturity levels.

6. The questions in this section are aimed at validating the model design requirements. Kindly indicate the level of your agreement with the following statements: *

Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
The design requirements are specific and easy to interpret?	◯	◯	◯	◯	◯
The design requirements are sufficient to direct the development of the I4.0 competency model that is useful for both industry and academics?	◯	◯	◯	◯	◯
The design requirements are sufficient to direct an I4.0CMM that could be used to assess and guide I4.0 competence requirements and development	◯	◯	◯	◯	◯

7. Kindly point out, from the provided list, design requirements that could be irrelevant in developing the model.

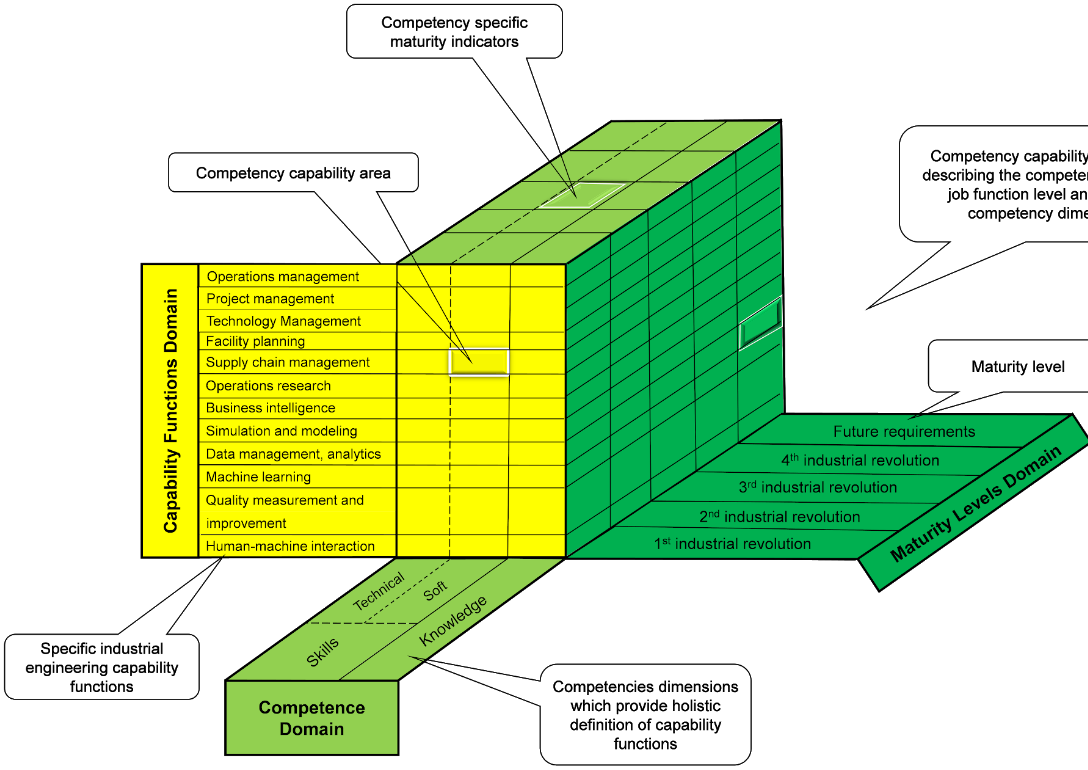
8. Kindly suggest additional design requirements that can add value in developing the model.

9. Comments on design requirments (optional)

Conceptual model verification questions

You are kindly requested to browse through the conceptual model and answer the following questions:

I4.0CMM conceptual model



10. The questions in this section are aimed at verifying the conceptual model structure and domains against the design requirements. Kindly indicate the level of your agreement with the following statements: *

Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
The conceptual model structure is simple to understand?	⬭	⬭	⬭	⬭	⬭
The conceptual model dimensions are sufficient and relevant?	⬭	⬭	⬭	⬭	⬭
The competencies dimensions are sufficient and relevant?	⬭	⬭	⬭	⬭	⬭
The functional capability areas are an accurate representation of the industrial engineering practise functional areas?	⬭	⬭	⬭	⬭	⬭
The maturity levels dimensions are sufficient and relevant?	⬭	⬭	⬭	⬭	⬭

11. Comments on conceptual model (optional)

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APPENDIX J: ROUND 1 RESULTS FEEDBACK TO PARTICIPANTS

ROUND 1 RESULTS SUMMARY

- **Scale used** - five-point Likert scale (1 - strongly disagree, 2 - disagree, 3 - I do not know, 4 - agree, 5 - strongly agree).
- **Consensus** on each statement was reached if the average score is 3.75 (75%)
- Number of participants – 19 experts

RESEARCH PROBLEM VALIDATION

Table A1 and Figure A1 presents research problem validation statements results summary.

Table A1: Research problem validation statements mean score

	Validation Statement	Avg Score
Q1	There is a misalignment between Industry 4.0 skills requirement in industry and skills development in the education system?	4.20
Q2	Industry 4.0 skills definition in the manufacturing industry is not clear?	4.30
Q3	There is a lack of I4.0 competency assessment models to assess and align workforce competence requirements in Industry 4.0 and future requirements?	4.00
Q4	There is need of an I4.0 competency maturity model (I4.0CMM) that can be used to assess and guide I4.0 competency requirements and development using industrial engineering capability functions	3.85

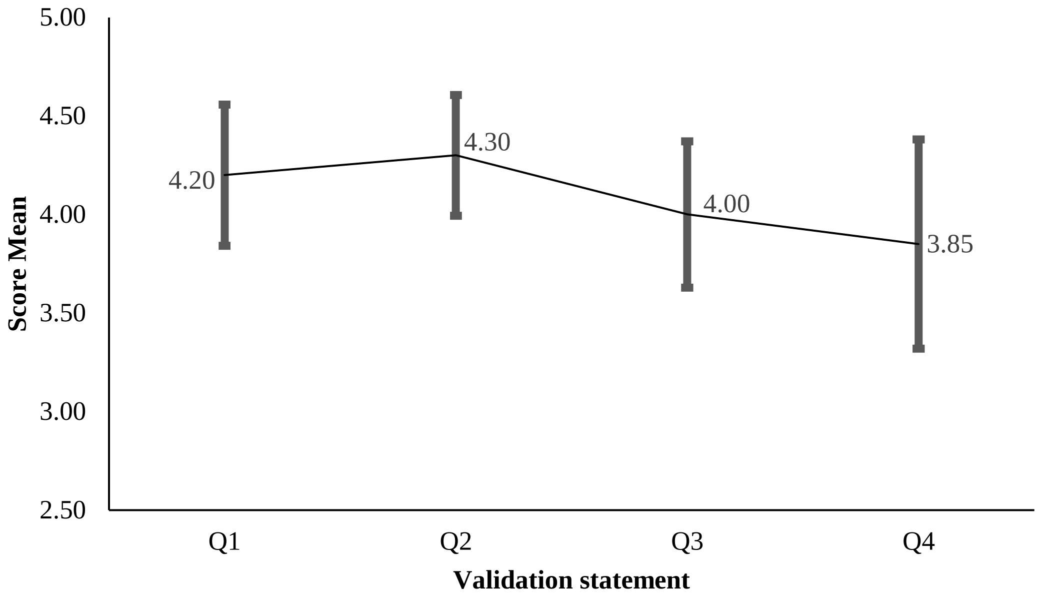


Figure A1: Research problem validation statements means graph with error bars (CI:95%)

Conclusion: The research problem statements are valid

DESIGN REQUIREMENTS VALIDATION

Table A2 and Figure A2 gives the design requirements validation statements results summary.

Table A2: Design requirements validation statements

Validation Statement		Avg Score
Q5	The design requirements are specific and easy to interpret?	3.55
Q6	The design requirements are sufficient to direct the development of the I4.0 competency model that is useful for both industry and academics?	3.50
Q7	The design requirements are sufficient to direct an I4.0CMM that could be used to assess and guide I4.0 competence requirements and development	3.70

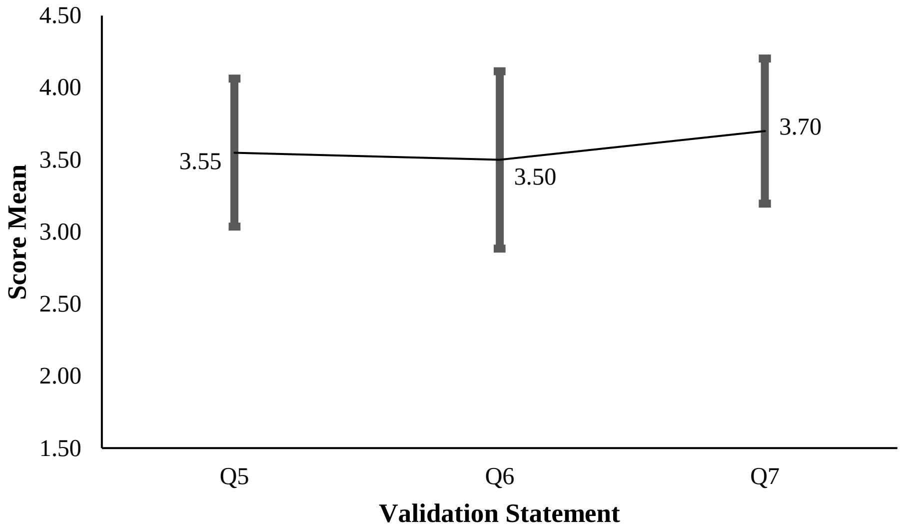


Figure A2: Design requirements validations statements means graph with error bars (CI:95%)

Conclusion: There was no experts' consensus on the validity of the research problem statements. Experts suggestions within the scope of the study were include. Consider round 2 questionnaire.

CONCEPTUAL MODEL VERIFICATION QUESTIONS

Table A3 and Figure A3 presents conceptual model verification statements results summary.

Table A3: Research problem validation statements mean score

Validation Statement		Avg Score
Q8	The conceptual model structure is simple to understand?	4.20
Q9	The conceptual model dimensions are sufficient and relevant?	4.30
Q10	The competencies dimensions are sufficient and relevant?	4.00
Q11	The functional capability areas are an accurate representation of the industrial engineering practise functional areas?	3.85
Q12	The maturity levels dimensions are sufficient and relevant?	

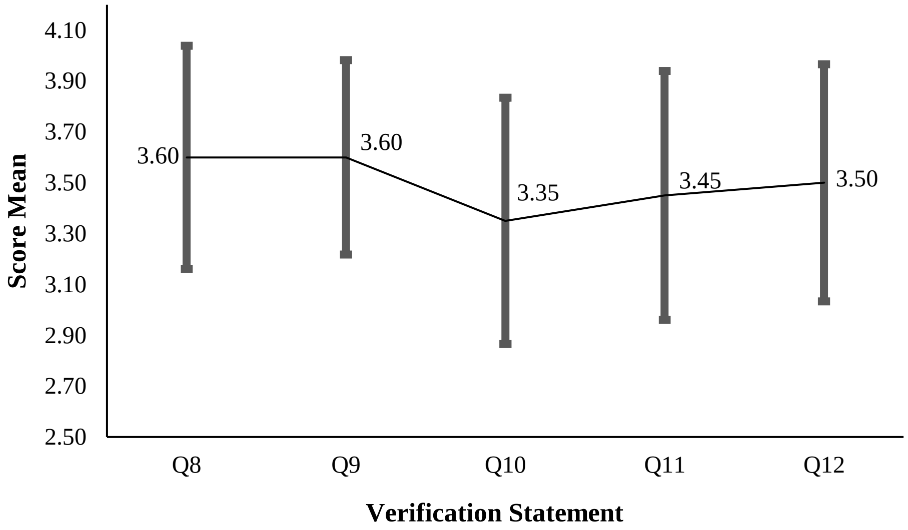


Figure A3: I4.0CMM conceptual model verification statements means graph (CI:95%)

Conclusion: There was no experts' consensus on the sufficiency of the I4.0CMM conceptual structure. Significant deficiency was pointed on the competency dimensions. Experts suggestions within the scope of the study were include in the incremental improvements. Consider round 2 questionnaire.

APPENDIX K: DELPHI STUDY ROUND 2 QUESTIONNAIRE

Round 2_Development of an Industry 4.0 competence maturity model (I4.0CMM)_Delphi process

Thank you for taking the time to participate in this questionnaire. The questionnaire will approximately take 15 to 20 minutes to complete.

The purpose of this questionnaire survey is to seek concensus on experts' views on the validity of the Industry 4.0 Competency Maturity Model (I4.0CMM) design requirements and the sufficiency of the I4.0CMM structure.

A synthesis of round 1 participants’ views is sent to your e-mail inbox.

* Required

Informed consent statement

Before participating in this research, the researcher assures you that all information gathered will be treated as confidential, and participation is entirely voluntary.

All information will be used for academic purposes only and may be quoted in the thesis, conference presentation and published papers, according to the strict ethical and confidential guidelines provided by the NWU research ethics certificates for this study (Ethics clearance no: NWU-00284-19-A1).

You can contact Whisper Maisiri at 0730497536 or 25727265@nwu.ac.za if you have any further questions regarding the survey.

You can also contact the North-West University Engineering Research Ethics Committee: Prof Hein Neomagus at Hein.Neomagus@nwu.ac.za if you have any concerns that were not answered about the research or if you have complaints about the research.

By completing this survey you give informed consent to participate in this study.

Skip to question 1

General questions

You are kindly requested to provide your information below. All information will be kept confidential and will not be shared. The information is only to identify participants for subsequent rounds of the survey.

1. Name and Surname *

Design requirements validation questions

Round 1 experts' responses were analysed and suggestions within the scope of this study were taken into consideration. The purpose of this section is to seek experts consensus on the validity of the design requirements statements and their sufficiency.

2. Kindly indicate your level of agreement to the importance of the following design requirements in the development of an I4.0CMM: *

Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
The I4.0CMM must outline engineering profession competency requirements for the manufacturing industry and adaptable to other sectors.					
The I4.0CMM must provide a set of knowledge, skills, attitudes, values, and self-concepts required to perform specific capability functions.					
The I4.0CMM must support and guide engineering professionals' practice and continuous professional development.					
The I4.0CMM must provide competence reference standards for engineering education and quality assessment of engineering processionals along the career continuum.					
The I4.0CMM must be helpful to assess employees' competency measured against the industrial revolutions and future requirements.					
The I4.0CMM must have a self-assessment function against which users can gauge their level of this competency proficiency.					
The I4.0CMM must be easily understood and useful for researchers, academics, practicing professionals, and human resources practitioners.					

The I4.0CMM must have a function to identify future competency requirements beyond I4.0 applications and technologies.					
The I4.0CMM must include a competency level domain, a capability functions domain, and a progressive maturity levels domain.					
The I4.0CMM competency statements must be clearly defined and easy to interpret.					
The competency statements must differentiate competency requirements progression through the different industrial revolutions.					

3. Kindly indicate the level of your agreement with the following statements: *

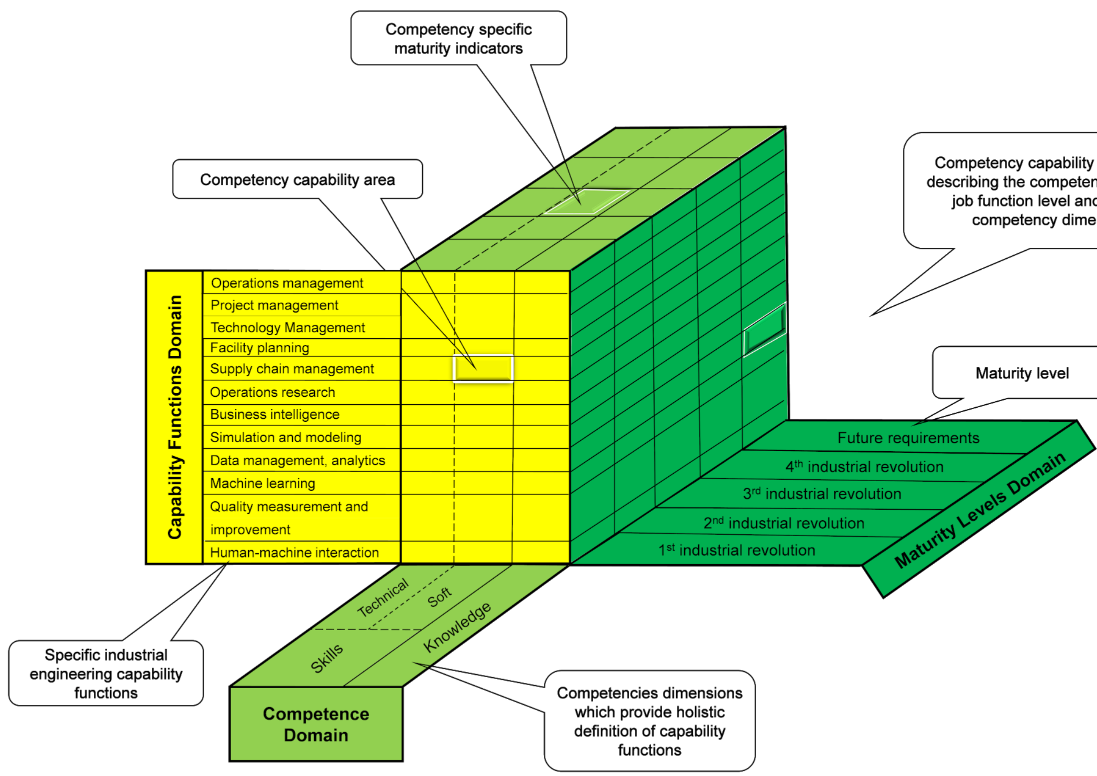
Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
The design requirements are specific and easy to interpret?					
The design requirements are sufficient to direct the development of the I4.0 competency model that is useful for both industry and academics?					
The design requirements are sufficient to direct an I4.0CMM that could be used to assess and guide I4.0 competence requirements and development					

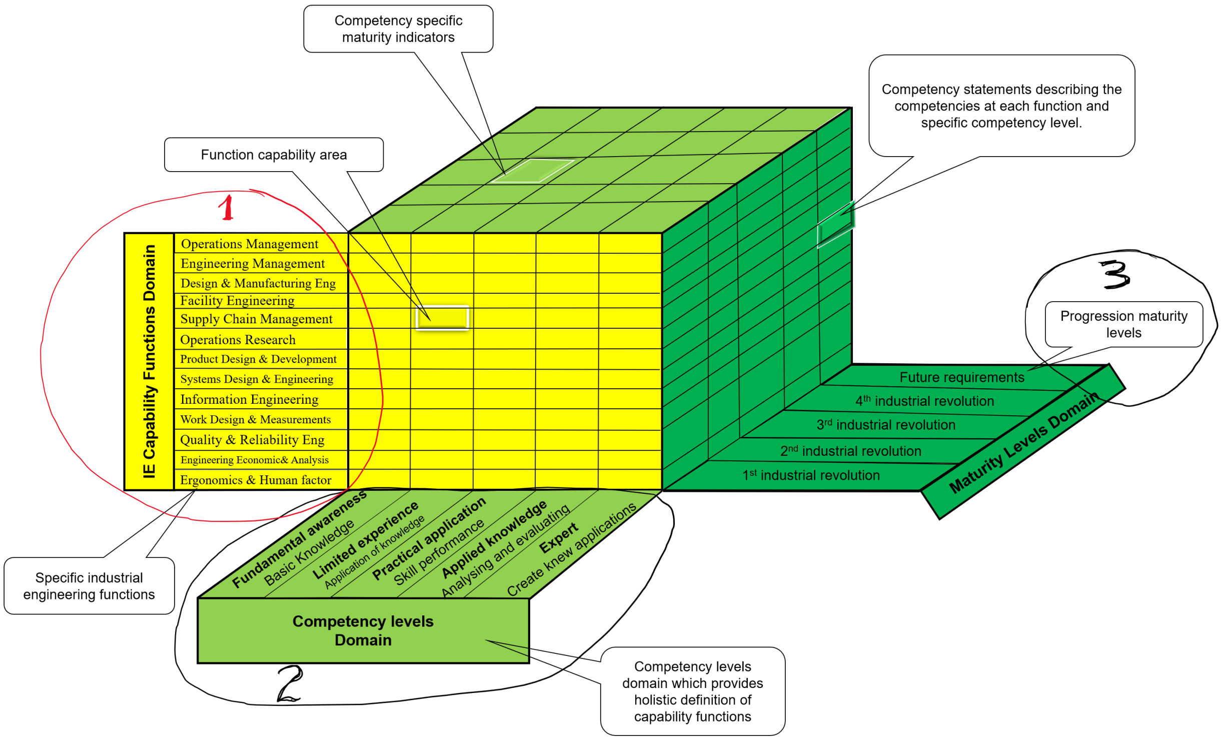
Conceptual model verification questions

Considering experts input from round 1, we have refined the competency domain and capability functions domain. You are kindly requested to browse through round 1 and improved round 2 conceptual model and answer the following questions:

Round 1 -I4.0CMM conceptual model



Round 2 - Improved I4.0CMM conceptual model



4. The questions in this section are aimed at verifying the *improved* conceptual model structure and domains against the design requirements. Kindly indicate the level of your agreement with the following statements: *

Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
The conceptual model structure is simple to understand?					
The conceptual model dimensions are sufficient and relevant?					
The competencies dimensions are sufficient and relevant?					
The functional capability areas are an accurate representation of the industrial engineering practise functional areas?					
The maturity levels dimensions are sufficient and relevant?					

5. Comments on conceptual model (optional)

APPENDIX L: ETHICS APPROVAL LETTER 1

Private Bag X1290, Potchefstroom
South Africa 2520

North-West University Engineering Research Ethics Committee (NWU-ENG-REC)

Tel: 018 299-2645
Email: ENG-REC@nwu.ac.za

8/28/2019

ETHICS APPROVAL LETTER OF STUDY

Based on approval by the North-West University Engineering Research Ethics Committee (NWU-ENG-REC) on 23-Aug-19, the NWU-ENG-REC hereby approves your study as indicated below. This implies that the NWU-ENG-REC grants its permission that, provided the general and specific conditions specified below are met and pending any other authorisation that may be necessary, the study may be initiated, using the ethics number below.

Study title:
An Industry 4.0 preparedness maturity model for the South African education system

Principal Investigator/Study Supervisor/Researcher: L van Dyk

Student: Whisper Maisiri (wmlisper27@gmail.com)
Ethics number: **NWU-00284-19-A1**

Institution-Study Number-Year-Status
Status: S = Submission; R = Re-Submission; P = Provisional Authorisation; A = Authorisation

Application Type: Single
Approval date: **23-Aug-19**
Expiry date: 8/23/2020

Risk: **Low**

Approval of the study is provided for a year, after which continuation of the study is dependent on receipt and review of annual monitoring report and the concomitant issuing of a letter of continuation.

General conditions:

While this ethics approval is subject to all declarations, undertakings and agreements incorporated and signed in the application form, the following general terms and conditions will apply:

- *The principal investigator/study supervisor/researcher must report in the prescribed format to the NWU-ENG-REC:*
  - *Annually on the monitoring of the study, whereby a letter of continuation will be provided annually, and upon completion of the study; and*
  - *without any delay in case of any adverse event or incident (or any matter that interrupts sound ethical principles) during the course of the study.*
- *The approval applies strictly to the proposal as stipulated in the application form. Should any amendments to the proposal be deemed necessary during the course of the study, the principal investigator/study supervisor/researcher must apply for approval of these amendments at the NWU-ENG-REC, prior to implementation. Should there be any deviations from the study proposal without the necessary approval of such amendments, the ethics approval is immediately and automatically forfeited.*
- *Annually a number of studies may be randomly selected for active monitoring.*
- *The date of approval indicates the first date that the study may be started.*
- *In the interest of ethical responsibility, the NWU-ENG-REC reserves the right to:*

- *request access to any information or data at any time during the course or after completion of the study;*
- *to ask further questions, seek additional information, require further modification or monitor the conduct of your research or the informed consent process;*
- *withdraw or postpone approval if:*
  - *any unethical principles or practices of the study are revealed or suspected;*
  - *it becomes apparent that any relevant information was withheld from the NWU-ENG-REC or that information has been false or misrepresented;*
  - *submission of the annual monitoring report, the required amendments, or reporting of adverse events or incidents was not done in a timely manner and accurately; and/or*
  - *new institutional rules, national legislation or international conventions deem it necessary.*
- *NWU-ENG-REC can be contacted for further information via ENG-REC@nwu.ac.za or 018 299 2645*

Special conditions of the research approval (if applicable): NA

Special in process conditions of the research for approval (if applicable): NA

The NWU-ENG-REC would like to remain at your service and wishes you well with your study. Please do not hesitate to contact the NWU-ENG-REC for any further enquiries or requests for assistance.

Yours sincerely,

Dr Rojanette Coetzee
Chairperson NWU-ENG-REC

Current details:(25767984) \NWUNextCloud\ENG-REC\Letters sent\[Date]\9.1.5.4.3_NWU-ENG-REC_REC_EAL_[student surname_name]

File Reference: 9.1.5.4.2

APPENDIX M: ETHICS APPROVAL LETTER 2

Private Bag X1290, Potchefstroom
South Africa 2520

North-West University Engineering Research Ethics Committee (NWU-ENG-REC)

Tel: 018 299-2645
Email: ENG-REC@nwu.ac.za

30/03/2021

ETHICS APPROVAL LETTER OF STUDY (Final phase)

Based on approval by the North-West University Engineering Research Ethics Committee (NWU-ENG-REC) on 30/03/2021, the NWU-ENG-REC hereby approves your study as indicated below. This implies that the NWU-ENG-REC grants its permission that, provided the general and specific conditions specified below are met and pending any other authorisation that may be necessary, the study may be initiated, using the ethics number below.

Study title: Development of an Industry 4.0 competency maturity model

Principal Investigator/Study Supervisor/Researcher: Prof Liezl Van Dyk
Student: Whisper Maisiri (25727265) 25727265@nwu.ac.za

Ethics number: **NWU-00284-19-A1**

Institution Study Number Year Status

Status: S = Submission; R = Re-Submission; P = Provisional Authorisation; A = Authorisation

Application Type: Single
Approval date: 22/04/2021
Expiry date: 22/04/2022

Risk: **Low Risk**

Approval of the study is provided for a year, after which continuation of the study is dependent on receipt and review of annual monitoring report and the concomitant issuing of a letter of continuation.

General conditions:

While this ethics approval is subject to all declarations, undertakings and agreements incorporated and signed in the application form, the following general terms and conditions will apply:

- *The principal investigator/study supervisor/researcher must report in the prescribed format to the NWU-ENG-REC:*
  - *Annually on the monitoring of the study, whereby a letter of continuation will be provided annually, and upon completion of the study; and*
  - *without any delay in case of any adverse event or incident (or any matter that interrupts sound ethical principles) during the course of the study.*
- *The approval applies strictly to the proposal as stipulated in the application form. Should any amendments to the proposal be deemed necessary during the course of the study, the principal investigator/study supervisor/researcher must apply for approval of these amendments at the NWU-ENG-REC, prior to implementation. Should there be any deviations from the study proposal without the necessary approval of such amendments, the ethics approval is immediately and automatically forfeited.*
- *Annually a number of studies may be randomly selected for active monitoring.*
- *The date of approval indicates the first date that the study may be started.*
- *In the interest of ethical responsibility, the NWU-ENG-REC reserves the right to:*

- *request access to any information or data at any time during the course or after completion of the study;*
- *to ask further questions, seek additional information, require further modification or monitor the conduct of your research or the informed consent process;*
- *withdraw or postpone approval if:*
  · *any unethical principles or practices of the study are revealed or suspected;*
  · *it becomes apparent that any relevant information was withheld from the NWU-ENG-REC or that information has been false or misrepresented;*
  · *submission of the annual monitoring report, the required amendments, or reporting of adverse events or incidents was not done in a timely manner and accurately; and/or*
  · *new institutional rules, national legislation or international conventions deem it necessary.*

- *NWU-ENG-REC can be contacted for further information via ENG-REC@nwu.ac.za or 018 299 2645*

Special conditions of the research approval (if applicable): NA

Special in process conditions of the research for approval (if applicable): NA

The NWU-ENG-REC would like to remain at your service and wishes you well with your study. Please do not hesitate to contact the NWU-ENG-REC for any further enquiries or requests for assistance.

Yours sincerely,

Prof. H Neomagus.
Chair NWU-ENG-REC

Current details:(25767984) \NWUNextCloud\ENG-REC\Letters sent\[Date]\9.1.5.4.3_NWU-ENG-REC_REC_EAL_[student surname_name]

File Reference: 9.1.5.4.2

APPENDIX N: ARTICLE 3 AND ARTICLE 5 SEARCH STRING

Article 3 search string

(TITLE-ABS-KEY (“industry 4.0” OR “fourth industrial revolution” OR “4th industrial revolution” OR "IR 4.0") AND TITLE-ABS-KEY (skill)) AND PUBYEAR > 2012 AND PUBYEAR < 2019

Article 5 search string

(TITLE-ABS-KEY (“Industry 4.0” OR “Industrie 4.0” OR “Fourth Industrial Revolution” OR “4th industrial revolution”) AND TITLE-ABS-KEY (“Competencies” OR “Skills”) AND TITLE-ABS-KEY (model OR framework)) AND PUBYEAR > 2011 AND PUBYEAR < 2020