A maturity model to enhance the adoption of Additive Manufacturing in spare part provisioning in South Africa

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ABSTRACT

The fourth industrial revolution (4IR) demands a significant change in the way businesses operate. The previous three industrial revolutions were initiated from the market and demanded that organisations adopt to the market requirements for more cost-effective, high-volume and standardised products. The 4IR started with the advent of several new disruptive technologies that will require a rethink of business models and customisation according to the process and customer requirements. One of the most disruptive technologies of 4IR is additive manufacturing(AM).

3D printing (3DP) is not the same as AM, but is a terminology commonly used by the general public. See ASTM F2792 for accurate definitions and the difference between 3DP and AM.

The current provisioning system for spare parts is based on a linear supply chain philosophy whereas successful participation in 4IR requires a focus on real-time customer demand, infused with agility and integrated in the global ecosystem.

AM also requires a change in paradigms from a linear paradigm in design and manufacturing based on the avoidance of complexity to a non-linear paradigm where complexity needs to be embraced and solved through new systemic and ecosystem-based thinking. It is difficult for organisations when they want to adopt AM for spare part provisioning to contemplate the systemicrelationship between all the risk areas in the business as well as to understand the disruptive impact of the adoption on the organisation. This contributes to the slow adoption of AM in spare part provisioning.

Therefore, the aim of this research is to develop a solution that can assist in enhancing the adoption of AM in spare part provisioning. The implementation of this model is beyond the scope of this thesis and can be conducted as part of further research in this field.

Utilising the elaborated action design research method within the design science research paradigm, a multidimensional maturity model was developed to improve the slow adoption of AM in spare part provisioning.

The elaborated action design research method was entered at the problem definition stage. This stage consists of five components that started with (1) a literature review. A summary of the literature review was used to compile questions for (2) discussions with AM experts in the South

African AM ecosystem. The researcher’s own experience (3) was added, and a triangulation exercise (4) was used to proof a valid research problem. From the triangulation exercise, themes were developed that required additional research in order for theories to be developed regarding the slow adoption of AM. Grounded theory (5) was used as an overarching and iterative method for the problem definition stage to develop three new theories explaining the slow adoption of AM. These three theories created the input for the concept design stage.

During the concept design stage, the three theories were researched and developed to create the input for the build stage. The output from the concept design stage was used in the build stage to design and build the Business Risk Provisioning Maturity Model (BRPM^2). Finally, the Delphi technique was applied to verify that the BRPM^2 adheres to all the design requirements and that it was a valid solution to address the research problem.

The BRPM^2 model allows organisations to determine their maturity development stage against the provisioning system evolution. The model creates a systemic as-is map for the organisation that can then be used to develop a roadmap of the requirements against the key business risk areas when adopting AM as part of spare part provisioning on their journey to improve their maturity when adopting AM for spare part provisioning.

The study contributes to the field of industrial engineering by extending a known solution to solve a new problem. Industrial engineering literature has been enriched by the definition of the provisioning system evolution and the way the model emphasises the importance of systems thinking in the adoption of disruptive innovations. The BRPM^2 model also adds to the organisational domain by supporting the key paradigm shift that is required in the organization to enhance the adoption of AM for spare part provisioning.

Key terms: Additive manufacturing, systems thinking, fourth Industrial Revolution, evolution, linear, non-linear, design science research, elaborated action design science research, provisioning system, business risk, maturity model.

PREFACE

This thesis was compiled and presented in article format in accordance with the academic 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.”

STATEMENT OF CO-AUTHORS

To whom it may concern,

The listed co-authors hereby give consent that Willem Hendrik Harmse, may submit the manuscript(s) as part of his thesis titled as “Development of a Maturity Model to enhance the adoption of Additive Manufacturing in spare part provisioning in South Africa” for the degree *Doctor of Philosophy in Industrial Engineering,* at the North West University.

(This letter of consent complies with rules A5.10.8 and A5.10.9 of the academic rules as stipulated by the North West University)

Signed at Potchefstroom

J.W. Holm Date

R. Coetzee Date

The following articles have been submitted, reviewed and published over the course of this research study:

CDP (1)

a. Harmse, H. and Holm, J. F. (2019) 'The evolution of business models from supply chain to agiledemand networks through additive manufacturing', paper presented at the *30th Annual Southern African Institute for Industrial Engineering (SAIIE) 2019*, Port Elizabeth, pp. 779–793,

Contribution of the co-author Holm J.F – Review and structural input

CDP (2)

b. Harmse, H. 2019. The business impact of adopting additive manufacturing in spare part provisioning. *Proceedings of the 20th Annual International RAPDASA Conference,* 06–08 November 2019, Bloemfontein, pp. 180–189, ISBN nr: 978-0-6398390-0-4

CDP (3)

c. Harmse, H. and Coetzee, R. 2020. Investigating how systems thinking can assist with the adoption of additive manufacturing in spare part provisioning. Paper presented at the virtual *31th Annual Southern African Institute for Industrial Engineering (SAIIE) 2020*.

Contribution of the co-author: Coetzee, R – Review and structural input

The thesis started with a literature review to determine the reasons for the slow adoption of additive manufacturing in South Africa. A summary of the literature review, expert discussions and the researchers own experience were combined in a triangulation exercise from where three grounded theories were derived. These grounded theories were used as the basis for each of the three articles as can be seen in Figure 1 as part of the concept design stage indicated as CDP1 (6), CDP 2 (7) and CDP 3 (8).

The literature review of an article based thesis can seem to be less pages than the traditional PhD but significant research had to be conducted for each individual article that forms part of the overall structure of the article based research.

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LIST OF ACRONYMS

3DP	-	3-Dimensional printing
4IR	-	Fourth Industrial Revolution
ADR	-	Action design research
AM	-	Additive manufacturing
AR	-	Action research
AM-MM	-	Additive manufacturing maturity model
BIE	-	Build, intervention and evaluation
$BRPM^2$	-	Business risk provisioning maturity model
CAD	-	Computer Aided Design
CD	-	Concept design
CMM	-	Capability maturity model
CMMI	-	Capability maturity model integration
CRM	-	Customer relationship management
DCM	-	Demand chain management
DfAM	-	Design for additive manufacturing
DfM	-	Design for manufacturing
DN	-	Demand networks
DREAMY	-	Digital readiness assessment maturity model
DS	-	Design science
DSR	-	Design science research
eADR	-	Elaborated design science research
ENG	-	Engineering
ERP	-	Enterprise resource planning
ECSA	-	Engineering Council of South Africa
I40 MM	-	Industry 4.0 maturity model
IP	-	Intellectual property

IR1	-	First Industrial Revolution
IR2	-	Second Industrial Revolution
IR3	-	Third Industrial Revolution
IR4	-	Fourth Industrial Revolution
MOM	-	Manufacturing operations management
NWU	-	North West University
OEM	-	Original equipment manufacturer
OSCM	-	Operations and supply chain management
PD	-	Problem diagnosing
RAPDASA	-	Rapid Product Development Association of South Africa
REC	-	Research ethics committee
SA	-	South Africa
SAIIE	-	South African Industrial Engineering Council
SCM	-	Supply chain management
SCMM	-	Supply chain management maturity model
SM	-	Smart manufacturing
SMSRL	-	Smart manufacturing readiness level
TCE	-	Total cost of ecosystem
TCO	-	Total cost of ownership
TQM	-	Total quality management
W1	-	World 1
W2	-	World 2
W3	-	World 3
WW	-	Worldwide

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CHAPTER 1: INTRODUCTION

Chapter 1 provides the background for this research, the aim, the objectives and the research questions.

1.1 Background

The world experienced three industrial revolutions that changed the face of manufacturing and provisioning systems also known as supply chain (Frank *et al*., 2017; Williams, 2018). During the era of craft production, highly skilled craftsmen created customised products according to customer requirements. The first Industrial Revolution (1IR) automated production equipment and more products could be manufactured to satisfy the market demand. The second Industrial Revolution (2IR) was the mass manufacturing revolution and the introduction of product standardisation. The third Industrial Revolution (3IR) started with the Internet and allowed the integration of different production entities. However, the fourth Industrial Revolution (4IR) differs from the other industrial revolutions since it has not been triggered by the industry on the shop floor (see Table 4), but has been promoted by governments, numerous related policies and initiatives and new disruptive technologies that will shorten the time to market, reduce the window of opportunity, create new markets and business models and will have a profound impact on the provisioning systems(Cimini *et al*., 2019; Erol *et al*., 2016).

According to Collins (2018), provisioning can be defined as the act of giving an item or making it available to people who need or want it. The provisioning system has changed significantly during the industrial revolutions. The 1IR allowed participants to sell goods and services beyond their own village into neighboring villages. The 2IR allowed participants to move beyond their own countries and cross continents and expanded the reach of the provisioning system significantly. The 3IR allowed participants to use integrated technologies to compare offerings in the provisioning system on a more real time basis and to source suppliers more effectively (Helo *et al*., 2006) (Erol *et al*., 2016).

Now the fourth Industrial Revolution (4IR) is introducing even more innovative and disruptive technologies that will again change the face of manufacturing and the provisioning systems (Frank *et al*., 2017; Handal, 2017; Holmström & Gutowski, 2017). According to Schwab (2016), 4IR will be a transformation of humanity and a disruption of business as it has been conducted up to now. One of the innovative and disruptive technologies introduced in 4IR is additive manufacturing (AM) or 3D printing (3DP) as it is colloquially known (Mohr & Khan, 2015). AM differs from traditional manufacturing in the freedom of design and the adding of complexity that is expensive with traditional manufacturing. (Swab, 2016). AM also allows for the localization of manufacturing and therefore shortening of lead times, integration of different components to create a module, the introduction of new creative designs at a lower cost and will replace mass production with mass customisation Some of the other benefits of AM is that it reduces cost, improve speed of delivery, improve the quality of products, reduce dependability on core suppliers and allow for greater flexibility (Holmström & Gutowski, 2017).

Using 3DP creates a component layer by layer as opposed to the traditional way of manufacturing, where material is removed from a block of material until the final component is generated. This 3DP method focusses on a specific technology (Pereira *et al.*, 2019). One of the misconceptions regarding AM is that AM and 3DP are similar (Sisca *et al.*, 2016). AM includes 3DP but is also a combination of several different processes including design, simulation, production (3DP) and post processing. Therefore, AM also requires a more systemic understanding of the impact of AM on the business, provisioning system and design philosophies (Kritzinger *et al.*, 2018; Zelinski, 2017).

The design philosophies for additive manufacturing (DfAM) create a new culture of innovation since more complex structures can be developed (Thomas-Seale *et al.*, 2018). This is in contrast to the traditional design methodologies or design for manufacturing (DfM) where complexity is limited because of the traditional manufacturing methods and increased costs when complexity is required for a process or a customer (Mohr & Khan, 2015; Orquera *et al.*, 2017). DfAM requires a more holistic approach by encapsulating the entire eco-system instead of focusing only on the specific component at stake (Sossou *et al.*, 2018). According to the Oxford dictionary (Simpson & Weiner, 1989), holistic can be defined as “the tendency in nature to wholes, that are greater than the sum of the parts, through creative evolution”, and is contrary to the common paradigm of reductionism which tries to break things down into their smallest parts. Therefore the only way to understand the parts is to view them in relation to the whole. (Cherry, 2020) The concept of holistic latches on to the understanding of the eco-system (Bergandi & Blandin, 1998) This eco-system perspective necessitates a paradigm shift in organisations when adopting AM for spare part provisioning (Hopp, Antons, Kaminiski, & Salge, 2018). This paradigm shift requires a shft from linear thinking to an understanding of systems thinking and a perspective on the impact of the various parts on each other. (Bergandi & Blandin, 1998).

A technology can be described as disruptive when it changes the way the current business processes are conducted and when it opens up many new value propositions that were not available to the organisation before such as new creative designs of spare parts (Christensen, 1997; Hatch, 2018). These new value propositions challenge the current status quo and can be perceived as threatening and complex if not well understood by organisations (Colchester, 2016). In *The Innovator's Dilemma*, by Harvard professor Clayton M. Christensen, the theory of disruptive innovation is discussed. The theory explains the phenomenon by which an innovation transforms an existing market or sector by introducing simplicity, convenience, accessibility and affordability where complication and high cost are the status quo. AM created a new market where home owners can design and print their own components and will not have to buy it from the traditional suppliers. A radical innovation stems from the creation of new knowledge and the commercialisation of completely novel ideas or products. (Hopp, *et al*., 2018). According to Hopp et al. (2018) the key for a disruptive innovation is determined by the need of the customers and therefore the eco system, where radical innovation lies within the organization itself.

One of the key indicators of a disruptive innovation is that it is used in the beginning for low level development (Hopp, et al., 2018). According to Berman, (2011), 3-D printing or AM can be compared to disruptive technologies like digital books and music downloads that enable consumers to order their selections on-line, allow firms to profitably serve small market segments, and enable companies to operate with little or no unsold finished goods inventory. In the past, AM has predominantly been used for rapid prototyping and for component provisioning in the medical, aerospace, automotive, railways and defense industries (Hatch, 2018;Ziyang *et al*., 2020). However, one of the areas where extensive value can be unlocked is the provisioning of AM-produced spare parts (Khajavi *et al*., 2013; Pour *et al*., 2015; Ziyang *et al*., 2020). According to the 2019 Wohlers report, there has been a 40% year on year growth in the consumption of AM materials. Wohlers (2019) contemplates that this is an indication of the use of AM in production applications.

Although the adoption rate of AM for spare part provisioning increased in the USA, Europe and Asia, there remains a slow adoption of AM for spare part provisioning in industrial component manufacturing in South Africa (Heinen & Hoberg, 2019). Two of the main reasons are, (1) the lack of a systemic understanding of the business risks involved (Oberg *et al*., 2018) when adopting an innovative, disruptive new technology (Blichfeldt *et al*., 2019), and (2) the requirements for the provisioning system to evolve from a linear supply chain to a provisioning system that can operate in the global, systemic ecosystem (Ferrantino & Koten, 2019; Garay *et al*., 2020; Harmse & Holm,2019; Helo *et al*., 2006).

In the 1980s, the first spare part provisioning system that integrated suppliers, operations and customers was called supply chain management (SCM) (Ballou, 2007). SCM focused on the supply of products to the customers and as Gattorna (2010:XI) indicated “SCM was never a good term to use since businesses are not operating in a linear chain and the focus is on the supply side of the business”. With the development of customer relationship management (CRM) systems, the focus shifted from the supply of products to a focus on customer demand (Bellenger *et al*., 2004). This new concept was called demand chain management (DCM) (Ericsson, 2011).

Globalisation and the real-time integration of systems through the internet linked more demand chains together in a global network and this led to the creation of demand networks as provisioning systems (Helo *et al*., 2006). The 4IR introduced the concept of the global ecosystem (Beltagui *et al*., 2020). The integration between these demand networks created a global ecosystem where response time to changes and requirements required agility (Helo *et al*., 2006),which is the ability of an organisation to reconfigure operations, processes and business relationships efficiently while flourishing in an environment of continuous change (Christopher, 2000). Researchers have identified the potential that AM created for new provisioning system solutions for spare parts as part of the agile AM ecosystem (Heinen & Hoberg, 2019; Holmström& Gutowski, 2017; Kritzinger *et al*., 2018).

One of the application domains that will be extensively affected by the adoption of AM is the provisioning system (Garay *et al*., 2020; Handal, 2017; Harmse & Holm, 2019; Lackey, 2019). However, the participation in the global ecosystem requires a shift from linear business processesand paradigms to dynamic, systemic and ecosystem-based networks (Helo *et al*., 2006). Holmström and Gutowski (2017) argue that the introduction of AM in spare part provisioning

should be approached as an evolutionary design problem. This will require the understanding of systems thinking and how different systems in the ecosystem interact (Blichfeldt *et al*., 2019). The same systemic thinking will also be required for the evolution of the provisioning systems from linear systems to dynamic agile networks (Lee, 2004; Ziyang *et al*., 2020). Schumacher *et al*. (2016) indicate that to overcome the uncertainty in manufacturing companies regarding the adoption of AM, new methods and tools are needed to provide guidance and support to improvethe adoption of AM for spare part provisioning. Several other researchers state there is a lack in business to understand the systemic relationship between the requirements of the spare part provisioning evolution and the key business risks when adopting AM as part of spare part provisioning (Handal, 2017; Khajavi *et al*., 2013; Kritzinger *et al*., 2018).

Schniederjans (2017) indicates that although research regarding the impact of AM adoption on the provisioning system is growing, there remains a lack of understanding and visible tools to assist the industry grasping the systemic relationship and the impact of AM adoption on the evolutionary nature of the provisioning system.

Schumacher *et al.* (2016) mention that increasing complexity on all levels in the organisation creates uncertainty about respective organisational and technological capabilities and strategies and how to develop them. Companies struggle to determine their developmental status regarding their 4IR vision and therefore fail to identify concrete fields of action, programmes and projects. De Carolis *et al*. (2017) and Schumacher *et al*. (2016) add that manufacturing companies lack a concrete methodology to define their evolutionary roadmap when adopting some of the disruptive technologies. This exacerbates the slow adoption of these technologies and the fear of the unknown relating to these disruptive technologies can lead to resistance to change (Lawrence, 1969). Jung *et al*. (2016) reason that organisations that adopt disruptive technologies may need to implement organisational and process improvements to realise the full benefits of these technologies (Kritzinger *et al*., 2018). Jung *et al*. (2016) argue in their study on the reasons for the slow adoption of disruptive technologies that past studies have not considered all the key aspects that can affect the adoption of disruptive technologies in 4IR. Blichfeldt *et al*. (2019) also argue that there is a gap between AM and the application domains and, according to their research, this can also contribute to the slow adoption of AM. Roos and Fusco (2014) further indicate that the slow adoption of AM results from the lack of strategic direction and instruments to understand the implications of AM adoption

1.2 Research problem

Thus, the research problem to be addressed is the slow adoption rate of AM as part of spare part provisioning in South Africa because of (1) the lack of a concise understanding of the evolutionary requirements of the provisioning system and (2) the complex systemic relationship between the key business risks applicable when adopting AM as part of spare part provisioning.

1.3 Research opportunity

Kohlegger *et al*. (2009:2) define that “A maturity model conceptually represents phases of increasing qualitative or quantitative capability changes of a maturing element to assess its advances with respect to defined focus areas”. Blondiau *et al*. (2013) argue that maturity models are recognised tools for the stepwise and systematic development and/or improvement of skills, processes, structures or general conditions of an organisation and can therefore be used to assist with the adoption of novel ideas.

Therefore, a maturity model is an instrument that could assist organisations to determine their current state of readiness to adopt a new technology or process (Schumacher *et al*., 2016).

1.4 Research aim

The aim of this research is to develop a maturity model that can be used as a concise business roadmap when adopting AM for spare part provisioning. The maturity model should allow organisations to understand (1) the systemic relationship between the evolutionary requirements of the provisioning system as well as (2) the complex systemic relationship between the key business risks when adopting AM as part of spare part provisioning.

1.5 Research objectives

Based on the research aim, the objectives of this study are:

- **Literature review** – Investigating the reasons for the slow adoption of AM for spare part provisioning and the different methods that can be used to address the research problem.
- **Problem diagnosing** – Using an iterative grounded theory methodology to identify new theories that can play an important role in the slow adoption of AM for spare part provisioning.
- **Empirical investigation (provisioning system evolution)** – Investigating the provisioning system evolution from supply chain to a business model that will support the adoption of AM in spare part provisioning.
- **Empirical investigation (business risk requirements)** – Determining a list of the applicable key business risks when adopting AM for spare part provisioning.
- **Empirical investigation (business paradigms)** – Investigating the key paradigms affecting the adoption of AM in spare part provisioning.
- **Design** – Designing a maturity model that will enhance the adoption of AM in spare part provisioning.

- **Verification** – Verifying that the model satisfies all the design requirements.
- **Validation** – Confirming that a valid research question was addressed, a valid research design was followed and that a valid research output was achieved.

1.6 Research questions

The central research question is:

What is required to improve the adoption of AM for spare part provisioning in South Africa?

The aim and the objectives of this research raise several questions that require the investigations outlined in Table 1 and to answer the central research question.

Table 1: Research questions

1.	**Literature review**	
	Research question 1.1	What are the differences between 4IR and the other industrial revolutions?
	Research question 1.2	What are the key technologies impacting 4IR?
	Research question 1.3	What is AM?
	Research question 1.4	What are the barriers to the adoption of AM in spare part provisioning?
	Research question 1.5	What are the different methods that can be used to address the research problem?
2.	**Problem diagnosing**	
	Research question 2.1	From the literature review, what are the barriers for the slow adoption of AM in spare part provisioning?
	Research question 2.2	What is the view of the ecosystem role players in South Africa regarding the barriers to the slow adoption of AM in spare part provisioning?

	Research question 2.3	According to the experience of the researcher, what are the reasons for the slow adoption of AM in spare part provisioning in South Africa?
	Research question 2.4	What are the themes that influence the adoption of AM in sparepart provisioning?
3.	**Empirical investigation – Provisioning system evolution**	
	Research question 3.1	What are the key requirements for a spare part provisioning systemin 4IR?
	Research question 3.2	What are the evolutionary stages of the spare part provisioning system?
4.	**Empirical investigation – Business risk requirements**	
	Research question 4.1	What are the key business risks involved when adopting AM in spare part provisioning?
5.	**Empirical Investigation – Business paradigms**	
	Research question 5.1	What are the key paradigms affecting the adoption of AM in spare part provisioning?
6.	**Design**	
	Research question 6.1	What are the design requirements for the model that will enhance the adoption of AM in spare part provisioning?
	Research question 6.2	What are the key design parameters for a maturity model?
7.	**Verification**	
	Research question 7.1	Does the model adhere to each of the design requirements?

8.	Validation	
	Research question 8.1	Has a valid research problem been identified?
	Research question 8.2	Was a valid research design followed?
	Research question 8.3	Does the research output address the research problem as well asthe specific and general limitations to the study?

1.7 Research design

This research is grounded in the design science research paradigm. Hevner *et al*. (2004) indicate that design science is a problem-solving paradigm that seeks to enhance human knowledge by creating innovative, new artefacts. Design science also allows multiple key stakeholders to participate and collaborate to understand and address important, complex problems or opportunities. The action design research (ADR) methodology within the DSR paradigm works best if there is an existing artefact. Therefore, it was decided to rather use the elaborated action design methodology (eADR) since a novel artefact had to be developed.

Figure 1 is a graphical representation of the eADR method applied to the research. Although the method is discussed in detail in chapter 2 (literature review) and chapter 3 (research design), a brief overview is also provided.

The research was conducted in three stages, each stage consisting of different subphases (table 2)

Table 2: Stages of research

1	**Problem diagnosing stage (PDS)**	
	Problem diagnosing phase 1 (PDP 1)	Literature review
	Problem diagnosing phase 2 (PDP 2)	Expert discussion and thematic analysis
	Problem diagnosing phase 3 (PDP 3)	Researcher’s own experience
	Problem diagnosing phase 4 (PDP 4)	Triangulation
	Problem diagnosing phase 5 (PDP 5)	Construction of grounded theory
2	**Concept design stage (CDS)**	
	Concept design phase 1 (CDP 1)	Literature review
	Concept design phase 2 (CDP 2)	Literature review
	Concept design phase 3 (CDP 3)	Systematic literature review

3	**Build stage (BS)**	
	Build phase 1 (BP 1)	Design of maturity model
	Build phase 2 (BP 2)	Construction of maturity model and Delphi questionnaire

The research design according to the eADR method enters the iterative design process at the problem diagnosing stage. This stage is divided in five phases and forms part of an iterative development in grounded theory to develop a new theory on the reason for the slow adoption of AM in spare part provisioning and to assist in solving the complex problem. The output of the firstphase (PDP 1) is a list of codes according to the literature review from chapter 2 that can influence the adoption of AM. These codes were grouped into themes and used for discussions with the selected AM experts in South Africa (PDP 2). The themes from the literature review study, feedback from the selected AM experts in South Africa and the researcher's own experience (PDP 3) were collated in a triangulation exercise (PDP 4) to determine the validity of the information. Three theories were developed during the problem diagnosing phase 5 (PDP 5). These theories formed the input for the concept design stage during which it was further investigated.

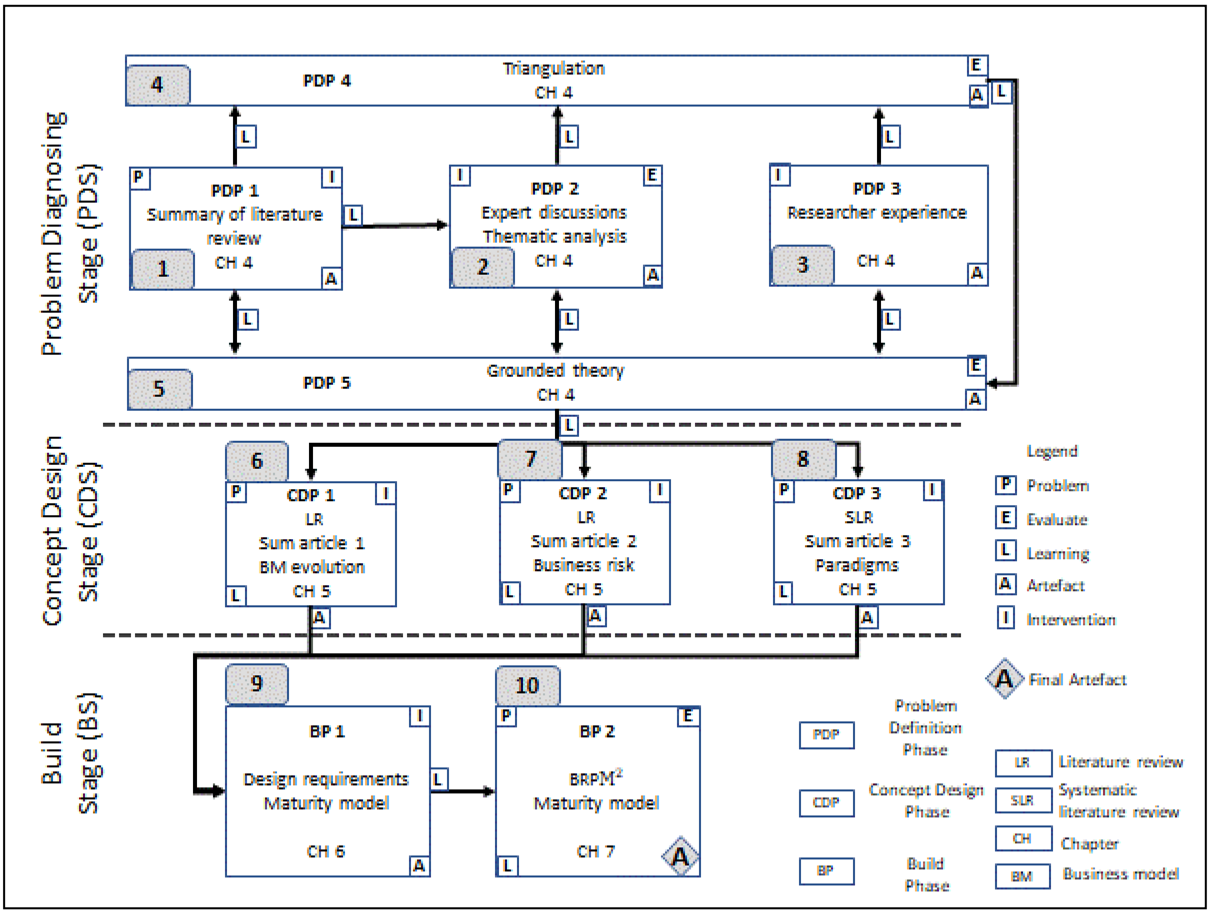

Figure 1: Research design according to eADR

The build stage is the last part of the eADR method and consists of the compilation of the design requirements (BP 1) for the maturity model and the actual design and development of the maturitymodel (BP 2) as a final artefact for this research. This will be discussed in chapter 7.

The entry point at the problem diagnosing stage was utilised for this research (see Figure 13) The problem diagnosing stage (PDS) consists of five iterative phases (1–5).

In the PDS, grounded theory was used as an overarching method to assist in defining the theory for the complex problem of the low adoption of AM in spare part provisioning.

The insight gained from the PDS and the grounded theories that were developed were used as the input for the concept design stage (CDS). The CDS contains of three phases (6–8) with three research papers as artefacts that were used as input for the build stage (BS). The BS consists of the compilation of the design requirements for a maturity model stage (9) and the final artefact the business risk provisioning maturity model (BRPM²) stage (10). A Delphi study is used in BS 2 to evaluate the rigour of the model as part of the eADR requirements in chapter 8.

1.8 Chapter division

A summary of the chapter division, research objectives and questions are set out in Table 3.

1.9 Summary

Although there is rapid growth in the AM market, the adoption of AM in spare part provisioning in South Africa remains slow. The main reason for the slow adoption can be related to the lack of a concise business roadmap that organisations can use to define their current status against a provisioning evolutionary stage and key business requirements of AM. The purpose of this study is therefore to develop a maturity model that will allow organisations to understand the systemic relationship between the evolutionary requirements of the provisioning system and the key business risks when adopting AM as part of spare part provisioning.

A maturity model as a final artefact will be developed based on the spare part provisioning evolutionary stages and the key business risks that can guide organisations in their AM adoption journey.

Table 3: Chapter division, research objectives and research questions.

Chapter		Research objectives	Research questions
1.	Introduction		
2.	Literature review	Investigate the adoption of AM for spare part provisioning in the South African context and clarify all reasons prolonging adoption. Investigate the different methods that can be used to address the research problem.	1.1. What are the differences between 4IR and the other industrial revolutions? 1.2. What are the key technologies impacting 4IR? 1.3. What is additive manufacturing? 1.4. What are the barriers to the adoption of AM in spare part provisioning? 1.5. What are the different methods that can be used to address the research problem?
3.	Research design		

4.	Problem diagnosing	Use an iterative grounded theory methodology to identify new theories that can play an important role in the slow adoption of AM for spare part provisioning.	2.1. From the literature review, what are the barriers for the slow adoption of AM in spare part provisioning? 2.2. What is the view of the ecosystem role players in South Africa regarding the barriers to slow adoption of AM in spare part provisioning? 2.3. According to the experience of the researcher, what are the reasons for the slow adoption of AM in spare part provisioning in South Africa? 2.4. What are the new theories that influence the adoption of AM in spare part provisioning?
5.	Concept design	Research the grounded theories developed during the problem diagnosing stage.	3.1. What is the evolution of business models from supply chain to a provisioning business model suited for 4IR? 3.2. What is the impact of adopting AM as part of spare part provisioning? 3.3 What are the key paradigms that influence the adoption of AM?

6. Design requirements	Design a model that will enhance the adoption of AM in spare partprovisioning.	4.1. What are the design requirements for the model that will enhance the adoption of AM in spare part provisioning? 4.2. What are the key design parameters for a maturity model?
7. The business risk provisioning maturitymodel (BRPM^2)		
8. The Delphi process		
9. Verification	Verify that the model satisfies the design requirements.	5.1. Does the model adhere to each of the design requirements?
10. Validation	Confirm the validity of the research problem, research design and the research output.	6.1. Has a valid research problem been identified? 6.2. Was a valid research design followed? 6.3. Does the research output address the research problem aswell as the specific and general limitations to the study?
Conclusion		

CHAPTER 2: LITERATURE REVIEW

This chapter addresses the following research questions by examining the literature relevant to this study:

Research question 1.1	What are the differences between 4IR and the other industrial revolutions?
Research question 1.2	What are the key technologies impacting 4IR?
Research question 1.3	What is AM?
Research question 1.4	What are the barriers to the adoption of AM in spare part provisioning?
Research question 1.5	What are the different methods that can be used to address the research problem?

2.1 Introduction

The purpose of the literature review is to define the evolution of the industrial revolutions and to define 4IR and the key requirements for success. This will include a review of the key technologies that support 4IR with a focus on AM as the most disruptive technology of 4IR and what the reasons are for the slow adoption of AM in spare part provisioning.

The literature review will conclude with research on paradigms and methodologies that will form the structure of the research design to solve the defined problem as stated in chapter 1

2.2 Industrial revolutions

Schwab (2016) states that the word revolution denotes abrupt and radical change. The first three industrial revolutions led to a significant increase in productivity, which was caused by a single technology that increased the standard of living and therefore influenced society fundamentally (Erol *et al*., 2016). According to Cimini *et al*. (2019), modern manufacturing organisations are the consequence of two centuries of continuous improvements in technologies, variations of organisational structures and management practices. Steenhuis and Pretorius (2017) deliberate that the fundamental changes caused by the industrial revolutions were more focused on what work was done, how work was organised, who participated in the workforce and where they were located. This also impacted the production volumes and varieties of products produced (Schwab,2016).

Figure 2 denotes a summary of the industrial revolutions and the impact that the revolutions had on product volume and variety.

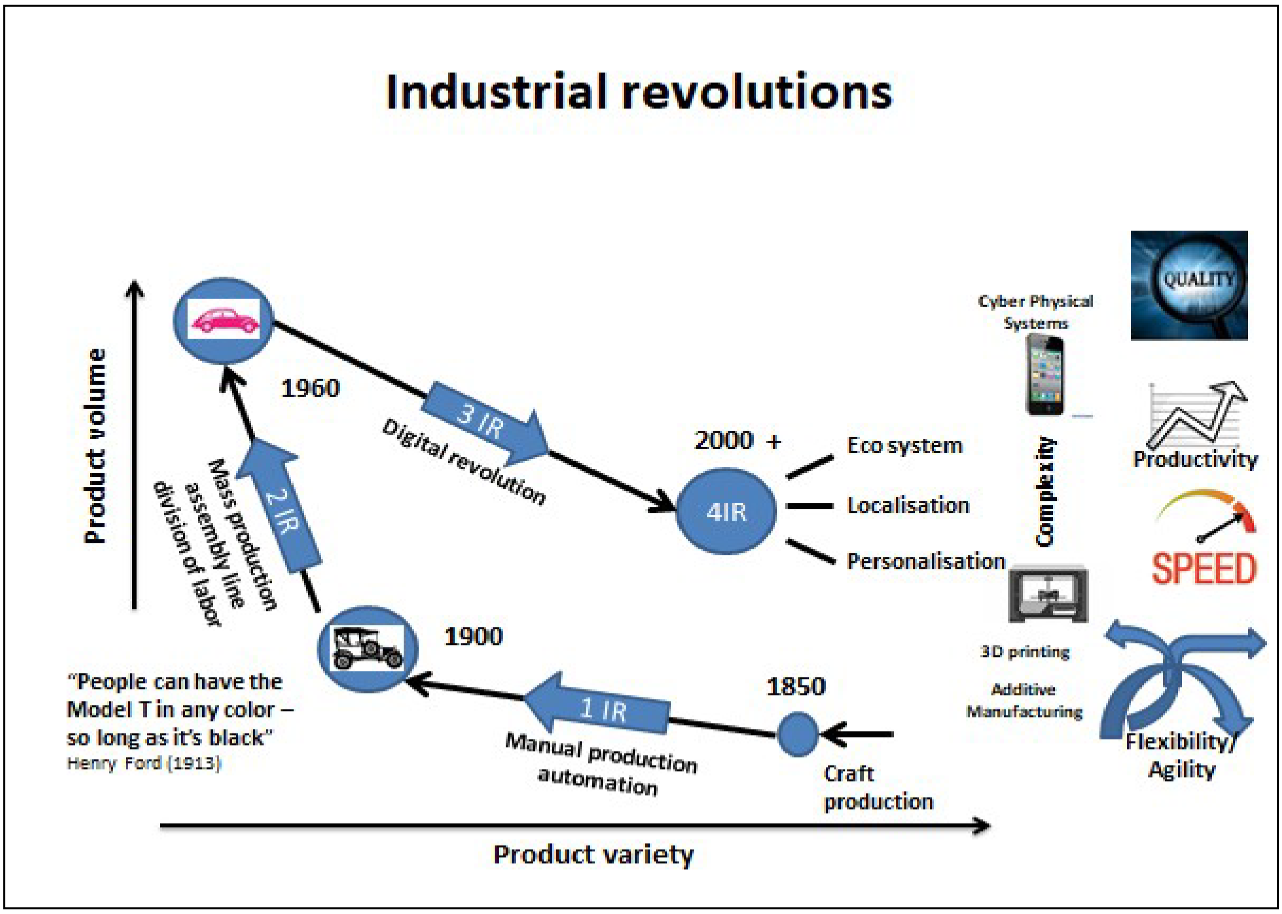

Figure 2: Summary of the industrial revolutions (author)

During the era of craft production, highly skilled craftsmen created customised products according to customer requirements. The first Industrial Revolution (1IR) automated production equipment and more products could be manufactured to satisfy the market demand. The second Industrial Revolution (2IR) was the mass manufacturing revolution and the introduction of product standardisation. The third Industrial Revolution (3IR) started with the Internet and allowed the integration of different production entities. However, the fourth Industrial Revolution (4IR) differs from the other industrial revolutions since it has not been triggered by the industry on the shop floor (see Table 4), but has been promoted by governments, numerous related policies and initiatives and new disruptive technologies (Cimini *et al*., 2019; Erol *et al*., 2016). The increase in production during the first three industrial revolutions were initiated by an increase in the market demand with an outside–in focus (Table 4). The 4IR requires the creation of innovative solutions that will attract customers and provide systemic solutions versus only new products or replacement of existing products, as in the previous three industrial revolutions. The 4IR will require an inside–out approach, incorporating the entire ecosystem (see Table 4)

Table 4: Industrial revolutions (Erol et al., 2016; Schuh et al., 2014).

Revolution	Manufacturingfocus	Catalyst	Impact	Driving force
1IR	Increased production of the same products Reduction of complexity Production scale increases	Water, steam-powered mechanical manufacturing	Productivity improvement on shop floor	Market Outside –in
2IR	Mass production – avoidance of complexity Economy of scale Division of labour	Electricity Mass production	Productivity improvement on shop floor	Market Outside –in
3IR	Mass production – little complexity Economy of scale Standardisation	Personal computerBasic networks Automation of production Internet	Productivity improvement on shop floor Link selective manufacturing entities	Market Outside –in
4IR	Craft–embrace complexity Economy of scope (sell solution) as customisation (adhere to specific customer requirements)	Government policies, Internet and new disruptive technologies	Rapid product development Collaborative productivity in ecosystem Integration between people and smart devices Move from shop floor to overall engineering and business processes	Sell creative, innovative systemic solutions Inside–out Focus on ecosystem

The term 4IR refers to rapid transformation in the design, production, implementation, operation and service of manufacturing systems, products and components (Oberer & Erkollar, 2019). In 4IR, customers will request a low-volume production of more innovative, creative and sustainable products with high, added value (Roitman & Shanks, 2016; Sisca *et al*., 2016). Schwab (2016) describes 4IR as a transformation of humankind and that 4IR will fundamentally change the way we live, work and relate to one another. The 4IR creates a world in which virtual and physical systems of manufacturing globally cooperate with each other in a flexible way, called cyber- physical systems (Camarinha-Matos *et al*., 2019; Strange & Zucchella, 2017). This will enable the absolute customisation of products and the creation of new operating models (Camarinha-Matos *et al*., 2019; Schwab, 2016).

In a report from the 2016 Global Industry 4.0 survey, 'Industry 4.0: Building the digital enterprise', Geissbauer *et al*. (2016) indicated that while 3IR focused on the automation of single machines and processes, 4IR focusses on (1) end-to-end digitisation of all physical assets, (2) integration into digital ecosystems with value chain partners, (3) networks and (4) a wide range of new technologies to create value (Strange & Zucchella, 2017). Schwab (2016) reasons that aside from the speed and breadth of 4IR, the uniqueness of 4IR lies in the growing harmonisation and integration of so many different disciplines and novel technologies (Camarinha-Matos *et al*., 2019). This will require a systemic understanding of the interrelationships between the different technologies and role players in the ecosystem. Schumacher *et al*. (2016) confirm the requirement for the systemic understanding of 4IR in stating that the vision for 4IR propagates a fundamental paradigm shift in production industries, which will be characterised by a new level of socio technical interaction. Table 5 is a summary of the key focus areas of 4IR according to researchers.

Table 5: Key focus areas of 4IR (Geissbauer et al., 2016; Schumacher et al., 2016 and Schwab, 2016).

Geissbauer *et al*. (2016)	**Schumacher *et al*. (2016)**	**Schwab (2016)**
Digitisation and integration of vertical and horizontal value chains	Vertical integration of all layers of a production system	Availability of new products and services that increases efficiency of personal lives without increase in cost
Digitisation of product and service offerings to meet the need of the end customers. Focus on demand	Horizontal integration of all partners in a value chain	Creation of new networks that will match buyers and sellers of products and services
Digital business models with customer access and focus on innovation and digital culture	Acceleration through exponential technologies of 4IR, co-innovation and agility.	Balance the benefits and risks of digital platforms by ensuring openness and opportunities for collaborative innovation

The summary in Table 5 is a clear indication that 4IR is not only a single intervention but requires a holistic/systemic view of the organisation and the networks in which the organisation participates. However, 4IR is not merely an extension of 3IR, but is a new industrial revolution because of its velocity, scope and disruptive effect on technologies and systems. This change is not as linear as in previous revolutions, but it occurs at an exponential pace (Schwab, 2016). The disruptive impact of 4IR will affect almost every industry in every country, and the breadth and depth of the change will transform entire productions, managements and governance systems (Schwab, 2016). According to Lawrence. L,

(1969) change can lead to resistance to the change when participants don't understand the social impact of the change and it is therefore important to create understanding and visibility of the required change or transformation. This transformation can only be achieved through the multidisciplinary interaction of a diverse range of entities inside and outside the organisation as part of the ecosystem (Erol *et al*., 2016; Ferrantino & Koten, 2019). Schumacher *et al*. (2016) argue, that because of the magnitude of 4IR, companies have substantial problems to grasp the idea of 4IR and to relate it to their specific domain (Magruk, 2016).

Leaders will be required to take bold steps into the unknown and view problems and challenges as opportunities (Mauri, 2020). In 4IR, leadership will have to guide the organisation to a new culture where creativity, teamwork, innovation and agility can thrive (Schwab, 2016). Schwab (2016) adds that 4IR will require entirely new economic and organisational structures. Erol *et al*. (2016) state that if organisations want to survive the challenges of 4IR, they will need both virtual and physical structures that will allow for close cooperation and rapid adaptation along the whole lifecycle, from idea initiation to production and the provisioning system. The new culture will require a comprehensive understanding of the digital requirements of 4IR (Geissbauer *et al*., 2016). According to several researchers, the digital impact of 4IR on organisations and the requirement to participate in the global ecosystem will necessitate a culture and business strategy change that is difficult to understand (Bongomin *et al*., 2019; Roitman & Shanks, 2016; Xu *et al*.,2018).

The digital impact of 4IR is based on multiple disruptive technologies (Cimini *et al*., 2019; Schwab,2016). Although technology follows an evolutionary path, the combined, systemic fusion of the different technologies will create a revolutionary effect where the business must adapt radically to new business practices in 4IR (Camarinha-Matos *et al*., 2019; Xu *et al*., 2018).

This section answers research question 1.1:

What are the differences between 4IR and the other industrial revolutions?

2.3 Technologies constituting 4IR

The 4IR is driven by a multitude of new technologies that will have a profound impact on businesses in the future (McKinsey, 2015). Figure 3 indicates the key technologies constituting the core of 4IR (Schwab, 2016). Although all the technologies will have an impact on 4IR, additivemanufacturing (AM) is identified by several researchers as the most disruptive technology of all the technologies of 4IR(Bonneau & Yi, 2017; Niaki & Nonino, 2017; Rylands *et al*., 2016; Steenhuis & Pretorius, 2017).

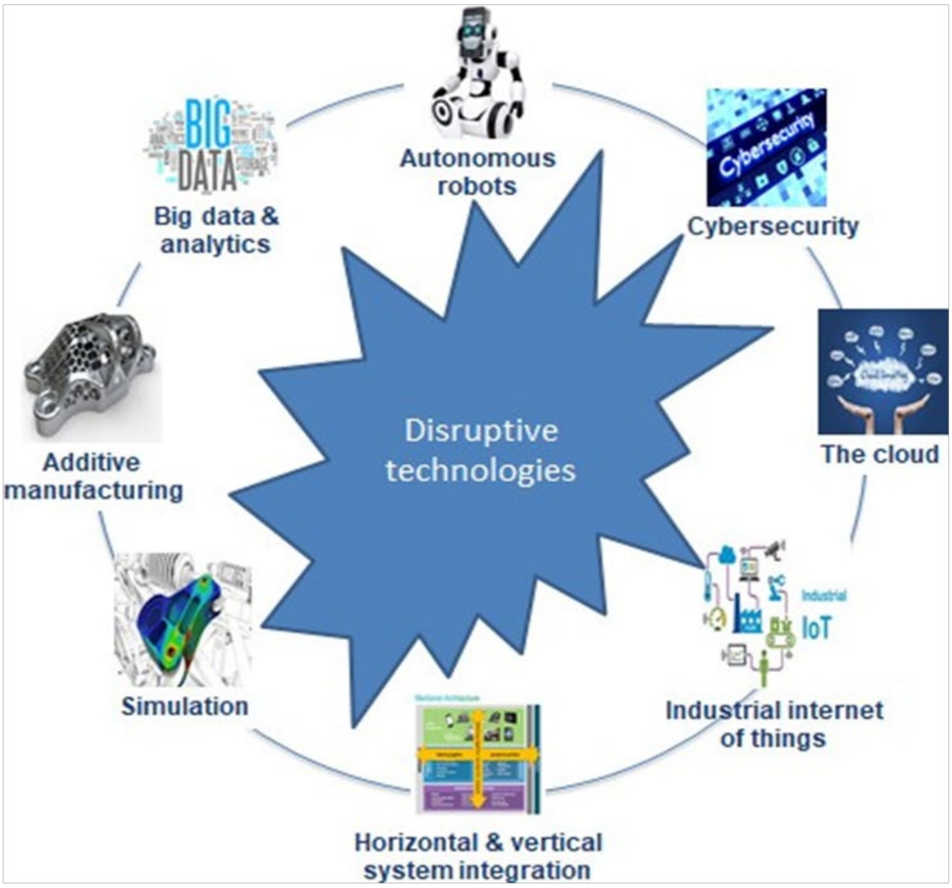

Figure 3: Key technologies of 4IR (Schwab, 2016).

This section answers research question 1.2:

What are the key technologies impacting 4IR?

2.4 Additive manufacturing (AM)

Charles W. Hull of 3D Systems Corp. created the first working 3D printer in 1984. The technology was very expensive and not feasible for the general market in the early days. As patents expired, the cost drastically decreased allowing 3D printing to find their way into many industries (Attaran, 2017). 3D printing uses an additive manufacturing process where products are built on a layer-by-layer basis, through a series of cross sectional slices (Berman, 2011)

All 3D printers use 3D CAD software that measures thousands of cross-sections of each product to determine exactly how each layer is to be constructed (Berman, 2011). The following list adopted from Berman (2011) indicates the advantages of 3D printing in comparison to other technologies:

a. 3D printing can be used to economically build custom products in small quantities and can improve cost effectiveness.

b. No need for costly tool, molds or punches

c. No scrap, milling, or sanding requirements

d. Automated manufacturing

e. Use of readily available supplies

f. Ability to recycle waste material

g. Minimal inventory risk as there in no unsold finished goods inventory

h. Improved working capital management

i. Ability to easily share designs and outsource manufacturing

j. Designs are digitized and can be produced on any 3D printer that is capable of printing with the selected material selected for the finished product.

k. Speed and ease of designing and modifying products

Components can either be measured or 3D scanned to create the digital model. When adjustments to the model are required, the digital design can be amended, a new prototype can be created and once the prototype is acceptable to the end-user, the final part can be 3D printed for installation.

3D printing has undergone a three-phase evolution process. During the first phase, architects, artists and product designers used 3D printing predominantly for the creation of prototypes. The second phase is the creation of finished goods that can be used as spare part replacement and the third phase will be once 3D technology is used by households to produce components (Berman, 2011) (Attaran, 2017). 3D printing will significantly streamline traditional methods of manufacturing and will have a profound impact on the manufacturing strategy of organisations (Attaran, 2017) (Pereira, et al., 2019). 3D printing or AM is best suited for low volume production with high complexity (Pereira, et al., 2019).

Some researchers indicate that AM and 3D printing (3DP) are the same concepts (Barnatts, 2013; Rylands *et al*., 2016; Ivanova & Campbell, 2013; Oettmeier & Hofmann, 2016). To the contrary, other researchers argue that AM is not the same as 3DP and contemplate that AM is not only a technology but consists of a multitude of different nodes and interactions that will have a disruptive influence on the organisation (Laplume *et al*., 2016; Ford & Despreisse, 2016; Korner *et al*., 2020;Mellor *et al*., 2016; Sisca *et al*., 2016).

Niaki and Nonino (2017) state AM will require new managerial approaches in different fields such as project design and development, production planning and optimisation, supply chain design, operations and business strategy. Pour *et al*. (2015) define AM as a term applied to a technological class which consists of multiple subsets that make up the technological variations. AM comprises of a group of technologies where the development in AM technologies is increasing exponentially, yet the potential benefits to industrial manufacturers has not been fully highlighted(Oettmeier & Hofmann, 2016; Sisca *et al*., 2016). These variations require as a strategy the same as companies define manufacturing strategies (Thomas-Seale *et al*., 2018). AM as a manufacturing technology will be playing an increasing role in many industries and will lower the entry barriers to manufacturing (Kianian *et al*., 2016; Thomas-Seale *et al*., 2018).

Oettmeier and Hofmann (2016) examined the inter-organisational impact of AM and concluded that AM is not only a single technology, but it will have an impact across a wide section of the organisation, and it will play an important part in the increasing demand of customers for customisation. However, this will require from organisations to take a holistic or systemic view when adopting AM (Pour *et al*., 2015). This latches on to the concept of dynamic capabilities as defined by (Madsen, 2010) as:

"Dynamic capabilities are acquired abilities which enable the firm to integrate, build/develop and reconfigure internal and external resources of the firm and ordinary capabilities in the manner, assumed and regarded as appropriate by the principal decision maker(s) in the firm". AM will require many different skills like eco-system integration, innovative design skills and a clear understanding of systems thinking. If these skills are not available in the organization, it can lead to resistance to change and become a barrier for the adoption of the technology (Madsen, 2010) Pardo-del-Val & Martinez-Fuentes (2003), states that resistance to change is a phenomenon that affects the change process, delaying or slowing down the beginning of the adoption as well as obstructing or hindering the implementation of the adoption process. Resistance can also be seen as an activity to keep the status quo.

Campbell and Ivanova (2013) argue that AM offers a new systemic paradigm for engineering design and manufacturing that could have significant economic, geopolitical, environmental, intellectual property (IP) and security implications. Traditional manufacturing is called subtractive manufacturing, where material is removed to reach the final state (Campbell & Ivanova, 2013). Casting, forming, moulding and machining forms part of the traditional manufacturing processes.Figure 4 is a graphical representation of subtractive manufacturing vs AM.

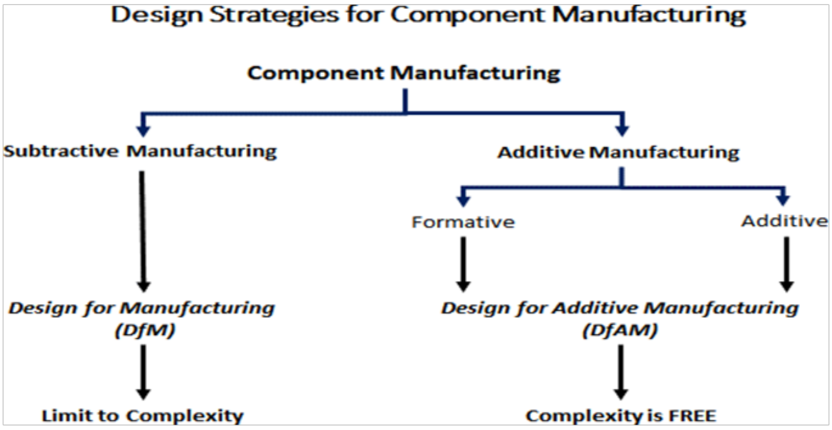

Figure 4:Subtractive vs additive manufacturing (author's own work).

The design methodology used for subtractive manufacturing is design for manufacturing (DfM) and limits complexity because complexity is expensive and time-consuming (Gebisa & Lemu, 2017). DfM focuses on the individual components and how the components can be manufactured with in the limitations of the manufacturing technology.

The design methodology used for AM is design for AM (DfAM) and accommodates complexity (Campbell & Ivanova, 2013; Mohr & Khan, 2015). DfAM drives a culture of innovation and a systemic approach to design solutions not only to solve the immediate problem but to redesign the system and to improve the reliability of the integrated system (Orquera *et al*., 2017;Sossou *et al*., 2018). According to Roitman and Shanks (2016), AM will create a new culture of design, moving away from traditional manufacturing based on a culture of innovation and creativity (Thomas-Seale *et al*., 2018). Innovation enabled by new technology is required for success in the new manufacturing environment (Mahidhar & Schatsky, 2013). This new culture necessitates a paradigm shift in the organisation when adopting AM for spare part provisioning from a reductionist approach focussing on the individual parts to a holistic approach focusing on the interaction of the different parts and how they support each other and perform as an integrated system. This paradigm shift will also have a profound influence on the provisioning system (Atteram, 2017).

One of the key benefits of AM is to produce components on demand and as close as possible to the point of consumption (Khajavi *et al*., 2013; Rylands *et al*., 2016). This will drive the localization of production where the trend over the past decade was to move production to low-cost production countries, adding complexity to the provisioning system (Ferrantino & Koten, 2019). Localisation of spare parts will reduce the long lead times for imported part and will buffer against currency fluctuations related to imported spares in the South African spare parts domain. Working capital will also be reduced since there will be no need to keep a finished parts inventory in a warehouse. The parts can be produced on demand and a digital inventory will be kept in an e- warehouse and not a physical warehouse (Goehrke, 2018; Heinen & Hoberg, 2019; Ituarte *et al*., 2017). AM will require the interaction of many different components inside and outside the organisation as part of the global ecosystem (Ismail *et al*., 2014).

This section answers research question 1.3:

What is additive manufacturing?

2.5 Ecosystems

The Oxford English Dictionary definition of holism is "the tendency in nature to form wholes, that are greater than the sum of the individual parts, through creative evolution." Therefore, it is important to understand that the focus should be on the way that the different components interact and support each other to create a more effective overall solution. Holism is sometime defined as that the whole is bigger than the sum of its parts (Freeman, 2005). This leads to defining the whole as a system where the individual parts interact as a system (Martin, 1997). Martin (1997) states that the holistic approach of the system approach implies that since systems are made of interacting parts, it is impossible to define those interactions in isolation from the rest of the system by studying a single component, unless the system fulfills at least two conditions: (1) interactions are weak, and (2) the relationship between the components is linear. Martin (1997) contemplates that unless the response of the different components is or can be considered to be independent from one another, the system (taken as the sum of its components and their interactions) cannot be studied by isolating the parts and therefore requires a systemic understanding. The simplest definition of systems, according to Bertalanffy (1968) is "entities composed of interacting parts."

Behl and Ferreira (2014) defines Systems Thinking as the ability to think holistically about a system, rather than only considering the parts individually. Senge (1990) defines Systems Thinking as a discipline for seeing wholes and as a framework for seeing interrelationships rather than things, for seeing patterns of change rather for seeing snapshots. Systems thinking can be defined according to (Arnold & Wade, 2015) as:

*"*a set of synergistic analytical skills used to improve the capability of identifying and understanding systems, predicting their behaviours, and devising modifications to them in order to produce desired effects. These skills work together as a system*"*.

A sub section of Systems Theory is Complexity Theory. Sammut-Bonnici (2015) indicates that Complexity Theory provides an understanding of how systems, grow, adapt and evolve. Complexity

Theory explains how the relationship between the members give rise to collective behavior and how to understand and utilize complexity for adopting disruptive innovation (Colchester, 2016).

The principles of Systems Thinking and Complexity Theory enables researchers to create an understanding of the systemic nature of the system and how to manage the perceived complexities. Behl and Ferreira (2014) specify that companies are faced with increased complexity due to the nature of the integrated networked business environment and dependencies. Critical to systems theory is firstly the recognition that because of dependencies, the properties of components cannot behave independently but must obey certain rules and secondly, it is their relationship that provides for emergence and can create complexity. In order to successfully managing a transition and understanding of a system and the complexity thereof, it is imperative that there is a comprehensive understanding of Systems Thinking and Complexity Theory and the inter-relationship of all the components in the eco-system (Colchester, 2016).

Complexity can be daunting especially if a myriad of activities requires different understanding away from the stable status quo. AM is a system that moves spare part provisioning from a complicated, linear environment to a complex, non-linear environment. Understanding complexity, allows companies that adopt AM not only to fulfil the immediate requirement but to use an understanding of the complexity to improve the efficiency of the total system. An understanding of Systems Thinking and Complexity Theory can play an important role in understanding and managing the complexity in the global network or eco-system. Complexity creates new risks and alters activities that were not seen as risks to become risks due to the new requirements in the global ecosystem.

Risks are identified and broken down into small manageable components. This is a reductionist approach the same as traditional manufacturing where the material is removed until the final component is created. AM is a process where components are manufactured layer by layer from the bottom up and an integrated view of the risks is required for an optimized solution. An understanding of the principles of Systems Thinking will contribute to understand the risks and to define the interrelationship between the different risks in the ecosystem (Martin, 1997).

Adner (2017:40) defines an ecosystem as “the alignment structure of the multilateral set of partners that need to interact for a focal value proposition to materialise”. The Collins Dictionary (2018, online) defines an ecosystem as “all plants and animals that live in a particular area together with the complex relationship that exists between them and their environment”. From the two definitions, an ecosystem constitutes a systemic interaction between all the role players for mutual benefit and the interaction of all the different role players can lead to complexity that needs to be understood by all the participating role players. Organisations are facing unprecedented levels of change and the ability to adapt to and manage the change should be well understood (Burnes, 2005). As the world becomes more interconnected as part of the participation in the ecosystem, so does the need to understand and manage complexity (Colchester, 2016).

Gartner (Gartner & Finck, 2018) indicates that AM is still perceived to be a single technology whereas AM consists of a whole manufacturing paradigm and a wide range of different processes and techniques that integrate across boundaries and networks adding to the complexity of the global ecosystem.

Rogers (Rogers, 2003) published the Innovation diffusion theory (IDT), an influential work which helps to explain the adoption of innovation. The IDT indicates that an innovation's adoption rate is influenced by five specific innovation attributes. Table 6 is a summary of these attributes.

Table 6: Innovation adoption Attributes – (Rogers, 2003)

Innovation Attributes	**Definition**
Relative advantage	Perceived superiority of an innovation to existing practices
Compatibility	Perceived consistency of an innovation with existing values, past experiences and needs of potential adaptors
Complexity	Perceived difficulty to understand and use the innovation
Trialability	Perceived degree to which the innovation can be experimented with
Observability	Perceived degree to which results of an innovation are visible to others

From table 6, the IDT indicates that a high degree of relative advantage, compatibility, trialability and observability of an innovation is positively associated with its adoption, whereas complexity is negatively related to an innovation's rate of adoption. Rogers (2003) further indicated that the idea about a disruptive innovation can cause some uncertainty by possible adopters and that some degree of risk is involved in the adoption that exacerbates the uncertainty and fear of complexity.

Gartner (2018) indicated in their study on the construction of a theoretical framework to explain the disruptive potential of AM that the complexity of AM technologies has been underestimated. According to Oettmeier (2016) this can be attributed to the insecurity about the how, where and why to deploy additive technologies.

Burnes (2005) contemplates that organisations are like complex systems in nature, they are dynamic, non-linear systems and that their actions can be unpredictable as part of the integrated network environment.

Table 7 indicates the difference between complicated (traditional linear) systems and complex (eco-based systemic, non-linear) systems. This summary is derived from Sammut-Bonnici (2015) and author own inputs.

Table 7: Difference between complicated and complex systems - [(Sammut-Bonnici, 2015), Author]

Complicated (Traditional systems)	**Complex/Complexity (AM Ecosystem)**
Complexity is a burden	Complexity is a challenge
Attention to detail	Investigate behaviour of whole system
Rich in detail	Rich in structure
Getting task done	Action in one-part affect other
Problems are broken down into small parts	Activities shift and adapt according to situation on hand
Experts solve parts	Agile, multi-disciplinary teams create solution
Management hierarchy	Evolves and adapt with internal systems and external environment
Rules established – linear processes	Operations framework
Organisations viewed as complicated and static	Organisations viewed as complex set of self-organizing components
Mass production and division of labour	Economic and organisational phenomena are like those observed in science and nature
Attributes: Diminishing returns, rules based regulated environment, stagnation, linear dynamics	Attributes: Increasing returns, self-organizing system, continuous adaptation, sensitivity to initial conditions, non-linear dynamics
Component design Methodology: Design for manufacturing (DfM)	Component design methodology: Design for Additive Manufacturing (DfAM)

Table 7 indicates that an organisation must transcend from complicated, linear systems to complex, non-linear systems to participate efficiently in the ecosystem. There needs to be a clear understanding of how to manage the complexity introduced by adopting AM and the required changes in the provisioning system. The traditional interaction in the provisioning system has been organised in a linear way (Beltagui *et al*., 2020). Figure 5 is an indication of a typical linear provisioning system.

Figure 5: Linear provisioning system (author).

Moore (1993) defines the eco system as:

"an economic community created from interaction between individuals or groups, with the emphasis on the networks between the actors within the ecosystem and the dynamic interaction between these networks."

Choi (Choi, *et al.*, 2001) indicate that eco-systems are complex adaptive systems that can function in a dynamic business environment. According to Ismail *et al*. (2014), ecosystems require exponential change, while organisations are structured linearly. Figure 6 is a representation of the difference between the traditional, linear provisioning system and the new, eco-based, systemic provisioning system managing the holism of the entire system.

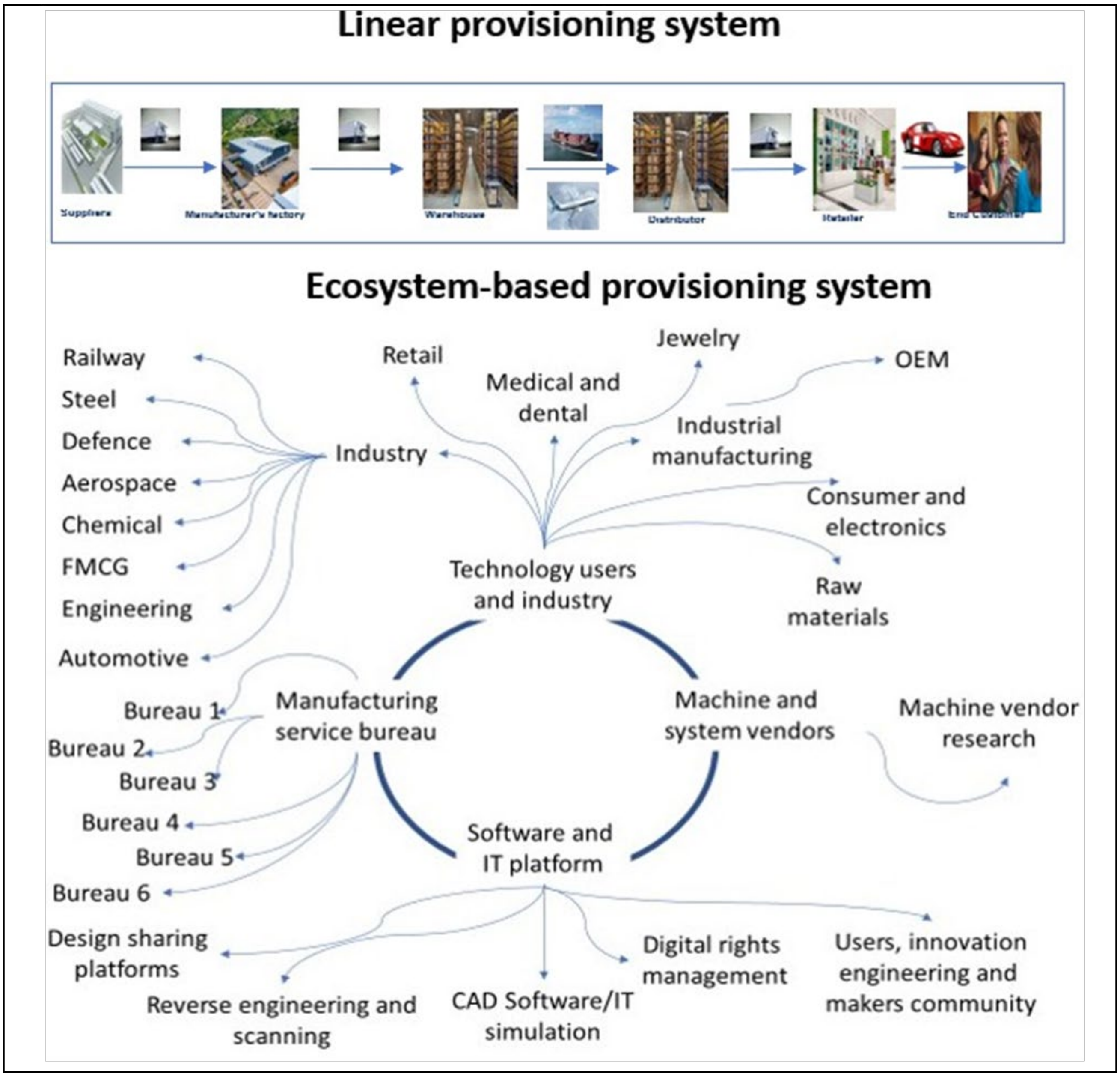

Figure 6:Linear provisioning system vs the networked ecosystem adopted from Ituarte et al, (2017)

In the ecosystem-based network, there are many different role players who participate and compete (Camarinha-Matos *et al*., 2019).

Figure 6 indicates the different communities that form part of the AM ecosystem and act as a source of innovation and knowledge development. One such community is the maker community and can be described as a group of people that share innovative ideas and design thinking through global networks or ecosystem participation (Jordan & Lande, 2015). Many of these communities work together in a complex ecosystem and a clear understanding of the systemic interaction of these communities is required when participating in the new ecosystem based economy. The different players in these communities will be connected through virtual teams. (Dey & Sharma, 2018)

2.6 Spare part provisioning in the ecosystem

According to Collins (2018), provisioning can be defined as the act of giving an item or making it available to people who need or want it. Provisioning systems followed an evolutionary path over recent years (Rylands *et al.*, 2016). The rollout of the Internet allowed different systems to be linked and instead of having different chains that linked together, integrated networks could be created (Strange & Zucchella, 2017).

One of the risks that remains inherent in the current Supply Chain or provisioning system, is that it re-enforces traditional linear thinking. Gattorna (Gattorna, 2010) states that the term Supply Chain Management was never a good term because it emphasizes the supply side of the enterprise. The chain descriptor implies, participants are dealing with linear chains or strings of enterprises, when in fact the provisioning systems are involved in multi-dimensional, integrated networks or eco-systems. 4IR necessitates that organisations move away from static, linear provisioning systems to dynamic eco-networked non-linear systems (Verboeket & Krikke, 2019).

Provisioning systems requires an evolution from Supply Chain to a new provisioning paradigm as part of the ecosystem This evolution will allow practitioners to focus on the dynamic interaction and the agility required for success in the global networks or ecosystem. and will transcend the Supply Chain from a linear system to a non-linear system where it is important to understand the interrelationship and cross-functional effect of the different components of the network or ecosystem Systems Thinking can assist to create this new paradigm of the holistic system in a non-linear complex network. The highest level of maintenance management is defined as Prescriptive maintenance and ensures the asset availability is optimised through a holistic consideration of production processes, rather than a time based, individual inspection of single items (Nemeth, *et al.*, 2018).

Apart from the exponential growth of AM, the adoption and provisioning systems for the use of AM for spare parts is not developing at the same rate (Vinod *et al.,* 2009). The advent of 4IR will require provisioning systems to evolve from a linear perspective where the sum of the parts makes up the whole, to a holistic systemic view where the interrelationship in the system needs to be managed and understood (Feldmann & Pumpe, 2017)

Disruptive technologies change the attributes required to manage the business and the nature of the provisioning systems which is sometimes ignored by companies (Christensen, 2000) (Muita, *et al.,* 2015). The business is not operating in a linear supply chain any more but will become part of the global network or eco-systems (Parker, 2015).

McCarthy *et al.* (2016) contemplated that a new Supply Chain evolution is needed to adapt to the requirements of 4IR. There should be a transition from Supply Chain to Supply Networks to incorporate the multitude of different actors in the operating environment with a shift from supply to demand.

The evolution from Supply Chain to the Demand Chain has been initiated by the implementation of Customer Relationship Management (CRM) software and a focus on the demand side of the business. The next evolution was initiated by the advent of the global internet. The internet allowed many different networks to be connected and created more real time visibility. 4IR, introduced new disruptive technologies and the requirement for agility became sturdier. With the proliferation of these technologies, where AM is the most disruptive, an improved systemic understanding of the provisioning system and how to function in turbulent, agile and complex, non-linear business networks will be required to fulfil the dynamic demand of 4IR.

Three of the key requirements for operating in 4IR are:

a. Focus on demand (Sisca *et al*., 2016)

b. Integration of the different networks or ecosystem (Camarinha-Matos *et al*., 2019)

c. Understanding agility (Tilman & Jacoby, 2019)

The key requirements from Table 5 will also be applicable for the adoption of AM where the provisioning systems become part of the integrated network or ecosystem. However, in future, customers will become more involved in the provisioning systems as providers of key information and real-time feedback of products. They can even become local manufacturers (Strange & Zucchella, 2017). The involvement of more role players in the provisioning ecosystem will also require a redesign of the provisioning system (D'Aveni, 2015). Satisfaction of the customer doesnot lead anymore to only fulfil the customer’s primary needs but to provide secondary services around the goods themselves, which will not be achievable within the old business models (Sisca *et al*., 2016). The focus will have to shift from pure product supply to the supply of value-added services (Ford & Despreisse, 2016). Figure 7 is a representation of the difference between the traditional spare part provisioning system and the AM provisioning system.

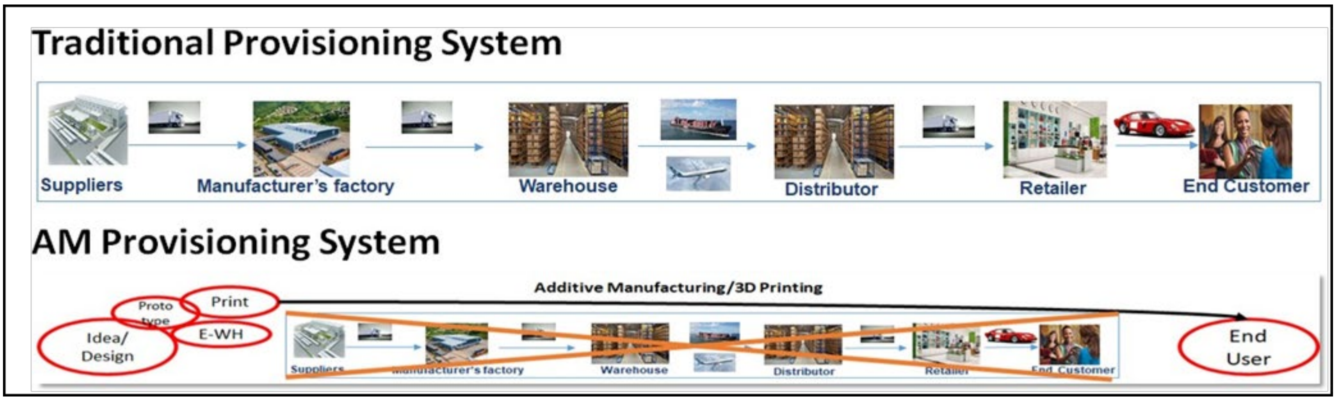

Figure 7: Traditional vs AM provisioning system (author).

The AM provisioning system is significantly shorter and reduces the lead time of delivering orders to the end customer (Campbell & Ivanova, 2013). Naghshineh and Carvalho (2020) contemplate that AM will require (1) agility, (2) flexibility and (3) resilience as part of the provisioning system capabilities as well as 4) fast product and process reconfiguration in both volume and design to address the ever-changing consumer demands and innovation requirements for 4IR (Camarinha-Matos *et al*., 2019). Ismail *et al*. (2014) argue that adaptability and agility will increasingly conceal size, as shown in Figure 7, and this will require a transition from linear structures and strategies to systemic and non-linear structures and strategies. Brettel *et al*. (2014) indicate that linking the knowledge and participation of non-linear networks together can lead to a sustainable advantage but pose an increase in risks.

Traditional, linear risk management practices will not be enough to manage risks in a dynamic, agile ecosystem where AM is adopted (Ismail *et al*., 2014; Naghshineh & Carvalho, 2020).

2.7 Adoption of AM

AM has predominantly been used for prototyping in the automotive, aircraft and medical sectors (Schwab, 2016). Recently, end users started to use AM to replace spare parts (Rylands *et al*., 2016). The Collins Dictionary (2018, online) defines a spare part as "duplicate or replacement component for a machine or other equipment". The adoption of AM for spare part provisioning is lacking due to the uncertainty to manage the business risks involved when adopting a disruptive new technology for spare part production (Oberg *et al*., 2018). A lack of a systemic understanding of the key business risks can also be a contributing factor to the slow adoption of AM (Roos & Fusco, 2014).

The adoption of a disruptive technology can also lead to disruptive innovation that will require a paradigm shift in the organisation (Ismail *et al*., 2014). In *The Innovator's Dilemma*, by Harvard professor Clayton M. Christensen, the theory of disruptive innovation is discussed. The theory explains the phenomenon by which an innovation transforms an existing market or sector by introducing simplicity, convenience, accessibility and affordability where complication and high cost are the status quo. Initially, a disruptive innovation is formed in a niche market that may appear unattractive or inconsequential to industry incumbents, but eventually the new product or idea completely redefines the industry (Christensen, 1997; Stapleton & Pande, 2016). Although AM can add significant value as a disruptive technology in the replacement of spare parts, the adoption of AM in spare part provisioning remains slow (Heinen & Hoberg, 2019).

Sisca *et al*. (2016) reason that AM can only be deployed successfully in organisations when employees, designers and managers would reach the appropriate maturity level to understand and contemplate the disruptive nature of AM. The adoption of AM will require new business skills and this notion can be daunting to the employees of an organization that can lead to resistance to change (Christensen, 2000). A disruptive technology can be seen as inconsistent with the existing values, needs and past experiences of potential adopters (Rogers, 2003) Straubb (2009) suggested that technology adoption is a complex, inherently social, developmental process and that to successfully facilitate technology adoption organisations must address cognitive, emotional and contextual concerns (Straub, 2009).

In a study on the adoption of AM in a developing economy one of the key factors relating to the low adoption of AM is the lack of knowledge regarding the impact of the technology (Marak, et al., 2018). This attributes to the resistance to change and slow adoption of disruptive technologies (Christensen, 2000) Lawrence (1969) provides five key factors that can improve the resistance to change when adopting a new technology:

a. Employees must be involved, participate and understand the required change

b. Understanding the real reason for the resistance where in most instances the resistance is not on a technical level but on a social level

c. Resolve the pre-occupation that participants have regarding the new technology by creating a visual map of the impact of the change.

d. Emphasising the evolutionary requirements from the current status to the new to be status

e. Buy in and involvement of leadership to lead in a constructive way and to proof their buy-in.

Resistance is not always negative since resistance to change can point out to managers areas where a proper change process was not followed or where the five factors that Lawrence (1969) states as important to overcome resistance to change have not been adequately addressed (Pardo-del-Val & Martinez-Fuentes, 2003)

Patel & Connely (2007) indicated that the culture of an organisation plays a vital role in the adoption of new technologies where the culture will determine the propensity for risk of the organisation. It is important to examine the factors that influence adoption of innovation in order to create an improved understanding of the factors responsible for technology adoption. (Patel & Connolly, 2007). Rogers (1995) explains that adoption of innovation as a time consuming process and the rate at which diffusion of innovation occurs becomes significant for organisations that are concerned with adoption of innovation. Butler (2002) states that in the right circumstances adoption of new technologies by an organisation will spread by diffusion. The rate of adoption is affected by many factors that includes the innovation's characteristics and various sociological, organizational, and psychological variables. Understanding the rate of adoption in any given scenario will require an analysis of all the factors that may facilitate the adoption and those that may operate as barriers to adoption (Butler & Sellbom, 2002)

Industry standards to produce AM components are also immature (Thomas-Seale *et al*., 2018). Kim *et al*. (2017) indicate that one of the areas that requires substantial improvement is the repeatability of components (Ituarte *et al*., 2017). Because of the magnitude of AM, users see the adoption process as complex, and this notion slows down the adoption (Gress & Kalafsky, 2015; Schumacher *et al*., 2016). The systemic nature of AM also requires organisational and process improvements as well as process redesign (Jung*et al*., 2016). The impact of AM on sustainability in terms of the sources of innovation, business models and the configuration of the provisioning system is not well understood (Ford & Despreisse, 2016). AM will also necessitate new business models that will be based on service design, value co-creation, strong networks and on economy of scope rather than on the traditional concepts of centralisation and economy of scale (Kai *et al*., 2016; Sisca *et al*., 2016). The adoptionof AM will also require an adjustment of current business paradigms (Ford & Despreisse, 2016). Ons of the new paradigms will require manufacturing to move away from mass production in large factories with dedicated expensive tooling to a world of mass customisation and distributed manufacturing in distributed locations (Kai *et al*., 2016; Sisca *et al*., 2016)

The adoption of AM will have an impact on the manufacturing, organisational and maintenance strategies of the organisation (Dey & Sharma, 2018).The direct production of parts through AM directly from CAD models offers benefits from conventional manufacturing. Additional advantages include flexibility and customisation (Weller, *et al.,* 2015). Mass customisation is a significant change from the mass production paradigm with economic order quantity and low levels of complexity as the grounding principles (Dey & Sharma, 2018).

The dimensions of organisational structure as suggested by Pugh *et al* (1968) consists of standardisation, specialisation, cenralisation formalisation, complexity and workflow. Organisations adopting AM will have to adjust their organizational structures and mix of attributes depending on their status on the maturity evolution of adopting AM (Dey & Sharma, 2018) Organisations will have to increase their propensity for failure and adopt a learning culture where exploration becomes part of the culture. In the Fifth Discipline, Senge (1990) described learning organisations as “places where people continually expand their capacity to create results, they truly desire, where new and expansive patterns of thinking is nurtured, where collective aspiration is set free, and where people are continually learning how to learn together"

Senge (1990) suggested five technologies to achieve learning organisations:

a. Systems thinking

b. Personal mastery

c. Mental models (paradigms)

d. Shared vision

e. Team learning

In a study by Garvin (1993) the author compiled a list of five traits that will be required for a successful learning organisation. Table 8 is a comparison between Senge (1990) and Garvin (1993) and the requirements for the adoption of AM from Rogers (1995). The author has added the elements from table (6) The attributes that affect the rate of innovation adoption.

Table 8: Summary of Senge (1990), Garvin (1993) and Innovation adoption Rogers (1995).

Senge (1990)	Garvin (1993)	Rogers (1995)
Systems thinking	Systemic problem solving	Relative advantage
Personal mastery	Experimentation	Trialability
Mental model paradigms	Learn from past experience	Complexity
Shares vision	Learning from others	Compatibility
Team learning	Transferring knowledge	Observability

From table 8 it is important to see that Systems Thinking and Systemic problem-solving assist in an improved understanding of the relative advantage of a technology. Personal mastery and experimentation can be described as activities to experiment and trialability is defined by Rogers (1995) as “the degree to which an innovation may be experimented with on a limited basis”. Metal model paradigms and learning from past experience can assist in defining the perceived complexity paradigm of the new technology. Shared vision and learning from others can only be achieved when there is a compatibility with the new technology. Team learning and transferring of knowledge leads to observability that is defined by Rogers (1993) as” the degree to which the results of an innovation are visible to the others”. To adopt an innovative technology will require a true learning culture in the organisation and a significant paradigm shift.

According to Gavin (1993), organisational learning develops in three overlapping stages. The first stage is where members of the organisation is exposed to new ideas, expand their knowledge and to begin to think differently than before on a cognitive level. This leads to a behavioral change where participants alter their behavior and start to adopt the new technology. During the third stage, adoption of the technology can now lead to new creative ideas and process improvement. (Garvin, 1993).

Nonaka (1991) characterised knowledge-creating companies as places where “inventing new knowledge is not a specialised activity, it is a way of behaving, indeed, a way of being, in which everyone is a knowledge worker.” Garvin (1993) states that better tools are required to assess an organisation’s rate and level of learning and sustainability of the organisation. Knowledge is an important influence on sustainability. Sustainability is how AM supports the circular economy of manufacturing spare parts through recycling, minimising waste at production or when the components are discarded. The ideas of the circular economy are (1) elimination of waste by design, (2) respect for the social, economic and natural environment and (3) resource-conscious business conduct (Sariatli, 2017). Sustainability is further impacted through AM by the extension of the life span of equipment called end-of-life (EOL) management. Equipment manufacturers discontinue equipment and replace the equipment with new or upgraded equipment. Spare parts for the old equipment are discontinued and the equipment must be replaced, which leads to an increase in inventory and redundant stock (Knofius *et al*., 2019).

AM can have a positive impact on the provisioning system integration where the integration takes place through (1) inventory optimisation, (2) integration into production systems and (3) ecosystem integration. This will reduce the working capital and inventory of the organisation (Delic *et al*., 2019; Naghshineh & Carvalho, 2020). Part of the inventory optimisation is that batch sizes are reduced to only one item instead of economy of scale where economic batch sizes had to be produced in the past (Khajavi *et al*., 2013). Obsolete parts will be reduced since only the required parts will be manufactured. This is contrary to economy of scale production where a minimum economic order quantity must be produced (Ford & Despreisse, 2016). Delic *et al*. (2019) postulate that real value creation in a business comes from the interaction between the different provisioning systems in the global ecosystem. This requires a systemic view of the business. One of the systemic requirements of AM is to manage the total cost of ownership (TCO) and not only a localised view of the lowest cost (Thomas-Seale *et al*., 2018).

The adoption of AM will impact the skills required by an organisation (Bongomin *et al*., 2019). Roitman and Shanks (2016) state that in the future manufacturing skills will be replaced by design skills, requiring knowledge of DfAM. The lack of design skills inhibits the unlocking of some of the important benefits of AM, such as part consolidation and weight reduction (Ford & Despreisse, 2016). Kai *et al*. (2016) indicate that AM will have a significant effect on the organisation's design and system dynamics or the culture of the organisation (Bongomin *et al*., 2019; Camarinha-Matos *et al*., 2019). Bailey (1993) proposes that a change in an organisation's technology will influence both its operational and administrative structures.

Schniederjans (2017) states that the lack of proper tools to evaluate and visualise the factors that impact AM is one of the key reasons why there is a slow adoption of AM for spare part provisioning. Several researchers are also requesting a roadmap that will aid in the successful implementation and leverage of AM in manufacturing and spare part provisioning (de Carolis *et al*., 2017; Jirsak & Brunet-Thornton, 2019; Roos & Fusco, 2014).

The adoption of AM as part of the spare part provisioning system, will not only disrupt the business or the eco-system but also requires fundamental new ways of operating and managing business risks and complexity and new paradigms are needed. Normal business processes can become business risks if the systemic relationship between the different processes are not well defined and understood. Participation in the global eco-system, will introduce complexity in the organisation that will require innovative and creative solutions. Both risk management and the provisioning system needs to transcend from a linear system with a functional view to a non-linear system with a systemic view. Systems Thinking can assist organisations to create an understanding of the true value that AM can deliver by eliminating the fear for complexity and to see risk as an opportunity as well as the relationship between the different role players.

Figure 8 is a summary from Mellor (2016) of the model that they propose for adoption of AM. This model indicates the integrated nature of the different activities when embarking on the adoption of AM for spare part provisioning.

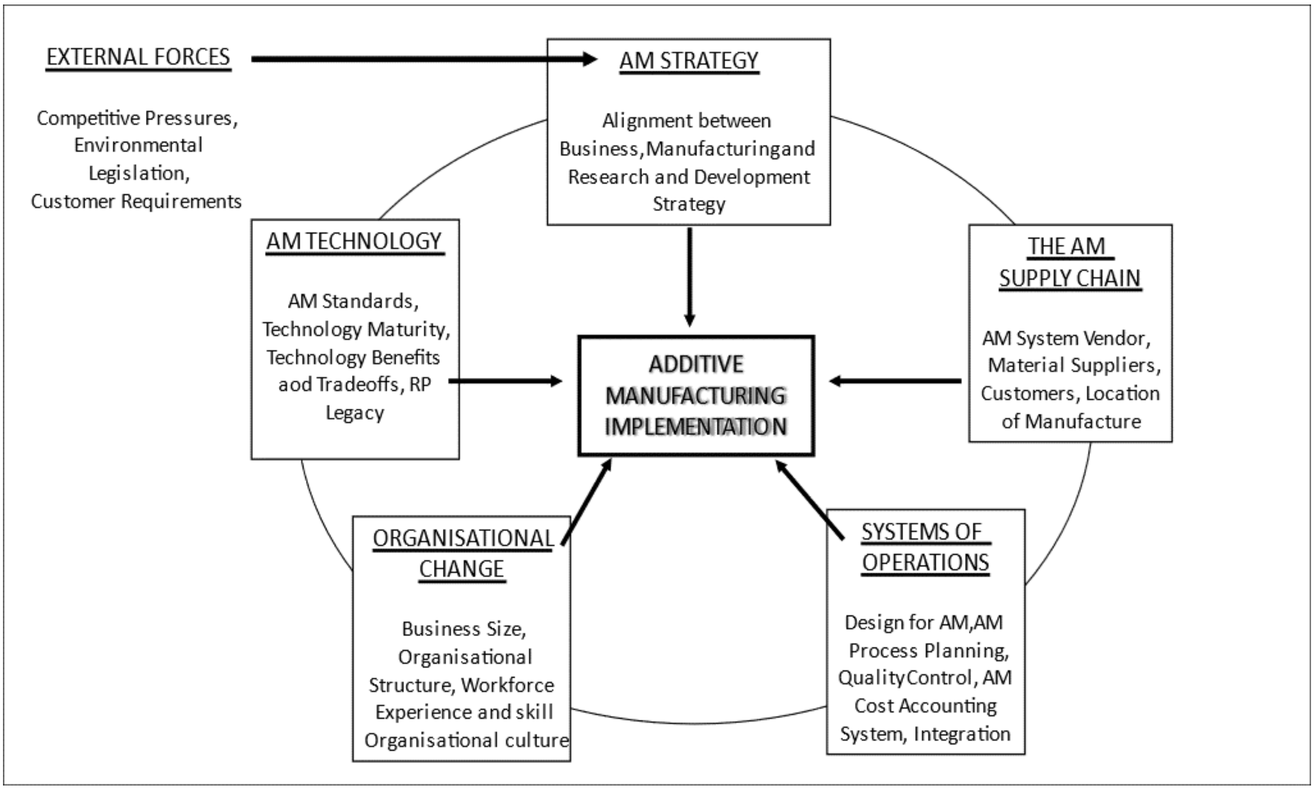

Figure 8:Model for AM adoption (Mellor et al., 2016)

The model in figure 8 indicates the interaction of the different entities upon each other and that all these concepts need to be taken into account when a company embarks on the adoption of AM. This integrated nature can create uncertainty and risks that requires a level of understanding and knowledge. Dynamic capabilities of an organization govern how the organisation integrates, builds, and reconfigure internal and external competencies to address changing business environments and risk (Teece, *et al.*, 2016). This will be a very important component of success when participating in the global ecosystem where there are many unknown role players that participate on different levels in the ecosystem. When risk can be defined, it can be managed but when risk becomes uncertainty that needs to be managed, the organization requires a certain level of agility and maturity when entering into the unknown arena of disruptive technology adoption (Teece, *et al.,* 2016). Disruptive technologies disrupt existing markets and position themselves far ahead of existing market trends and affect three of the major domains i.e. product, process and supply chain (Dey & Sharma, 2018)

Dynamic capabilities require from the organization to be adaptable and agile in the way that it define and create new business models in a changing environment as organisations are experiencing during IR4 and the proliferation of disruptive technologies. Teece *et al.* (2016) states that dynamic capabilities define the organisations capacity to innovate, adapt to change, and create change that is favorable to customers and unfavorable to competitors and adds to organisational agility.

The resources in the organization needs to be defined as part of the dynamic capabilities of the organization and the value that the resources can add in a dynamic agile environment where uncertainty needs to be managed and understood. It is therefore important to explore the resource-based view of the organization not only internally but also as part of the wider ecosystem (Holdford, 2018). The resource based theory of competitive advantage argue that the long term success of any business innovation is based upon the internal resources of the firm offering it, the firm's capabilities in using those resources to develop a competitive advantage over competing options, and the innovations contribution to financial performance of a firm in a market (Holdford, 2018). The success of adopting AM innovation is also based on the knowledge of the key resources regarding the materials and how innovative designs can utilize the benefits of AM to create business value in the ecosystem (Weller, et al., 2015). The differentiating factor is that AM requires less resources but more highly skilled, creative resources (Dey & Sharma, 2018) Therefore the adoption of AM will require different skills in the organization that enhances the dynamics capabilities of the organization as part of the larger ecosystem. According to a study by Dey (2018), an important factor contributing to the slow adoption of AM is the lack of a different organizational strategy and structure. This contest to the fact that AM is not only a new technology but a disruptive strategic intervention spanning across the organization and the eco-system.

This section answers research question 1.4:

What are the barriers to the adoption of AM in spare part provisioning?

2.8 Research design

The following section contains the theoretical foundation of the research design chosen for this study. The choice of research style, strategy and data collection methods and procedures are explained in this section by adopting the research paradigm of design science research (DSR) as an umbrella paradigm for this study.

Research design refers to the plan to which a study is executed (Mouton, 2001). It refers to all the planning involved regarding the study as well as all the decisions that the researcher had to make to answer the research questions as effectively and efficiently as possible. The researchers'decisions and actions as well as the research questions determine to a certain extent the type of design that will be followed for this study (de Vos *et al*., 2005).

Mouton (2001) developed a framework of three worlds that creates the foundation for this research and forms an integral part of design science research.

2.8.1 The three-worlds frameworkMouton (2001) developed a framework of three "worlds" or "frames" to describe the interaction between real life problems and scientific research (see Figure 9).

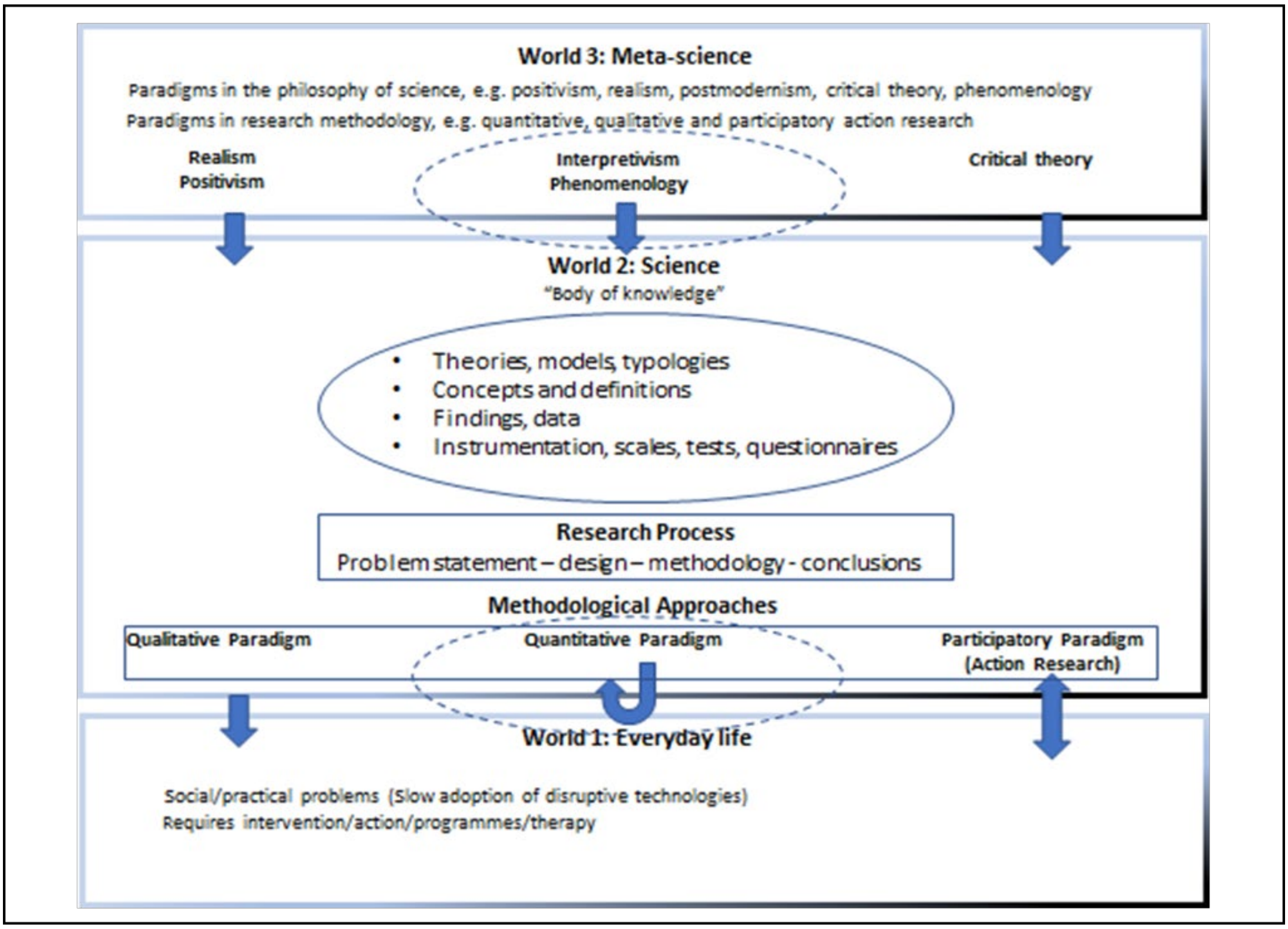

Figure 9:The three-worlds framework adopted from Mouton (2001)

World 1 (W1) is the world of everyday life and practical knowledge. World 2 (W2) is the world of science and scientific research and world 3 (W3) is the world of meta-science. Phenomena from W1 are selected and subjected to rigorous and systematic enquiry in W2. W3 is the world of meta-science and it reflects on the paradigms in the philosophy and methodology of science. In other words, all empirical, scientific inquiry begins with a movement from W1 to W2 and is subject to a design paradigm from W3.

There should be synergy between W1, W2 and W3 since an organisation does not only function in W1 and W2 but integrates all three worlds as indicated in Figure 9.

2.8.2 Selection of a qualitative research style for the study

According to de Vos *et al*. (2005), qualitative research honours an inductive style where data from W1 is analysed to find new meaning and it focuses to understand the complexity of a situation creating innovative new artefacts. Considering that AM is a disruptive, innovative strategy that requires adoption in a complex business environment, a qualitative research strategy will be the most appropriate research style to explore and link to design science research.

2.8.3 Design science research

2.8.3.1 Design science Design science has its roots in engineering and is predominantly a problem-solving paradigm that seeks to create innovative and creative artefacts (Hevner *et al*., 2004; Peffers *et al*., 2008). Holmström *et al*. (2009) state that action researchers are not content with merely explaining and perhaps prescribing but indeed shaping the phenomenon of interest. Design science can be defined as research that seeks (1) to explore new alternatives to solve problems, (2) to explain the explorative process and (3) to improve the problem-solving process (Hevner *et al*., 2004).

Lawrence *et al*. (2010) argue that design science has the potential to empower the user if the user (1) can fully participate, (2) the culture surrounding the newly created artefact is fully understood and considered when creating the artefact and that (3) the content must be designed through the eyes of the subject, i.e. the context and role players where the phenomenon under investigation exists (Sein *et al*., 2007).

Design science research pursues the underlying truth in a phenomenon and relies on two paradigms. The first paradigm is the behavioural science paradigm that tries to find “what is true”regarding this research, the reasons for the slow adoption, and in contrast the design science paradigm that seeks to create “what is effective” (Hevner *et al*., 2004). The design science paradigm is a pro-active, innovative paradigm and the behavioral science paradigm is a reactive paradigm focusing on what causes the phenomenon (Hevner *et al*., 2004).

Hevner *et al*. (2004) prepared a design science research guideline to ensure that there is a structured methodology to conduct design science research (see Table 9). The research design of this study will be validated against this guideline.

Table 9:Design science research guidelines (Hevner et al., 2004).

Design science research guideline	
Guideline	**Description**
Guideline 1: Design as an artefact	Design science research must produce a viable artefact in the form of a construct, a model, a method or an instantiation.
Guideline 2: Problem relevance	The objective of design science research is to develop technology-based solutions to important and relevant business problems.
Guideline 3: Design evaluation	The utility, quality and efficacy of a design artefact must be rigorously demonstrated via well-executed evaluation methods.
Guideline 4: Research contributions	Effective design science research must provide clear and verifiable contributions in the areas of the design artefact, design foundation and/or design methodologies.
Guideline 5: Research rigor	Design science research relies upon the application of rigorous methods in both the construction and evaluation of the design artefact.
Guideline 6: Design as a search process	The research for an effective artefact requires utilising available means to reach desired ends while satisfying laws in the problem environment.
Guideline 7: Communication of research	Design science research must be presented effectively both to technology-oriented as well as management-oriented audiences.

The design science guideline of Hevner (2004) in Table 9 was critiqued for the absence of action research (AR) components since action research aims to contribute to both the practical concerns of people in an immediate problematic situation and to the goals of social science by collaboration within a mutually acceptable, ethical framework (Livari & Venable, 2007). Although some researchers contemplated AR is the same as DSR (Jarvinen, 2007), other researchers argued DSR and AR have similarities, but yet they are not the same (Jarvinen, 2007; Livari & Venable, 2007). To accommodate the contextual requirements of AR with DSR, Hevner (2007) proposed a three-cycle model of design science, as indicated in Figure 10.

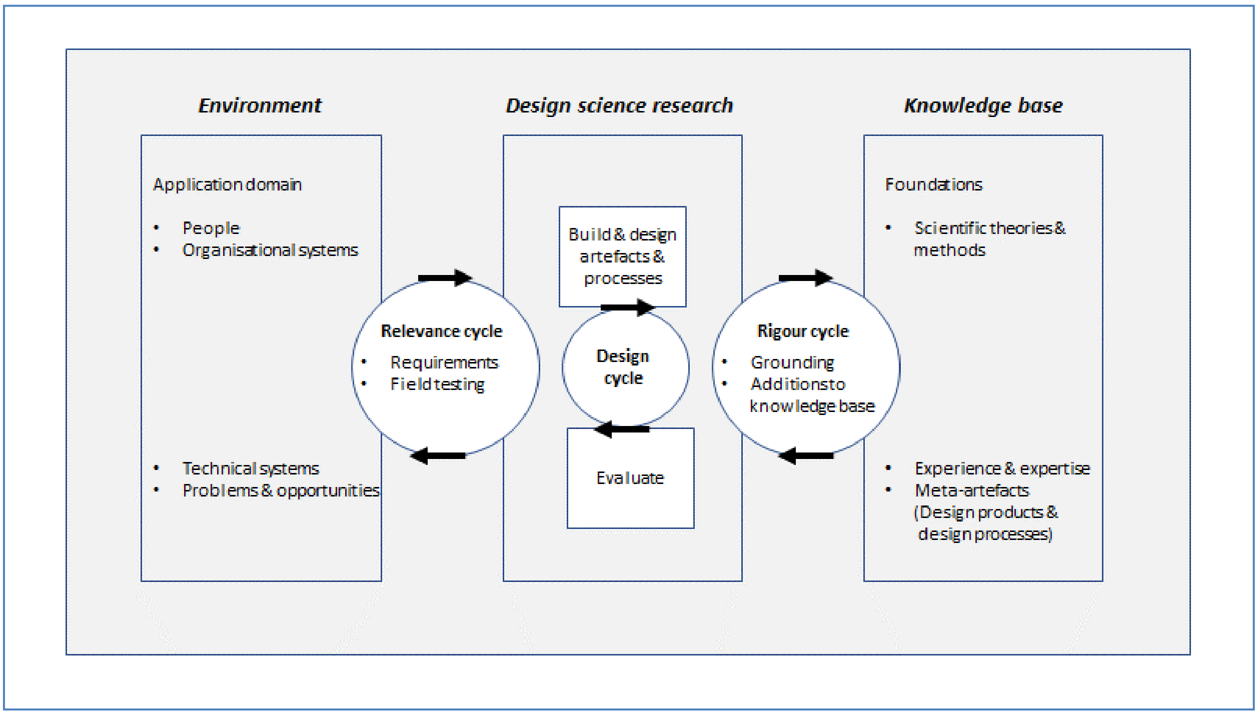

Figure 10: Design science research framework (Hevner, 2007)

Hevner's (2007) model in Figure 10 combines behavior science and design science.The three research cycles can be defined as follow:

Relevance cycle	Bridges the contextual environment of the research project with the design science activities.
Design cycle	Iterates between the activities of building and evaluates the design artefacts and processes of the research
Rigour cycle	Connects the design science activities with the knowledge base of scientific foundations, experience and expertise that informs the research project.

It is the synergy between relevance and rigour and the contributions along both the relevance cycle and the rigour cycle that define good design science research (Hevner, 2007). Sein *et al*. (2011) state that the relevance challenge for researchers requires a research method that explicitly recognises that artefacts should be shaped by the interests, values and assumptions of a wide variety of participants from the internal and external communities while learning from the intervention when addressing a problematic situation (Hevner *et al*., 2004). Sein *et al*. (2011) further argue that traditional design science does not fully recognise the role of the organizational context in shaping the design and the deployed artefact. Designing an artefact is an emergent process and the context plays a vital role in the design process (Sein *et al*., 2007).

De Figueiredo and Cunha (2007) argued that rigour without relevance becomes meaningless and that AR and DSR complement each other. Production of knowledge moves from a linear innovation model in an explanations-oriented world to a networked/systemic innovation model in a solutions-oriented world. The practice of design in engineering and industry and the practice ofresearch in academies are getting closer and closer. The linear world of knowledge creation, DSR and the non-linear world of real applications, AR cannot be separated and should be practiced together (de Figueiredo & Cunha, 2007).

Sein *et al*. (2011) proposed a solution for a new research method for DR that draws on AR and suggested to call it action design research (ADR). ADR stresses the influence of the relevance cycle by providing explicit guidance for combining building, intervention and evaluation in a concerted research effort.

2.8.3.2 Action design research (ADR)

ADR will accommodate designers, building and organisational stakeholders shaping a single definition, softening the distinction between development and context assumed in dominant DR thinking (Sein *et al*., 2011). ADR represents a variant of DSR that allows organizational influences on the design and evolution of the designed artefact, emphasising concurrent building, intervention and evaluation as an alternative to the stage gate model (Haj-Bolouri *et al*., 2018).

ADR cannot be a linear process as proposed by some of the stage gate models designed for DSR (Sein *et al*., 2011). ADR stresses the influence of the relevance cycle, as depicted in Figure 10, by providing explicit guidance for combining building, intervention and evaluation in a concerted research effort (Hevner, 2007). Since ADR focusses on ensemble artefacts, it deals with certain critical issues.

(a) Evaluation efforts cannot follow building in a sequence as suggested in prior stagegate models of DR (Sein *et al*., 2011).

(b) Controlled evaluation efforts are difficult to design and to conduct.

Innovation must be defined for the class of systems typified by the constructed artefact. The different components of the proposed ADR model are presented in Figure 11 and discussed below.

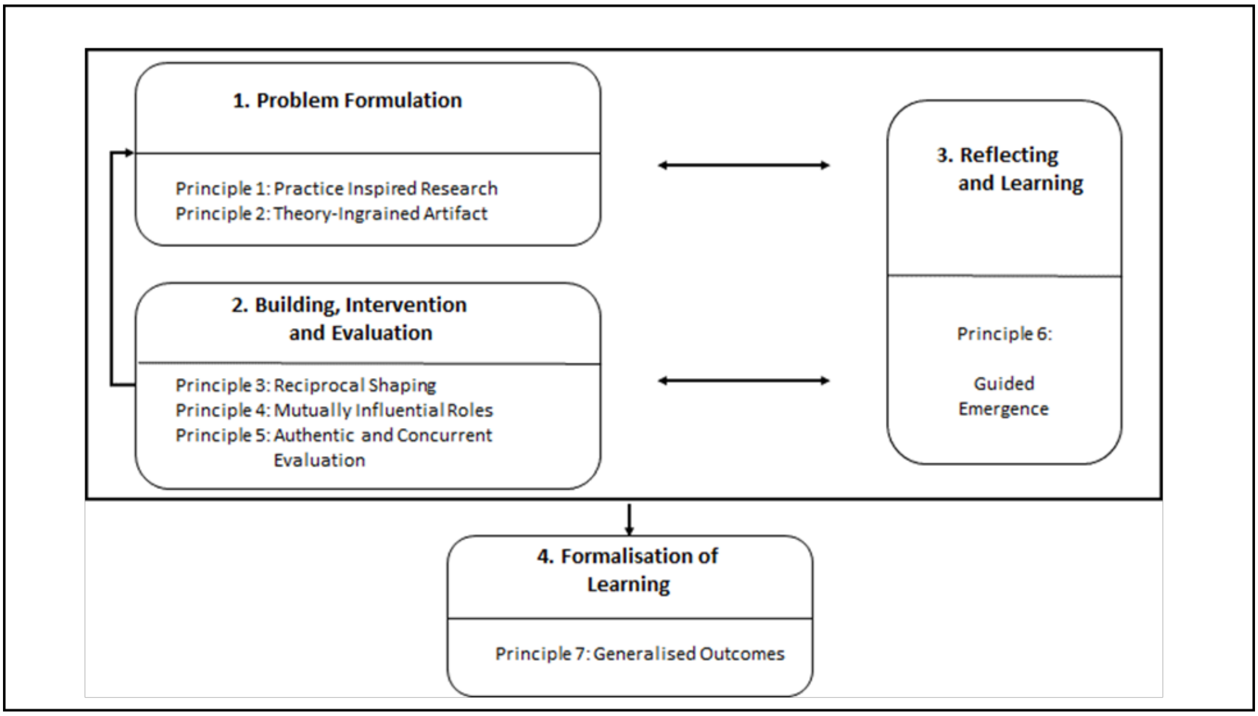

Figure 11:ADR method of Sein et al. (2011).

(a) Stage 1 – Problem formulation

This stage is initiated by a problem perceived in practice or anticipated by researchers (Sein *etal*., 2011).

- **Principle 1**: Practice-inspired research

  Field problems should be viewed as knowledge-creating opportunities.

- **Principle 2**: Theory-ingrained artefact

  The created artefact should be informed by theory.

(b) Stage 2 – Building, intervention and evaluation

This stage uses the defined problem and theoretical premises adopted in stage 1. These premises provide a platform for generating the initial design of the artefact, which is further shaped by organisational use and subsequent design cycles (Sein *et al*., 2011). This stage is carried out as an iterative process in a target environment and interweaves the building of the artefact (B), intervention in the organisation (I) and evaluation (E), (BIE). Sein *et al*. (2011) proposed an iterative process design of an artefact, as shown Figure 12.

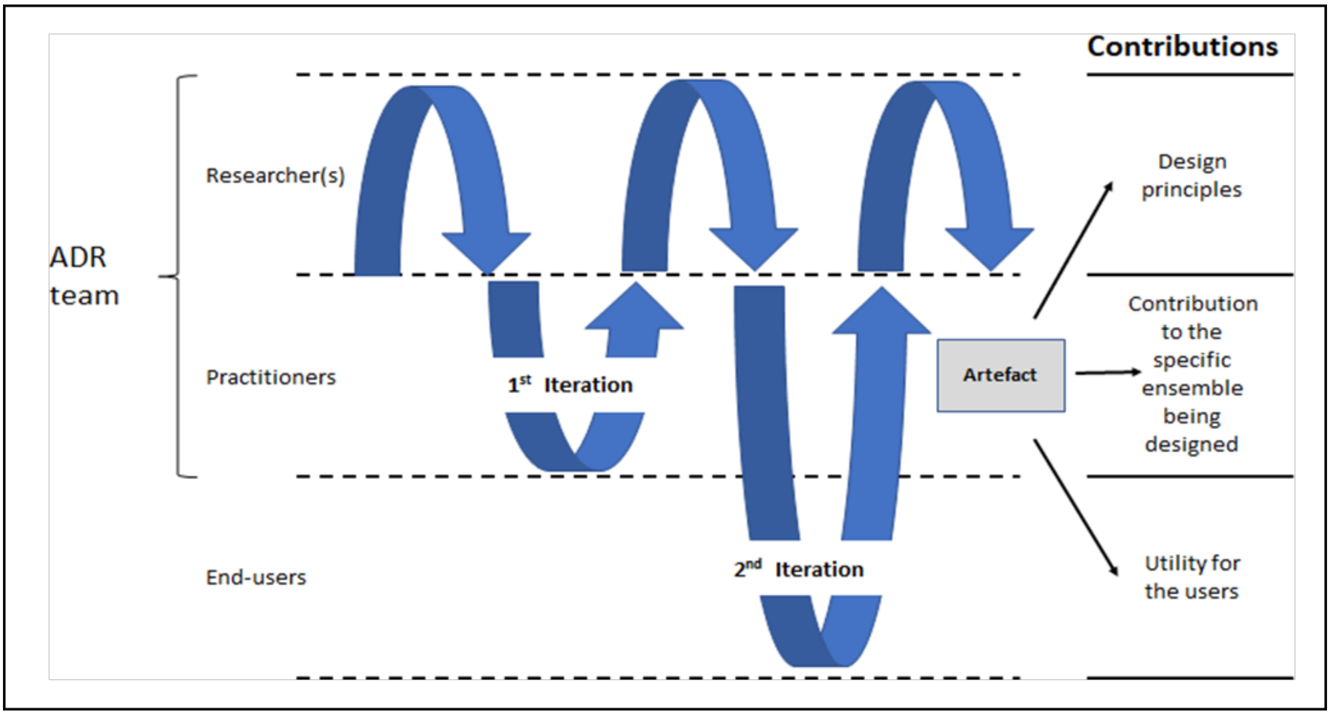

Figure 12 : Iterative process of artefact design (Sein et al., 2011)

During the iterative stages, the problem and the artefact are continually evaluated, and the design principles articulated. The locus of innovation is also clarified that can come from the artefact design or the organisational intervention (Sein *et al*., 2011).

- **Principle 3**: Reciprocal shaping

  This principle emphasises the inseparable mutual forces of the artefact design and the organisational context.

- **Principle 4**: Mutually influential roles

  The notion of this principle is to emphasise the importance of mutual learning among the different team members from all dissimilar role players. Cronholm *et al*. (2016) stipulate that the culture of the different role players needs to be accommodated as an activity influencing the completeness of the design.

- **Principle 5:** Authentic and concurrent evaluation

  This principle emphasises that evaluation is not a separate stage of the research process that follows the building process but should rather form part of the building process.

(c) Stage 3 – Reflection and learning

The reflection and learning stage applies the knowledge gained during the building process to other processes as well and recognises that the research process involves more than simply solving a problem. It is important to adjust the research process early in the research stage as and when new knowledge is gained and adjustment might be required to improve the outcome (Sein *et al*., 2011).

- **Principle 6** – Guided emergence

  This principle emphasises the importance of an evolutionary process where the outcome of the artefact will continuously be shaped by the design inputs and the organisational inputs. Since thisthesis is also based on an evolutionary concept, it is important that this aspect forms part of the design process.

  Haj-Bolouri *et al*. (2018) indicated in their research regarding ADR that reflection and learning throughout the ADR project seemed to be difficult to achieve amongst practitioners of ADR.

(d) Stage 4 - Formalisation of learning

The purpose of the final stage is to formalise the learning. The learning should be developed into a general solution concept and the accomplishments should be shared. ADR supports knowledge creation through the design and appreciation of ensemble artefacts.

- **Principle 7** – Generalised outcomes

  Due to the integrated nature of the project between the design and the organisational requirements, some change management will be required when the new artefact is rolled out and implemented. This implies the move from the specific-and-unique to generic-and-abstract and this is a critical component of ADR (Sein *et al*., 2011)

There are several key requirements that emphasise the importance of ADR:

(a) ADR requires a DR contribution in the form of design principles

(b) These principles should address a class of problems

(c) The outcome should be innovative

Haj-Bolouri *et al*. (2018) indicate that ADR should provide tools for researchers to apply their knowledge to solve real-world problems, therefore W1 problems, and generate new scientific knowledge that is highly applicable. Cronholm *et al*. (2016) argue that ADR is designed for a single organisational context and suggest that an extension of ADR is required to cover a multi- organisational context with entry points at different phases of the design.

2.8.3.3 Elaborated action design research (eADR)

Mullarkey and Hevner (2015) contend that ADR tends to suggest a single DSR entry point focused on an existing artefact using an action research cycle from problem formulation (Stage 1) to build,intervene and evaluate (BIE, stage 2), see Figure 13. However, in some research, there might not be an artefact in the problem domain and ADR must be applied at any other point in the DSR process (Mullarkey & Hevner, 2015).

Therefore, Mullarkey and Hevner (2015) suggest an elaborated action design research (eADR) method that compliments the work of Pfeffers *et al*. (2007) and Sein *et al*. (2011).

In the ADR model of Sein *et al*. (2011), see Figure 13, the problem formulation stage consisted of two principles, i.e. practice-inspired research and theory-ingrained artefacts, and required the execution of four tasks to complete, assuming the presence of an artefact. However, when thereis no artefact, another point of entry might be required. Further research by Mullarkey and Hevner (2015) also revealed the requirement to separate the problem definition stage into a problem diagnosing (PD) and a concept design (CD) stage. This emphasises the importance of these two stages prior to the building and implementation of an innovative artefact (Mullarkey & Hevner, 2015).

Mullarkey and Hevner (2015) indicated that it is important for ADR to start with a PD stage informed by theory as well as an expressed need in practice after which the CD stage starts with a rigorous evaluation of design principles and features. These two additional stages are essential to ensure a fully elaborated design emerges. Once this is completed, then only can the build stage of the artefact start (Mullarkey & Hevner, 2015). Intervention (I), evaluation (E) and learning (L) should also happen in every phase of the ADR method. This allows the researcher to include the organisational setting in every stage of the artefact (Mullarkey & Hevner, 2015), as displayed in Figure 13.

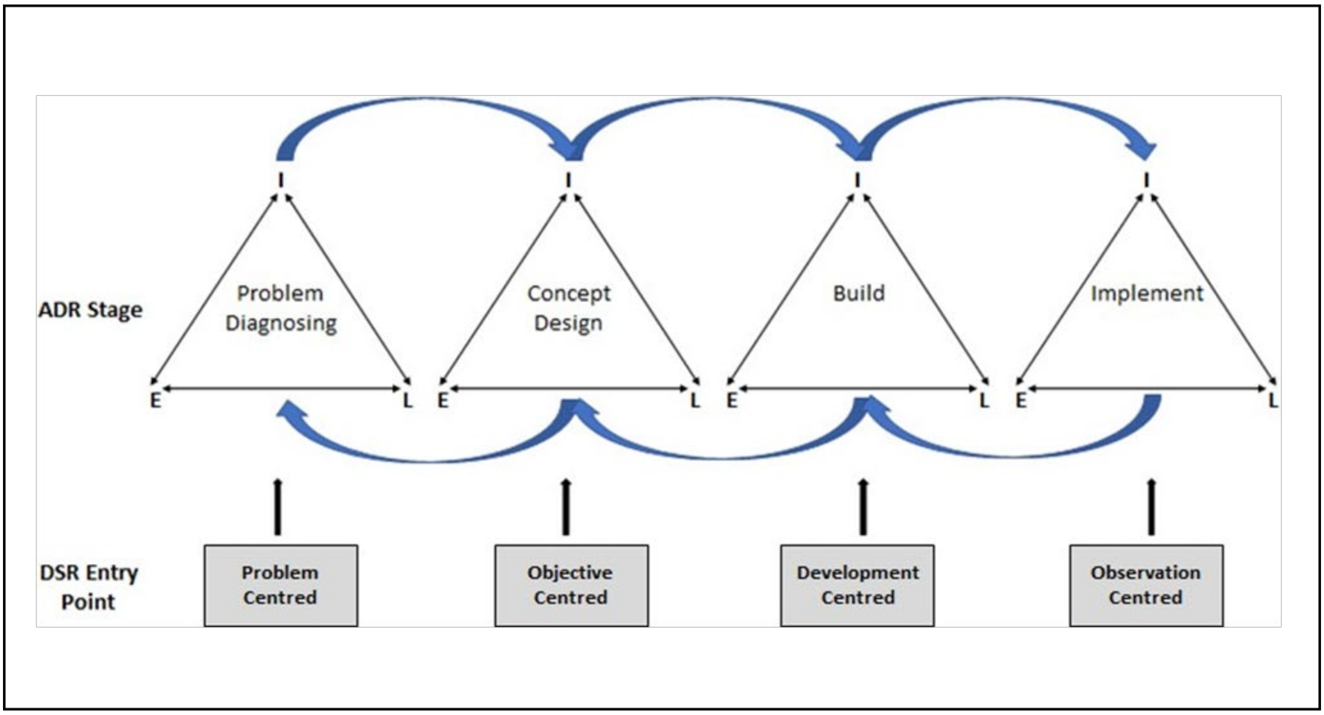

Figure 12:Elaborated ADR (eADR) method identifying DSR entry points (Mullarkey & Hevner, 2015)

Mullarkey and Hevner (2015) reported that by adding the additional stages to the ADR model, as shown in Figure 13, they believe that for any problem class and innovation the research point of entry could occur at any of the stages in an ADR investigation and that innovative artefacts should emerge from the interaction between researchers and practitioners by being allowed to ask many more fundamental research questions. This process will then assist researchers to design innovative artefacts in complex, evolutionary business environments (Mullarkey & Hevner, 2015).

Because of the novel status and perceived complexity of AM, data will have to be collected from multiple sources. Triangulation facilitates the validation of data through cross-verification from more than two sources. The evolutionary business environment might also require the possibility to develop a new theory and that requires the use of grounded theory to construct new concepts.Data can be collected in various forms and two of the methods to structure the unstructured data for interpretation are thematic analysis and triangulation.

2.8.4 Thematic analysis

Thematic analysis is the process of identifying patterns or themes within qualitative data (Maquire & Delahunt, 2017). It is a very flexible method that is not tied to a specific methodology. This allows the researcher to focus on interpreting and explaining the data and underlying ideas as well as assumptions (Maquire & Delahunt, 2017). A thematic analysis can be classified as a top-down or a bottom-up analysis. The top-down analysis is driven by the research question and the bottom-up analysis by the data itself (Braun & Clarke, 2006)

2.8.5 Triangulation

Triangulation involves the use of multiple sources of data to research a question. It tests the consistency of findings obtained through different instruments. Triangulation is not just about validation but about deepening and widening the understanding of the data (Heale & Forbes, 2013). Cohen and Manion (2000) define triangulation as an attempt to map out, or explain more fully, the richness and complexity of human behavior by studying it from more than one standpoint.

Denzin (1973) proposes four basic types of triangulation:

- Data triangulation involves time, space and persons and validates the credibility of information from different sources.
- Investigator triangulation involves more than one theoretical scheme in the interpretation of the phenomenon.
- Theory triangulation uses more than one theoretical scheme in the interpretation of the phenomenon.
- Methodological triangulation uses more than one option to gather data, such as interviews, observations, questionnaires and documents.

2.8.6 Abductive reasoning

Abductive reasoning can be described as a creative process of producing new theories-based research evidence. Researchers progress from old to new insights based on the observation that the phenomenon is related to other observations through a cause-and-effect relationship that is hidden from the view. The researchers' own experiences play an important role in the abductive reasoning process. This process is an iterative process and supports the formulation of groundedtheory (Tavoy & Timmermans, 2012). Teece (2016) states that abductive reasoning and imaginative hypothesis building need to kick into gear when there is deep uncertainty about the future.

2.8.7 Grounded theory

Grounded theory is a qualitative research method where data is collected to develop the theory rather than to test or refine an existing theory (Creswell, 2013). The theory is developed based on reciprocal phases of qualitative data collection, where each phase builds on the next phase, constituting an evolutionary process (Walliman, 2011). Grounded theories are constructed through the researcher's past and present involvements and interactions with people, perspectives and research practices (Charmaz, 2014). In grounded theory, the data is organised, and labels are attached to construct themes that can be used for the construction of the new concepts. The data for the grounded theory originates in W1 from the model of Mouton *et al*. (2001) where the phenomenon exists.

Unlike quantitative inquiry approaches, grounded theory does not begin with an existing theory, but rather generates a specific substantive or formal theory through an iterative process involving various information sources (Tavakol *et al*., 2006). Substantive theory is grounded in data on a specific substantive or empirical area of investigation (Glaser & Strauss, 1967). Grounded theory complements other qualitative research methods rather than it stands in opposition to them and provides a structured process to construct a novel theory from different sets of data (Charmaz, 2014). Figure 14 is a graphical presentation of the data inputs and the formation of the groundedtheory method.

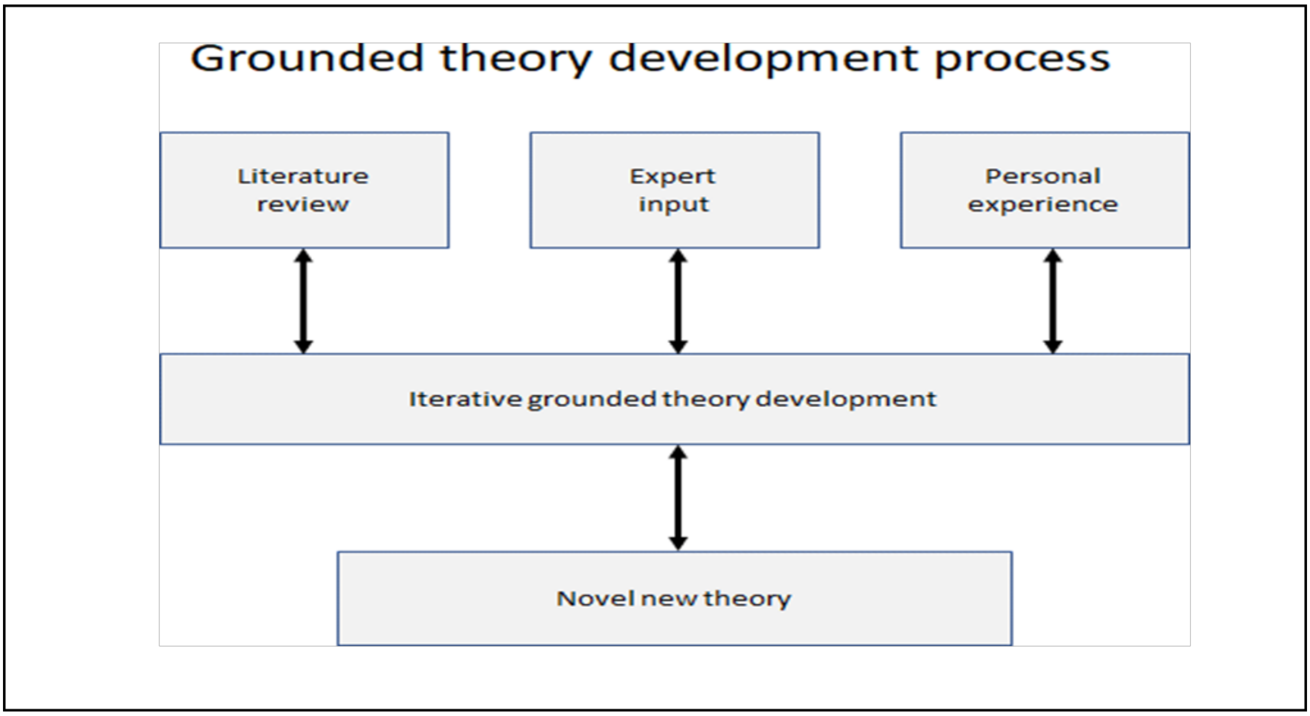

Figure 13:Grounded theory development process (Charmaz, 2014).

2.8.8 Maturity models

The purpose of this thesis is to find or develop an innovative artefact with an evolutionary nature.A maturity model is an innovative and creative artefact. The development of maturity models is viewed as a matter of design science research by some researchers (Becker *et al*., 2009; Mettler& Rohner, 2009;

Pöppelbuβ & Röglinger, 2011). Design science research seeks to create innovative and creative artefacts that are useful for coping with human and organisational challenges (Hevner *et al*., 2004).

Based on the assumption of predictable patterns of evolution and change, maturity models usually include a sequence of levels (or stages/maturity levels) that together form an anticipated, desired or logical path from an initial state to maturity (Becker *et al*., 2009). The development of the maturity levels for a maturity model requires an evolutionary process and grounded theory supports the evolutionary development of new theory concepts (Charmaz, 2014). The design principles and structure of the maturity model will be discussed in chapters 6 and 7.

According to Xavier *et al*. (2020), maturity modelling is a generic approach that describes the development of an organisation over time through defined levels to a final state. It describes an improvement process where organisations can obtain new capabilities that will eventually lead to a more mature organisation. The key value of a maturity model is that an organization can capture the current perception towards the current state and then define an improvement plan or roadmap going forward. Pfeffers and Sutton (1999) also agree that the purpose of maturity models is to identify a gap between the actual and the anticipated business model, which needs to be closedby succeeding activities.

Xavier *et al*. (2020) state that maturity models can provide holistic support for a transformation project. A maturity model conceptually represents phases of increasing qualitative or quantitative capability changes of a maturing element to assess its advances with respect to defined focus areas (Kohlegger *et al*., 2009). Blondiau *et al*. (2013) argue that maturity models are recognized tools for the stepwise and systematic development and/or improvement of skills, processes, structures or general conditions of an organisation and can therefore be used to assist with the adoption of novel ideas. Becker *et al*. (2009) define maturity models as "artefacts which serve to solve the problems of determining a company's status quo of its capabilities and delivering measures for improvement there from".

Pöppelbuβ and Röglinger (2009) indicate that, based on the assumption of predictable patterns,maturity models basically represent theories about how organisational capabilities evolve in a stage-by-stage manner along an anticipated, desired or logical maturation path. King andKraemer (1984) postulate that maturity models should not focus on a sequence of levels toward a pre-defined end state, but on factors driving evolution and change.

The roots of maturity models started in the software engineering arena, where it was used to guide and monitor the maturity of software development practices (Blondiau *et al*., 2013). The popularity of maturity models was intensified by the introduction of the CMM in early 1990. CMM has been criticised for its over-reliance on organisational processes and its disregard for people's capabilities (Bach, 1994). This led to the development of the CMMI that integrated three different maturity models and focused more on integrating different business processes (Mahmood, 2016).The CMMI forms the basis for many maturity models and assists in the enterprise-wide process improvement.

Hundreds of different maturity models have since been designed and constructed for different domains that include typical classes such as people, processes, persons and social systems (deBruin *et al*., 2005; Kohlegger *et al*., 2009; Pöppelbuβ & Röglinger, 2011; Wendler, 2012). Maturitymodels are typically used for representing theories of stage-based evolution and therefore their basic purpose consists in describing stages and maturation paths (Pöppelbuβ & Röglinger, 2011).Many of the maturity models do not describe how to effectively manage the steps defined in the gap between the current state and the desired state (Mettler & Rohner, 2009).

2.8.8.1 Definition of maturity The *Oxford Dictionary* (Simpson and Weiner, 1989) defines maturity as the state of being complete, perfect or ready. Mettler (2011) states that maturity implies an evolutionary progress in the demonstration of a specific ability or in the accomplishment of a target from the initial stage to the desired end stage. Maturity is a measure of how well the organisation can manage self- improvement. Kohlegger *et al*. (2009) define capabilities as aspects of reality.

According to Maier *et al*. (2009), the concept of maturity can be divided in the following categories:

(a) Process maturity: The concept of process maturity stems from total quality management (TQM), where the application of statistical process control techniques showed that improving maturity of any technical and business process ideally leads to a reduction in variability inherent in the process and therefore an improvement in the mean performance of the process.

(b) Organisational maturity: Through the widely adopted capability maturity model (CMM) for the improvement of a software development process, the concept of process maturity migrated to a measure of organisational maturity. Integral to CMM is the concept that organisations advance through a series of stages. These stages describe an evolutionary path from the initial stage to a matured, final stage.

(c) Process capability: Rather than measuring organisational capability with a single value, ISO/IEC 15504 measures process capability directly and organisational capability with a process capability profile. Capability maturity model integration (CMMI) combines both organisational maturity and process capability. Project maturity: Because software is developed through projects, it is natural that the concept of organisational maturity would migrate from software development processes to project management, and that has been reflected in an interest in applying the concept of maturity to project management.

(d) Maturity of organisational capabilities: Capabilities represent the ability of an organisation to use resources, get things done and behave in ways leading to accomplishments (Ulrich & Smallwood, 2003). Organisational capabilities can be defined as the collective skills, abilities and expertise of an organisation and refer to design, innovation, project management, knowledge management, collaborations and leadership (Ulrich & Smallwood, 2003). Organisations can be viewed as a set ofcapabilities, which are the skill sets that provide an organisation with its competitive edge (Ulrich & Smallwood, 2003).

2.8.8.2 Domains of maturity models

Table 10 is a summary of the application-specific domains distinguished by the following authors (Becker *et al*., 2009; de Bruin *et al*., 2005; Maier *et al*., 2009).

Table 10:Application specific domains of maturity models (author's own creation).

Domain	Description
Descriptive	The maturity model is applied for as-is assessments where the current capabilities of the entity under investigation are assessed regarding given criteria (Becker *et al*., 2009) The maturity model is used as a diagnostic tool (Maier *et al*., 2009) The assigned maturity levels can be reported to internal and external stakeholders (Pöppelbuβ & Röglinger, 2011) This model is used as a single point encounter (de Bruin *et al*., 2005)
Prescriptive	The maturity model indicates how to identify desirable maturity levels and provides guidelines on improvement measures (Becker *et al*., 2009) Specific and detailed actions are suggested (Maier *et al*., 2009) A prescriptive model provides emphasis on the domain relationships to business performance and indicates how to approach maturity improvement to positively affect business value, therefore enabling the development of a roadmap for improvement (de Bruin *et al*., 2005)
Comparative	The model is used for internal or external benchmarking. Given enough historical data from many assessment participants, the maturity levels of similar business units and organisations can be compared (de Bruin *et al*., 2005; Maier *et al*., 2009)

De Bruin *et al*. (2005) argue that although these model types can be seen as distinct, they represent evolutionary phases of a model's lifecycle.

2.8.8.3 Maturity models versus maturity grids

Maier *et al*. (2009) indicate that the differentiation between maturity grids and maturity models can be difficult. While they are complementary improvement frameworks with several similarities, key distinctions can be made with respect to the work orientation, mode of assessment and the intent. Table 11 is a comparison between maturity models and maturity grids.

Table 11:Difference between maturity model and maturity grid (Maier et al., 2009).

	Maturity model	**Maturity grid**
Work orientation	Identifies the best practices for specific processes and evaluates the maturity of an organisation in terms of how many of these practices it has implemented	Applies to companies in any industry and does not specify how a particular process should look like. They identify the characteristics that any process and every enterprise should have to design and deploy high-performance processes
Mode of assessment	Uses Likert or binary yes/no-based questionnaires and checklists to enable assessment of performance	Structures around a matrix or grid. Levels of maturity are allocated against key aspects of performance or key activities, thereby creating a series of cells. Descriptive text is provided in the cells for the characteristic traits of performance at each level
Intent	Follows standard format, is internationally recognised and can be used for certification of performance	Less complex and does not aspire for certification. Guides on improvement required to reach a certain end goal

2.8.8.4 Cross-domain comparison of maturity models

Maier *et al*. (2009) request as part of the construction of a new maturity model to compare between existing maturity models and the intended new design (Wendler, 2012). According to deBruin *et al*. (2005), more than 150 new models have been developed across different domains. Some of these models overlap with existing models and that dilutes the value of the models, showing that these models are developed from unsuitable foundations.

(a) Some of the cross-functional studies intended to aid the development of maturity models are: Becker *et al*. (2009) – compared six maturity models for information technology management and suggested a procedural model for their development.

(b) Kohlegger *et al*. (2009) – did a qualitative content analysis of 16 maturity models.

(c) De Bruin *et al*. (2009) – presented a cross-domain review of two maturity models forknowledge management and for business process management.

The purpose of these cross-domain maturity model comparisons is to try and find a guideline thatcan be followed when new maturity models or grids are developed.

2.8.8.5 Top-down vs bottom-up design methodologies

Maturity models can be designed by either using a top-down or a bottom-up approach. When using a top-down approach, the focus is on developing the maturity levels and then define the dimensions or focus areas. Once this is completed, the evolutionary elements are developed through practical experience or literature research. The top-down development always represents a fixed number of maturity levels (Becker *et al*., 2009). The top-down approach is more applicable when the maturity model is applied to a relatively new research field where there is little evidence on what constitutes maturity. The emphasis is first on what constitutes maturity and then on how it can be measured (Maier *et al*., 2009).

A bottom-up approach implies that the dimensions are defined first and then the maturity levels. Each dimension can have a different maturity level (van Steenbergen *et al*., 2010).

2.8.8.6 Key components of a maturity model

A maturity model as an artefact often takes on the form containing the following components as illustrated in Figure 15.

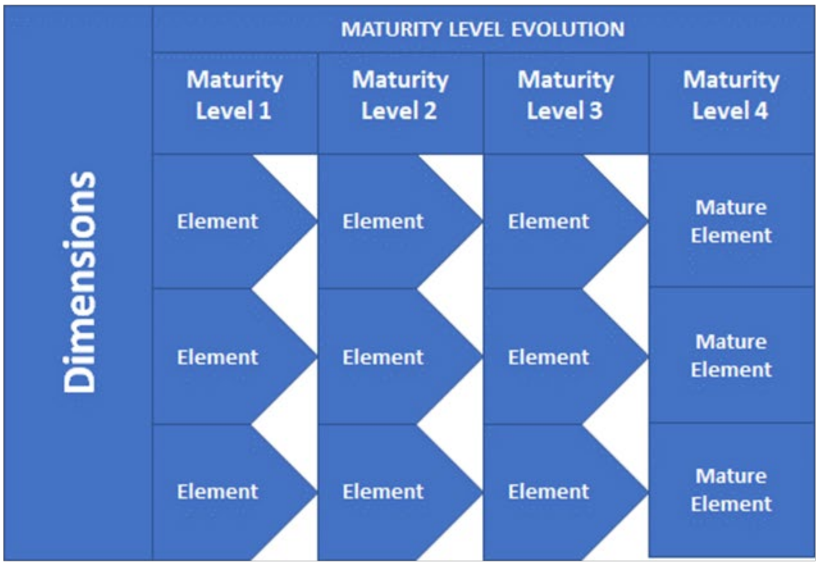

Figure 14:Components of a maturity model.

A -A scale that describes maturity levels or stages

B- Dimensions that represent areas of application of a domain

C -Elements defining the different evolutionary stages

2.8.8.6.1 Maturity level

Maturity levels need to be distinct, well defined and show a logical progression as clear definition (Maier *et al*., 2009). Each level must be identified by a concise descriptor (Fraser *et al*., 2002). The rationale behind maturation needs to be disclosed by means of the logical relationship between successive levels (Pöppelbuβ & Röglinger, 2011).

The decision on the rationale for the maturity level indicates the leverage point for organisational change (Fraser *et al*., 2002). Mettler (2011) also states that when defining the levels of maturity for a domain, a trade-off between the state of an innovation's uncertainty and its actual diffusion (which assists in predicting whether and how an innovation will be successful) must be considered to guarantee useful applications. According to Becker *et al*. (2009), maturity levels can vary between four to six and need to be evolutionary in nature.

2.8.8.6.2 Dimensions

Dimensions must be mutually exclusive and collectively exhaustive. The dimensions should be generated from traceable principles of good practice. The selection of dimensions provides an insight into the author's conceptualisation of the field. The conceptual framework underlying the assessment method determines the scope of the assessment (Maier *et al*., 2009). Dimensions can be derived from experience, literature reviews or interviews with experts in the field (Maier *etal*., 2009).

2.8.8.6.3 Elements

The elements create the intersection between the maturity level and the dimensions. According to Maier *et al*. (2009), the identification and formulation of behavioural characteristics for capabilities or processes is one of the most important steps in developing a maturity model. Maier*et al*. (2009) indicate that there are several options available to formulate the text descriptions in each cell in the element matrix:

(a) By synthesising viewpoints from a sample representing the future recipients of the assessment.

(b) By reviewing or comparing practices from several organisations, for example through empirical studies, and a review of written case studies in literature and best practices from various sources.

In an innovative research field, the text descriptions can be designed by taking the description that constitutes the lowest maturity level and the highest maturity level and then formulating the evolutionary maturity levels in between (Maier *et al*., 2009). The key determinant in formulating the element text is to decide if the model is going to be a descriptive or prescriptive model (Maier*et al*., 2009). There should be coherence (systematic or logical connection) amongst all the elements in the model (Becker *et al*., 2009).

2.8.9 Design specification for a maturity model

Wendler (2012) states that maturity models are not only applicable to the information systems domain where it originated but have expanded to a plethora of different domains. The development of maturity models incorporates elements of design science research (Becker *et al*.,2009; Mettler & Rohner, 2009). Design science research pursues to create innovative artefacts that are useful for coping with human and organisational challenges (Hevner *et al*., 2004). Action design research (ADR) is used for generating prescriptive design knowledge through building and evaluating artefacts in an organisational setting (Sein *et al*., 2011).

De Bruin *et al*. (2005) developed a generic framework consisting of six steps that can be used across multiple disciplines. Table 12 summarises the phases of a maturity model development as outlined by de Bruin *et al*. (2005).

Table 12:Summary of maturity model development as proposed by de Bruin et al. (2005)

Model Phase	**Description**
Scope	The combination of scoping decisions will influence all the other phases of the maturity model. During this phase, the focus of the model and development stakeholders are decided.
Design	The architecture for the model is determined that includes the selection of the audience, the method of application, the driver of the application, the respondents, the application and the maturity stages. This phase addresses why the audience seeks the model, how the model can be applied to various organisational structures, who needs to be involved in applying the model and what can be achieved through application of the model.
Populate	In this phase it is necessary to identify what needs to be measured in the model and how it can be measured. This can be achieved through literature reviews, focused groups, interviews, questionnaires and personal experience.
Test	Once the model is populated, it needs to be tested for relevance and rigour. Depending on thescope, this phase needs to be conducted with multiple industries and organisations.
Deploy	Following population and testing, the model must be made available for use and to verify the extent of the model's use and acceptance.
Maintain	The goal of the model significantly impacts the resources necessary to maintain the model's growth and use. A prescriptive model requires resources to track the evolution of the model longitudinally.

Maier *et al*. (2009) developed a model for maturity grid design. Figure 16 is a comparison between the model of de Bruin *et al*. (2005) and Maier *et al*. (2009).

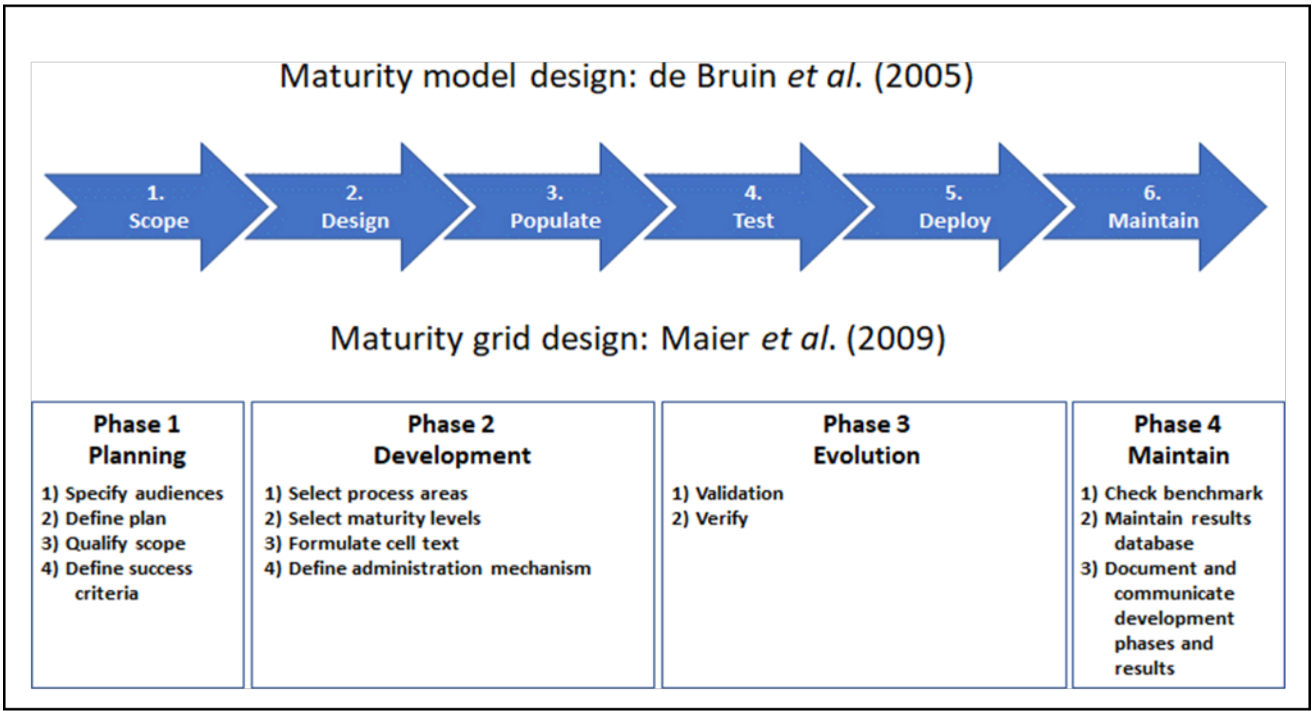

Figure 15: Comparison of maturity model and maturity grid design phases of de Bruin et al., (2005) and Maier et al. (2009).

Both the models of de Bruin *et al*. (2005) and Maier *et al*. (2009) cover the same key requirements for the development of a maturity model. The model of Maier *et al*. (2009) elaborates more on the detailed steps for the maturity grid development.

Becker *et al*. (2009) suggested a methodology for the design of maturity models that is based on design science guidelines for information systems research (Hevner *et al*., 2004). Since the methodological foundation of this research is elaborated action design research (eADR) and is presented in chapter 2, the design of the maturity model for the research will use the methodology of Becker *et al*. (2009) as a basis. eADR allows researchers to create novel artefacts considering the organisational setting in the development and improvement of the artefact through multiple iteration stages.

Becker *et al*. (2009) linked the requirements for the design of a maturity model to the design science guidelines proposed by Hevner *et al*. (2004). The letter “R” represents the requirementsin Table 13. Refer Table 9 for design science guidelines.

Table 13:Maturity model requirements extracted from Becker et al. (2009).

Design science guidelines		Maturity model requirements
1.	Design as an artefact	R1: comparison with existing maturity models
2.	Problem relevance	R5: identification of problem relevance R6: problem definition
3.	Design evaluation	R3: evaluation
4.	Research contributions	R1: comparison with existing maturity models
5.	Research rigour	R4: multi-methodological procedures
6.	Design as a search process	R2: iterative procedure R3: evaluation
7.	Communication of research	R7: targeted presentation of the results R8: scientific documentation

The model that Mettler (2011) proposes for the design of maturity models is also based on design science principles. Mettler contemplates that when the model design is based on a highly innovative phenomenon, the resultant model is rather an artefact than a theory. When using design science research, the developer will search for solution patterns for important unsolved problems or giving advice in solving problems in more effective and efficient ways (Hevner *et al*.,2004). Wendler (2012) indicates in his research on maturity models that the design science paradigm delivers a useful contribution for developing maturity models.

The aim of this research is to develop a maturity model that can assist in the adoption of AM in spare part provisioning, and it is based on the eADR method that uses multiple iterations at different entering points. According to Wendler (2012), maturity models should be based on an iterative process grounded in design science. Table 14 is a comparison between the design models of de Bruin *et al*. (2005), Maier *et al*. (2009), Becker *et al*. (2009) and Mettler (2011).

Table 14:Comparison between maturity model design of de Bruin et al. (2005), Maier et al. (2009), Becker et al. (2009) and Mettler (2011).

De Bruin *et al*.(2005)		**Maier *et al*. (2009)**		**Becker *et al*. (2009)**			**Mettler (2011)**
1	Scope	1	Planning	1	Define the problem	1	Define scope
2	Design	2	Development	2	Compare existing maturity models	2	Design model
3	Populate			3	Determine the design methodology		
				4	Develop MM with iterative method		
4	Test	3	Evaluation	5	Determine model communication and evaluation method	3	Evaluate design
5	Deploy			6	Deploy MM		
6	Maintain	4	Maintain	7	Assess the performance of the MM	4	Reflect evolution
				8	Withdraw MM if inadequate or obsolete		

All four models cover the same aspects for the design process of a maturity model. De Bruin *et al*. (2005) were the first to propose a structure for the design of a maturity model. Maier *et al*. (2009) based their model on a maturity grid. Becker *et al*. (2009) and Mettler (2011) based their models on DS principles.

From the comparison of the different proposed design methodologies for maturity models, Mettler(2011) suggested a framework for the development of maturity models. The framework that Mettler (2011) recommended can be divided in the following decision parameters during the development of a maturity model. See Table 15.

Table 15:Maturity model design framework adopted from Mettler (2011).

Phase	Decision parameter	Characteristics			
Definescope	Focus/breadth	General issue		Specific issue	
	Level of analysis/depth	Group decision-making	Organisational considerations	Inter-org considerations	Global and societal considerations
	Novelty	Emerging	Pacing	Disruptive	Mature
	Audience	Management-oriented	Technology-oriented		Both
	Dissemination	Open		Exclusive	
Design Model	Maturity definition	Process-focused	Object-focused	People-focused	Combination
	Goal function	One-dimensional		Multidimensional	
	Design process	Theory-driven	Practitioner-based		Combination
	Design product	Textual description of form	Textual description of form and function		Instantiation (assessment tool)
	Application method	Self-assessment	Third-party assisted		Certified professionals
	Respondents	Management	Staff	Business partners	Combination
Evaluate design	Subject of evaluation	Design process	Design product		Both
	Timeframe	Ex-ante	Ex-post		Both
	Evaluation method	Naturalistic		Artificial	

2.8.10 Delphi method

Okoli and Pawlowski (2004) state that the Delphi method is a versatile research tool. Linstone and Turnoff (1975) indicate that the Delphi method can be characterised as a method for structuring a group communication process so that the process is effective in allowing a group of individuals to deal with a complex problem.

The Delphi technique is an option for complex and intertwined subjects that cross over disciplinary boundaries (Grisham, 2009). Skulmoski and Hartman (2007) reason that the Delphi method is well suited as a research instrument when there is incomplete knowledge about a problem or phenomenon. Since the creation of a maturity model is an innovative artefact in a complex ecosystem environment like AM, the use of the Delphi method will support the verification and validation of the artefact. The Delphi method uses multiple iterations of the questionnaire to reach consensus. The different iterations will be discussed in chapter 8.

Okoli and Pawlowski (2004) state that one of the advantages of using the Delphi method is that it can lead to generalisability of the resulting theory since a Delphi study solicits information from experts who have a wide range of experience. By inquiring about their experiences and opinions, researchers significantly extend the empirical observations upon which the initial theory is based.This will add to the strength and grounding of the theory. Sarittas and Oner (2004) recommend a systems approach to the Delphi methodology. This means to take multiple perspectives, not only following the Delphi questionnaire, but also use additional tools like the qualitative feedback provided by the experts and personal experience.

2.8.11 Sampling

This study utilises the Delphi technique for data gathering and analysis. Therefore, a non- probability, purposive sampling method was used. Participants are selected for their knowledge regarding AM and the role that they play in the AM ecosystem in South Africa (Atkins *et al*., 2005;de Vos *et al*., 2005; Grisham, 2009; Hasson *et al*., 2000). Snowball sampling is the appropriate non-probability technique, which implies that the researcher will rely on the identified individuals to request participation from other knowledgeable members in the AM ecosystem and spare part community to participate in the research (Naderifar *et al*., 2017).

2.8.11.1 Size of sample

The size of the sample does not depend on statistical analysis but rather on the group dynamics for arriving at a consensus among the selected experts (Atkins *et al.*, 2005). Okoli and Pawlowski(2004) suggest that the optimal group should vary between three and eighteen for a Delphi study. Choosing more participants than the minimum will allow enough response in case of attrition, even though the participant drop-out tends to be very low when respondents have assured their participation (Okoli & Pawlowski, 2004).

2.8.11.2 Data collection method

The questionnaire that will be used will be constructed in Google forms and will be e-mailed to the selected experts. As part of the snowball process, they will be requested to forward the questionnaire to other experts to participate as well. The completion of the questionnaires will be electronic, using the internet. The purpose of only using an electronic platform is that it speeds up the turnaround time between questionnaires. Included as part of the questionnaire will be a short description of the maturity model and the reason for the development of the model.

No questionnaire should take more than 20 minutes to complete. The Delphi technique is a multistage process designed to combine opinion into group consensus and therefore the processcan be described as follows:

(a) Initial questionnaire – feedback solicited

(b) Initial feedback – after the statistical analysis of the initial opinions and answers to the questions

(c) Subsequent questionnaire – qualitative comments solicited again

(d) Subsequent feedback – after statistical analysis. This allows participants to change their opinions

Depending on the convergence of the expert feedback in the first round, the questionnaires might be contained to only one cycle (Grisham, 2009). Details on the Delphi technique will be discussed in chapter 8.

2.8.11.3 Recording of data

The data will be collected in the Google forms database as the participants complete the questionnaire. The data will be stored in an electronic version and will be password protected. All raw data will be stored for five years after the completion of the research, thereafter it will be permanently deleted.

2.8.11.4 Data analysis

Grisham (2009) suggests dividing the data analysis for the Delphi technique into three components.

(a) Data analysis – discovery of opinions

(b) Data analysis – process of determining the most important issues

(c) Data analysis – managing opinions

The data analysis for this research will be explained in chapter 9.

2.8.11.5 Strategies to ensure data quality and integrity

The Delphi technique removes the bias that is possible when diverse groups of experts meet since none of the experts know each other during the process (Grisham, 2009). Each expert will only be allowed to complete the questionnaire once in each consecutive iteration.

2.8.11.6 Reporting of data

The data will be transferred from the Google forms database to Microsoft Excel. After data analysis in Microsoft Excel, the feedback from the experts will be captured in tables and figures to determine what will be the content of the subsequent questionnaire. The final set of data will be reported as confirmation or suggestions to improve the model and if the model will satisfy the research opportunity and requirements.

2.8.12 Ethical considerations

The researcher aims to conduct an ethical research study and in doing so will abide by advice setout by de Vos *et al*. (2005) taking the following into consideration.

- **Avoidance of harm** – The researcher will do all in his power to ensure the safety of the participants during the study. If informal discussions are required, it will be conducted in a private, safe venue, such as a boardroom or office.
- **Voluntary participation** – It will be explained to all participants that the involvement in the study is strictly voluntary. Participants will be informed that they can withdraw from the research at any time.
- **Informed consent** – Informed consent will be part of the introduction section of the questionnaire. The questionnaires will be completed in the participants' own privacy.

- **Non-deception of subjects and/or respondents** – The research will not withhold and misrepresent information or mislead participants about context related to the research.

- **Non-violation of privacy/anonymity/confidentiality** – The researcher will always respect the privacy of all participants during the study and will not publish any confidential information provided by the participants. The researcher will password protect all data.

- **Compensation** – Participants will not be offered compensation for taking part in the research.

- **Debriefing of participants** – The surveys will not cover any topics that are traumatic andwill therefore not require any debriefing sessions afterwards.

- **Actions and competence of research** – The researcher will ensure that he is adequately skilled, honest and competent enough to undertake this research.

- **Publication of findings** – The researcher will cover all his findings in the publication of a PhD thesis. The researcher will ensure that all relevant findings are conveyed, and that no information is misrepresented or altered/adjusted for the publication.

- **Ethics committees** – The researcher will ensure that permission is obtained from the NWU-ENG-REC.

- **Professional code of ethics** – The research will adhere to the professional code of ethicsof the NWU and ECSA (Code of conduct) (ECSA, 2017).

This section answers research question 1.5:

What are the different methods that can be used to address the research problem?

2.9 Summary

The literature review in chapter 2 investigated the industrial revolutions with emphasis on the requirements for successful operation of a provisioning system in the 4IR. As part of this investigation the impact of the key technologies affecting the 4IR was researched and AM was indicated as the most disruptive technology of the key technologies. A requirement for operatingin the 4IR is an understanding of the global ecosystem and therefore an overview of players in the ecosystem had to be developed.

The literature review indicated that one of the key reasons for the slow adoption of AM as part of spare part provisioning was the lack of a roadmap or strategic guidance to assist organisations that are contemplating the adoption of AM as part of spare part provisioning. This chapter concluded with the methods used to design a solution for the research objective. Chapter 3 will elaborate on the detailed research design for this study.

CHAPTER 3: RESEARCH DESIGN

The structure of the research design is presented in this chapter.

3.1 Introduction

The study addresses the slow adoption of AM in spare part provisioning in South Africa by designing a business risk provisioning maturity model (BRPM[2]). The model will operate in W1 that forms part of everyday decision making (refer to paragraph 2.2.1). Research methods from W2 and theory development from W3 will be used to support the development of the final artefact (refer Figure 9) that will be placed back in W1 after verification and validation of the model for everyday use.

(De Beer, et al., 2016) confirms that AM is a new, emerging and disruptive manufacturing technology and is generally considered as one of the key technologies for manufacturing in the future of South Africa. AM brings a number of advantages to the manufacturer compared to the more traditional manufacturing technologies. Complex designs can be manufactured without the need for hard tooling, wastage of material is significantly reduced during the manufacturing process, and time to market can be drastically reduced since AM allows the rapid production of prototypes, tooling as well as final parts

In South Africa the uptake of the technology is rapidly growing. The first programmes in South Africa in AM started in the early 1990s with the acquisition of a rapid prototyping system by 3D Systems (Pty) Ltd in 1990 followed by two systems at the Council for Scientific and Industrial Research (CSIR) four years later. Uptake in the technology was initially slow, but since 2011 there has been a rapid escalation in the number of AM or 3D printing systems in South Africa. Research and development (R&D) competence in the technology has also grown, with very strong areas of expertise established in niche areas at several South African higher educational institutes, as well as at the CSIR (De Beer, et al., 2016).

A number of promising market applications have been identified for AM in South Africa. South Africa has abundant mineral reserves and is the world's second largest producer of Ilmenite and Rutile, from which Titanium (Ti) pigment is extracted. South Africa is also the second largest mining producer of Vanadium. Aluminium and Vanadium are key to titanium alloys used in the medical and dental implants and the aerospace manufacturing industries. These markets also require highly complex designs for parts, or parts that have to be customised, which provide an excellent opportunity for value addition through AM in these markets. The direct tooling market in South Africa amounts to an estimated R13 billion, with an additional R2 billion for maintenance and servicing. The tooling industry is an important industry segment; it supports key manufacturing sectors such as the automotive, aerospace, consumer goods, packaging and electronics sectors. AM has the potential to contribute to the rejuvenation of South Africa's tooling and foundry industries by introducing innovative technologies to improve tool performance, as well as time to market (De Beer, et al., 2016).

The South African Additive Manufacturing strategy of 2016, identified a number of key areas where AM has to focus for the future. These areas are (De Beer, *et al.*, 2016):

High priority opportunities:

(a) Production of medical devices and implants

(b) Production of parts for the aerospace industry

(c) Refurbishment of parts and tools for the automotive and other industries

(d) Impact on the local footwear industry through AM tooling and prototyping

(e) Raw material development for AM processes

(f) Development of high end AM systems, and

(g) Development of low-cost 3D printers

Medium priority opportunity:

(a) Production of prosthetics

(b) Production of crows and bridges for the dental industry

(c) Production of customized hearing aids

(d) Manufacture of jewellery, and

(e) Use of AM in the creative arts industry

Other opportunities which are currently considered as low priority areas for South Africa included the production of:

(a) Low-cost rocket engine combustion chambers

(b) Replacement parts for household appliances

(c) Replacement parts for old vehicles

(d) Customised packaging for the food industry

(e) Customised packaging for high tech products

(f) Architectural element

(g) Final parts for the automotive industry

(h) Pre-assembled robotic components

(i) Consumer goods e.g. cell phone covers, and

(j) 3D scanning and printing of archeological artefacts

From these priorities set as part of the South African Additive Manufacturing strategy, it is clear that spare part provisioning is not high on the agenda and therefore the importance to develop a model to enhance the adoption of AM for spare part provisioning in South Africa.

The BRPM^2 model is an innovative artefact and therefore design science research (DSR) was chosen as the problem-solving research paradigm.

Within the paradigm of DSR, elaborated action design research (eADR) was considered since it addresses two challenges:

(a) The real-world class of problems that should be resolved, i.e. the slow adoption of AMin spare part provisioning from world 1.

(b) Design of an innovative artefact, the BRPM^2 model, as opposed to the evaluation ofan existing artefact.

The eADR research method facilitates the use of different research phases. Figure 17 indicates that the entry point for the eADR method for this research design is at the problem diagnosing stage since a problem regarding the slow adoption of AM for spare part provisioning has been defined in chapter 1. After the problem diagnosing stage follows a concept design stage that will be concluded with a build stage where the final artefact will be designed and tested as a solutionto solve the research problem.

3.2 The elaborated action design (eADR) method

The eADR method allows for entry at any point in the ADR model (Mullarkey & Hevner, 2015). Each stage can consist of multiple phases and each phase can consist of multiple steps comprising a problem (P), evaluation (E), intervention (I) and a learning (L) step. The entry point at the problem diagnosing stage was utilised for this research (see Figure 17). The problem diagnosing stage (PDS) consists of five iterative phases (1–5).

In the PDS, grounded theory was used as an overarching method to assist in defining the theoryfor the complex problem of the low adoption of AM in spare part provisioning.

The learnings from the PDS and the grounded theories that were developed were used as the input for the concept design stage (CDS). The CDS contains three phases (6–8) with three artefacts that were used as input for the build stage (BS). The systematic and scientific design and development of these artefacts are described in the research papers contained in annexures A, B and C. The BS consists of the compilation of the design requirements for a maturity model stage (9) and the final artefact, the business risk provisioning maturity model (BRPM^2) stage (10). A Delphi study is used in BP2 to evaluate the rigour of the model as part of the eADR requirements in chapter 8. Figure 17 is a graphical representation of the different stages of the eADR method followed in this study.

The sections that follow elaborate on the detail of each stage of the research.

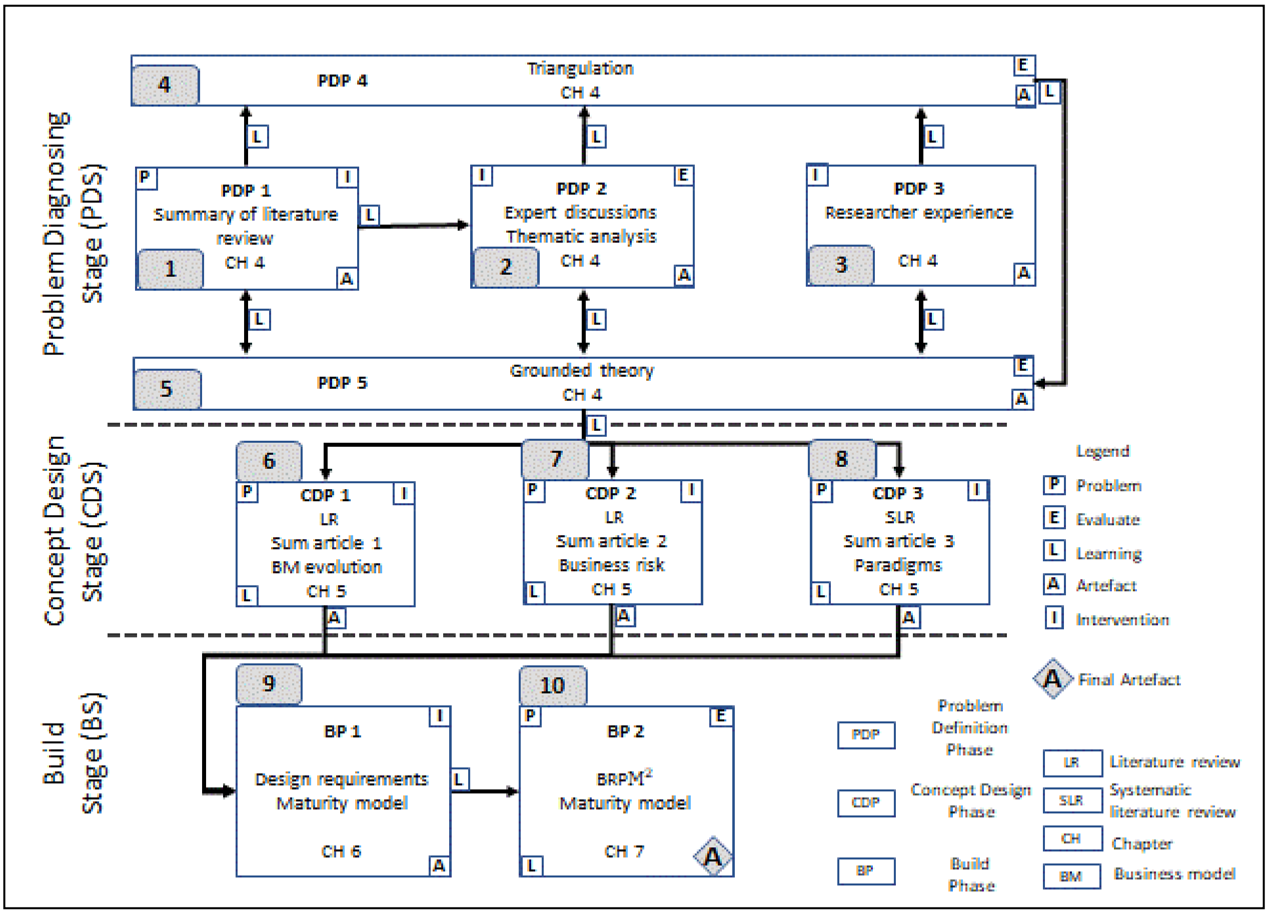

Figure 16: Different stages of the research design according to the e-ADR method

3.3 Problem diagnosing stage (PDS)

3.3.1 Literature Review (PDP 1) (1)

- **Problem definition** – The problem (as stated in chapter 1) is the slow adoption of AM inspare part provisioning in South Africa.

- **Intervention** – The literature review (see chapter 2) revealed several aspects that can contribute to the slow adoption rate of AM in spare part provisioning.

- **Artefact** – The list of codes from the literature review that can have an impact on the adoption of AM in spare part provisioning were summarised and this will be used as part of the triangulation in phase 4 of the PDS and will be discussed in detail in chapter 4.

- **Learning**
    - **as input to expert discussions** – The literature review summary of the themes influencing the adoption of AM in spare part provisioning were used to compile a list of discussion points with selected AM ecosystem participants in South-Africa (phase 2) to determine their view on the applicability of the themes from the literature review in the South African context.
    - **as input to grounded theory method** – The literature review themes were also used as input into the grounded theory method to formulate a new theory based on these inputs to solve a problem.

3.3.2 Expert discussions (PDP 2) (2)

- **Intervention** – The defined intervention was informal discussions with selected role players in the AM ecosystem in South Africa to determine the applicability of the literature review summarised aspects of the factors influencing the adoption of AM from the literature review (chapter 4).
- **Evaluation –** An informal list of discussion points was compiled based on the codes fromthe literature review to elicit feedback and input from selected participants. The feedback was compiled through a top-down thematic analysis that will be discussed in chapter 4.
- **Artefact** – The artefact for phase 2 is a summarised list of the feedback from the AM experts relating to the informal discussions grouped according to the discussion point.
- **Learning**
    - **as input to triangulation** – Valuable input was received from the selected AM experts regarding the themes defined in the literature review that impacts the slowadoption of AM and the applicability in the South African context. The feedback was summarised and used as input into the triangulation exercise.
    - **as input to grounded theory method** – The summarised feedback was also used as input into the grounded theory to formulate a new theory based on the inputs to solve a problem.

3.3.3 Researcher experience (PDP 3) (3)

- **Intervention** – The researcher’s own experience included various workshops and discussions with role players.

- **Artefact** – The researcher synthesised his own experience into codes regarding the findings from the literature and practical experience obtained during this research (chapter4).

- **Learning**

  - **as input to triangulation** – The experience of the researcher was used as an input to the triangulation exercise as part of the problem definition stage.

  - **as input to grounded theory method** – The experience of the researcher was also used as input to the grounded theory to formulate a new theory based on theexperience to assist in creating a solution to the problem.

3.3.4 Triangulation (PDP 4) (4)

As part of the PDS, triangulation is used as a research approach where the input from more thanone resource or method for data collection about a specific phenomenon is employed. The purpose is to compare the different inputs and thereby ensure the credibility of the output (Heale & Forbes, 2013).

- **Evaluation** – Codes from the literature review (1), expert discussions (2) and the researcher's own experience (3) were compared, and themes were constructed from the data (reported on in chapter 4).

- **Artefact** – The artefact for the triangulation is a verified list of codes based on the literature review, feedback from the informal discussions and the researcher's own experience grouped according to themes (chapter 4).

- **Learning**

  - **to grounded theory method** – The combined list from the triangulation exercise was also used as input to the grounded theory to formulate a new theory based on the inputs to solve a problem.

3.3.5 Grounded theory method (PDP 5) (5)

- **Evaluation** – The grounded theory method is a qualitative inquiry method that looks systematically at qualitative data aiming at the generation of an inductively derive theory that accounts for a pattern of behaviour that is relevant and problematic for those involved (Strauss & Corbin, 1998). Through grounded theory, the researcher developed explanations of key social processes that are grounded in empirical data (Glaser & Holton,2005).

The data collection for the grounded theory method consists of the following sources (Charmaz, 2014), see Figure 17.

(a) Literature review relating to the phenomenon – chapter 2

(b) Informal discussions with experts in the field – chapter 4

(c) Observations by the researcher – chapter 4

The construction of the grounded theory for this research will be discussed in chapter 4.

- **Artefact** – The artefact for phase 5 of the problem definition stage is a list of three grounded theories that will be used in the concept design stage.

- **Learning**

  - **to concept design phase** – The construction of the new paradigms from the variables will be used in the concept design phase for further research and to construct novel artefacts (discussed in chapter 5).

3.4 Concept design stage (CDS)

3.4.1 Concept design phase 1 (CDP 1) (6) – Business model evolution

- **Problem definition** – The problem is that the current provisioning system focuses on a linear supply system and this enforces the current linear provisioning system practices. The adoption of an innovative and disruptive technology requires an evolution of the business model aligned with the requirements of successful operation in 4IR. Since this research is based on the adoption of AM for the provisioning of spare parts, a thorough understanding is required of the evolutionary requirements of the provisioning business model from supply chain to a model that is aligned with the key requirements to function in 4IR and to support the adoption of AM as part of spare part provisioning.

- **Intervention** – A literature study was conducted to determine the evolution of the provisioning system and to determine what are the key requirements for a provisioning system to operate in 4IR.

- **Artefact** – The artefact from CDP 1, will be used as maturity levels for the newly designed maturity model since the maturity levels should be evolutionary in nature and should followin a logical manner as part of the provisioning evolution.

- **Learning** – The learning from CDP 1 is a research paper that was presented at the SAIIE conference in Port Elizabeth in 2019. It is summarised in chapter 5 and included as annexure A.

3.4.2 Concept design phase 2 (CDP 2) (7) – Business risk

- **Problem definition** – The problem is that the impact on the business risks with the adoption of AM for spare provisioning is not well understood.
- **Intervention** – A literature study was conducted to determine the key business risks from literature. This was compared with the input from the problem definition stage to determine the business risks that will be included in the development of the maturity model as the dimensions of the maturity model (chapter 7).
- **Artefact** – The artefact from this phase will be used as the dimensions for the maturity model in the second build phase.
- **Learning** – The learning for CDP 2 is a research paper that was presented at the RAPDASA conference in Bloemfontein in 2019. It is summarised in chapter 5 and included as annexure B.

3.4.3 Concept design phase 3 (CDP3) (8) – Business paradigms

- **Problem definition** – The problem is that the current linear business paradigms contributeto the slow adoption of AM for spare part provisioning.
- **Intervention** – A systematic literature review combined with abductive reasoning was applied to determine the key business paradigms that prolong the adoption of AM in spare part provisioning.
- **Artefact** – The adoption of AM as part of spare part provisioning requires a systemic understanding of the impact of the business risks. The key paradigms were included as part of the second build phase in the development of the multidimensional maturity model.
- **Learning** – The learning from CDP 3 is a research paper that was presented at the virtual SAIIE conference in 2020. It is summarised in chapter 5 and included as annexure C.

3.5 Build stage (BS)

3.5.1 Build phase 1 (BP 1) (9) – Design requirements for the maturity model

- **Intervention** – Literature regarding the design of maturity models was consulted to determine the design requirements for this new artefact.

- **Artefact** – The artefact is a design requirements traceability matrix that will be used in the second build phase to ensure that the newly constructed BRPM^2 model complies to all the design requirements.

3.5.2 Build phase 2 (BP 2) (10) – Business risk provisioning maturity model (BRPM^2)

- **Problem definition** – The problem has been defined as the lack of an integrated model to understand the systemic impact of the key business risks and provisioning system evolution when adopting AM as part of spare part provisioning.

- **Artefact** – The business risk provisioning model (BRPM^2) was designed based on the design requirements traceability matrix as well as all other inputs from the previous eADR stages. An explanation of the model is provided in chapter 7 and the new model will be populated in chapter 8.

- **Evaluation** – The evaluation of the artefact was done by means of the Delphi technique,a process used for the collection and synthesis of the opinions from selected experts in the industry. A questionnaire with a 5-point Likert scale was used in combination with qualitative feedback (Atkins *et al*., 2005; Grisham, 2009). This will be discussed in chapter 9 (verification) and chapter 10 (validation).

- **Learning –** The learning that occurred throughout this study is documented in chapter 11 (conclusion).

3.6 Summary

Chapter 3 framed the research design and positioned the research design as a design that can create the freedom to develop an artefact for an innovative and disruptive intervention. This research design will be embedded in the DS domain since DS seeks to explore new alternativesto solve problems, have a structured approach for the exploration process and then improve the problem-solving process. eADR is a branch of DS that allows for multiple iterations and entry of the research at any point.

The PDS (problem diagnosing stage) will be discussed in chapter 4.

CHAPTER 4: PROBLEM DIAGNOSING STAGE

Chapter 4 will address the following research questions:

Research question 2.1	From the literature review, what are the barriers for the slow adoption of AM in spare part provisioning?
Research question 2.2	What is the view of the ecosystem role players in South Africa regarding the barriers to slow adoption of AM in spare part provisioning?
Research question 2.3	According to the experience of the researcher, what are the reasons for the slow adoption of AM in spare part provisioning in South Africa?
Research question 2.4	What are the themes that influence the adoption of AM in sparepart provisioning?

4.1 Introduction

Chapter 4 presents the problem diagnosing stage of the eADR method. Grounded theory was applied (PDP 5) as an all-embracing methodology within the problem diagnosing stage and was applied to introduce a structured framework on how to analyse the unstructured data sets and define the context and boundaries of the analysis. There are five phases in the problem diagnosing stage. Regarding phase 1 (PDP 1), the literature review was presented in chapter 2 and a summary of the themes influencing the adoption of AM will be compiled as part of the problem diagnosing stage. This summary was used to compile discussion topics with selected industry experts (PDP 2) to confirm the status of AM adoption in South Africa. A triangulation exercise (PDP 4) combined the input from the literature review (PDP 1), expert discussions (PDP2) and the researcher's own experience (PDP 3). Figure 18 indicates the position of the problem diagnosing stage and phases as part of the eADR method that was used for this study. The sections to follow will elaborate on each of the five phases.

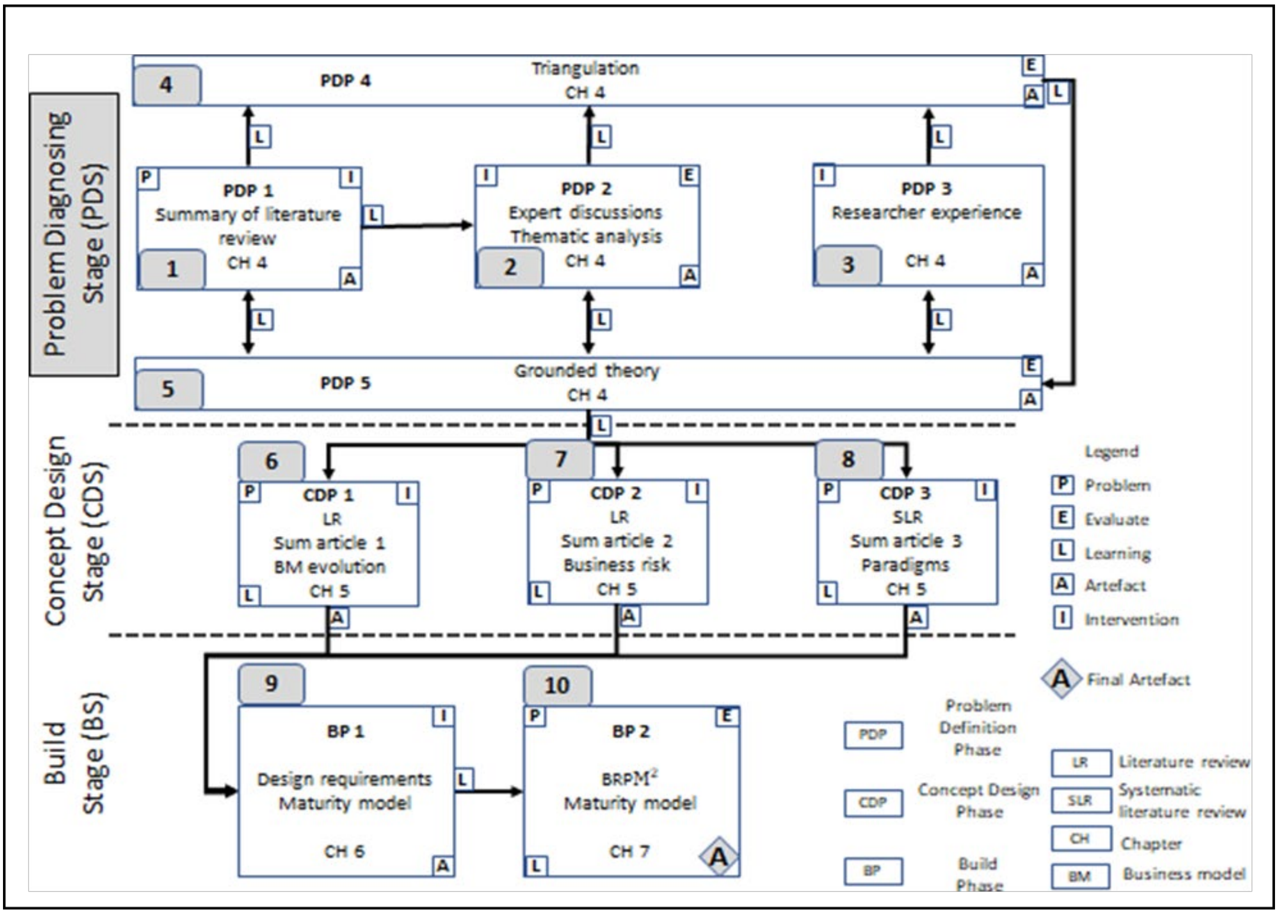

Figure 17: eADR method problem diagnosing stage (PDS).

4.2 Summary from literature review (PDP 1) (1)

Figure 19 is a graphical presentation of the themes from the literature review affecting the adoption of the AM.

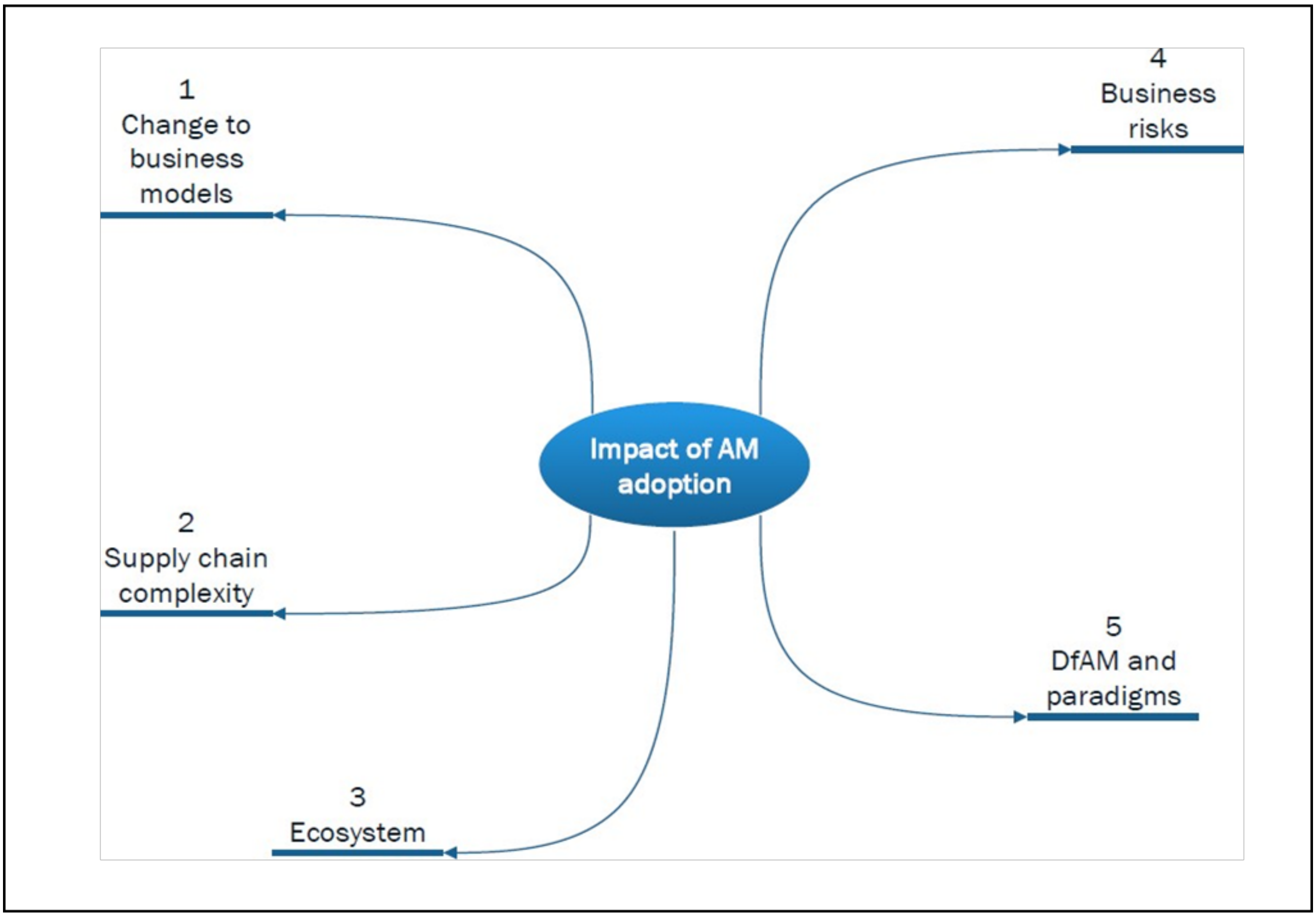

Figure 18:Themes impacting the slow adoption of AM.

The different codes from literature were summarised and grouped into different themes (Figure19). Table 16 is a summary from the literature review grouped into the themes from Figure 19.

Table 16:Summary from literature review – impact of AM adoption (researcher's own work).

	Themes				
	1	**2**	**3**	**4**	**5**
CODES	**Change to business models**	**Supply chain complexity**	**Ecosystem**	**Business risk**	**DfAM and paradigms**
	Understanding the effect on business models	Understanding change to supply chain and provisioning systems	Sustainability as a key requirement for 4IR	Skills and knowledge required	Entrenched paradigms – linear vs system
	Require comprehensive understanding of business impact	Evolutionary path of provisioning system	Co-innovation in network	Not Understandin g the impact of the business risks	Customisation of components to customer requirements
	New business models based on service and values	Point of consumption	Total cost of ownership (TCO)	Lack of visibility of key requirements for AM implementation	Design flexibility DfM vs DfAM
	Lower barriers to market entry	Low-volume batch size one	Distributed manufacturing in ecosystem	Business culture change	Parts consolidation
	Maintenance strategies	On-demand manufacturing	Ecosystem role players	Disruptive, innovative technologies	Change manufacturing paradigm
	Economy of scale vs economy of scope	Reduction in lead time	Circular	Risk identification and management	Weight reduction of components
			Economy and recycling of components		
	End-of-life equipment	Provisioning system agility	Integration in ecosystem	Intellectual property	Innovation
	Agility	Reduction of complexity in supply chain	Network relationships	Leadership adoption	Systems and design thinking
	Focus on supplying solutions	Reduction in inventory	Makers community	Standards to manufacture components	Resilience

		Reduction in obsoleteparts			View adoption of AM as complex
		E-warehousing			
		Flexibility			
		Key requirements for supply chain in 4IR			

This section answers research question 2.1:

From the literature review, what are the barriers for the slow adoption of AM in spare part provisioning?

The barriers affecting the adoption of AM according to the literature review were summarised in five themes. These themes were used to define discussion topics for the informal discussions with the South African ecosystem role players that will be discussed in PDP 2 section 4.3.

4.2 Expert discussions (PDP 2) (2)

The experts who participated in the informal discussions were identified as part of the South African AM ecosystem, see Figure 20, and adopted from Ituarte *et al*. (2017). The selection process will be discussed in section 4.3.1. A top-down thematic analysis was applied to summarise the responses from the participants since the themes from the literature review were used to guide the thematic analysis. This summary served as an input into the triangulation exercise in section 4.5.

4.2.1 Selection of participants in South African AM ecosystem

Figure 20 indicates the key areas from where to select the participants for the expert discussions.The Collins Dictionary (2018, online) defines an expert as “a person who has extensive skill or knowledge in a particular field”. Participants for the informal discussions should be selected based on their expert knowledge of the phenomenon under inquiry (Tavakol *et al*., 2006). The phenomenon for this research is the slow adoption of AM in spare part provisioning in South Africa. The sample size is not fixed, and theoretical sampling is used. Theoretical sampling is a process of data collection for developing theory whereby the analyst jointly collects codes and analyses the data and then decides what data to collect next and where to find the data, in orderto develop the theory as it emerges (Glaser, 1978).

The expert opinions will be used as an input for the development of the iterative grounded theory(PDP 5) in section 4.6. One of the key requirements for the selection of participants for the development of grounded theory is to select experts in the respective area where the phenomenon occurs (Glaser, 1978). The phenomenon is the slow adoption of AM in spare part provisioning in South Africa and therefore the experts will be identified and selected from the South African AM ecosystem.

Figure 20 is a graphical representation of the South African AM ecosystem. The ecosystem can be divided into the following key groups.

a. Technology users and industry

b. Machine and system vendors

c. Software and IT platforms

d. Manufacturing service bureaus

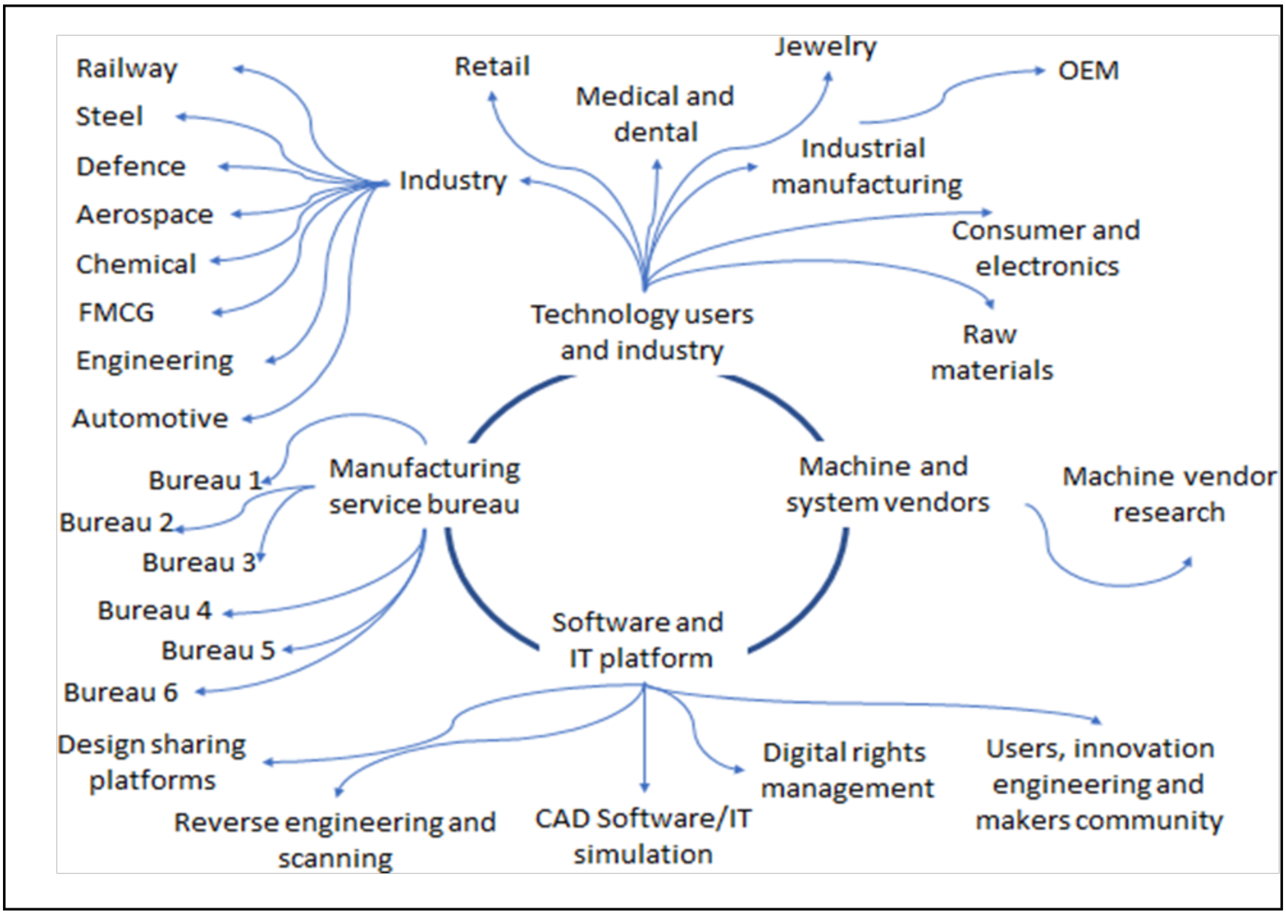

Figure 19:South African AM ecosystem (adopted from Ituarte et al., 2017).

Figure 21 indicates the South African ecosystem and role players that could participated in the informal discussions regarding the impact of AM adoption. Figure 22 is a distribution of the ten (10) participants that participated inthe informal discussions. The focus of this research is on spare part provisioning and since the adoption of AM in spare part provisioning is low, it reduced the number of available participants at the start of this research in 2018. After the literature review, the researcher wanted to validate some of the concepts with participants in the AM eco-system in South Africa and obtain their view regarding some of the key principles derived from the literature review. These participants were selected on their participation in the AM Ecosystem in South Africa, their willingness to participate since the AM business in SA is small and their availability to participate. Due to these requirements, and the fact that informal discussions are used to verify information gathered through a research process and to verify any possible gaps that require additional research, no other information regarding the role players were collected except the industry that they represented as part of their role in the SA ecosystem. All the participants were senior employees in the respective areas that they represented.

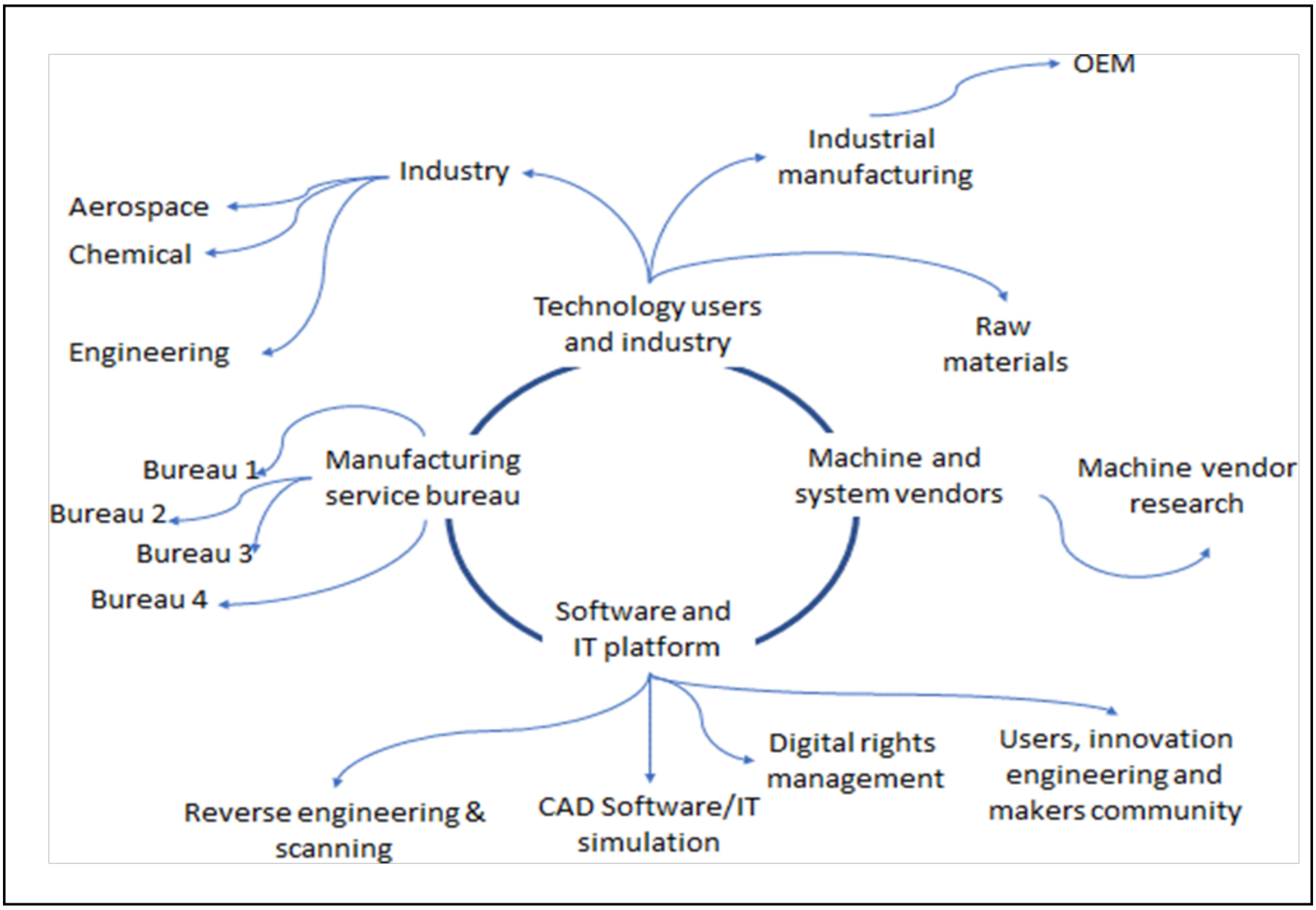

Figure 20:Industry selection of informal discussion participants as part of the South African ecosystem

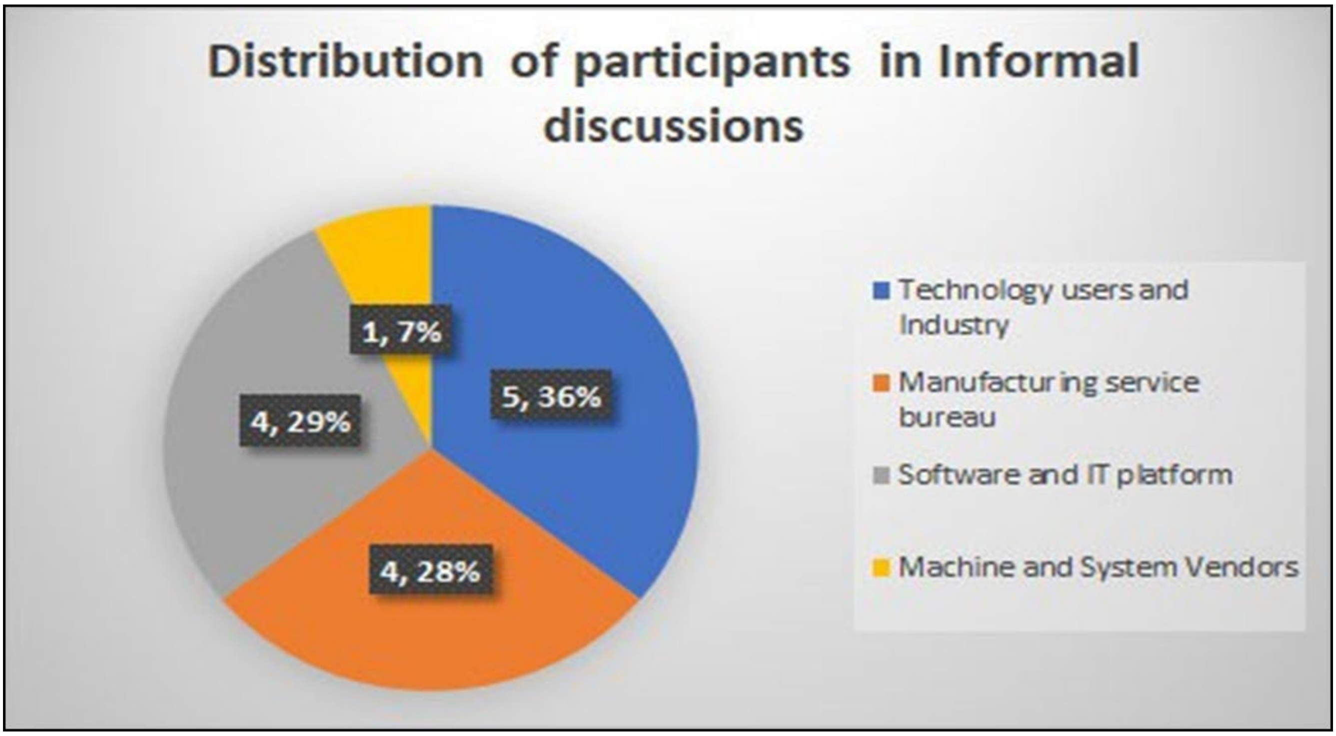

Figure 21:Distribution of participants in informal discussions

Some of the participants represented multiple industries. The numbers in figure 22 indicate the participants per industry sector that total 14 where there were 10 physical participants.

4.2.2 Discussion topics with South African AM ecosystem experts

The following questions (Table 17) were compiled from the themes in Figure 19 and used for the informal discussions with the South African AM ecosystem experts.

Table 17:Questions for informal discussion with SA AM ecosystem experts.

Theme	Question
1	Do you think that the adoption of AM as part of a business strategy will have an impact on the business model?
3	How would you define the AM ecosystem for asset management in South Africa?
5	What do you think are the reasons for the slow adoption of AM in asset management in South Africa?
5	How would you go about in creating an entry point for AM in asset management?
2	How will AM influence your supply chain?
4	What are the skill sets required for the adoption and successful practising of AM?
4	What do you think are the risks that need to be mitigated with the implementation of AM as a business strategy?
5	What is your view regarding the protection of IP?
5	Do you think you will be able to print parts for OEMs?
2	How do you think will the concept of e-warehousing work?
5	What is your view regarding the future of AM in South Africa?
5	What is your view regarding the required capabilities to design for AM (DfAM)?

The questions were compiled to cover the themes and to collect information that could enrich and verify the data from the literature review. Ten participants were selected that represented the sections of the South African AM ecosystem as indicated in figure 22.

Table 18 is a summary of the feedback provided by the selected South African experts.

Table 18: Summary of the feedback provided by selected SA experts.

Discussion topic	Summative feedback
Do you think that the adoption ofAM as part of a business strategy will have an impact on the business model?	Yes, business model will change New business models will require a systemic focus Business models will be based on economy of scope with focus on added value of the system New business models will require agility and customer focus Business models will require new innovative paradigms
How would you define the AM ecosystem for asset management in South Africa?	The South African ecosystem is still fragmented The participants do not understand how to unlock real value of ecosystem Traditional paradigms are entrenched Some role players act as bureaus, but they should focus on the academic development of AM Focus is predominantly on prototyping
What do you think are the reasons for the slow adoption of AM in asset management in South Africa?	There is no clear understanding of the true value of AM by users There is a functional focus vs a system focus Users are risk averse Users do not understand the business impact of AM Linear, traditional view of risk Organisations are still silo-based AM is a business philosophy and not only a disruptive technology Lack of top management adoption of AM as a business strategy Organisations still do not understand the evolutionary requirements of the supply chain and the impact of AM
How would you go about in creating an entry point for AM in asset management?	Leadership adoption as novel new strategy Implement use cases to define true value of AM
How will AM influence yoursupply chain?	There will be a reduction in lead time Products can be printed at the point of consumption Focus on true demand and agility Reduction in inventory and obsolete spares Change to dynamic new paradigms of how to improve total system Reduction in complexity of supply chain

	Support sustainability strategies Reduction in warehouse space Paradigm shift from supply chain to ecosystem integration and participation
What are the skill sets requiredfor the adoption and successful practising of AM?	Innovation Creativity Design for AM skills Holistic and systemic understanding of network or ecosystem Agility Change management Resilience
What do you think are the risks that need to be mitigated with theimplementation of AM as a business strategy?	Clear understanding of AM requirements on business risksCulture will change New leadership models Lack of standards Repeatability and quality control of components Material availability Organisational structure will change Lack of skills to implement AM
What is your view regarding the protection of IP?	IP protection will require new models IP can be violated by design changes to components
Do you think you will be able toprint parts for OEMs?	OEMs protect turf OEMs continue with linear models instead of network integration and development
How do you think will the concept of e-warehousing work?	Components will be saved as an e-file and not as a physical component any more E-warehouse will be linked to ecosystem and maintenance strategies
What is your view regarding thefuture of AM in South Africa?	Adoption is slow for spare part provisioning due to traditional paradigms and leadership adoption AM is growing at a rapid rate for prototyping and other components, but business risks for spare part adoption must be defined and understood to break through traditional paradigms
What is your view regarding the required capabilities to design forAM (DfAM)?	Innovation skills required Designers must understand the systemic value of AM to unlock the true value of system optimisation and part consolidation Systemic understanding of business process integration

The expert feedback (Table 18) was analysed and grouped according to the themes defined in Figure 17 as part of the top-down thematic analysis (refer to Table 19). The top-down thematic analysis starts with the themes and then the collected data is allocated to the relevant themes as applicable.

Table 19:Thematic analysis of expert feedback.

Themes	Expert feedback
Change to business models	Business models will change New business models will require a systemic focus Business models will be based on economy of scope with focus on added value of the system New business models will require agility and customer focus Users do not understand the business impact of AM Organisations are still silo-based AM is a business philosophy and not only a disruptive technology Agility OEMs protect turf
Supply chain complexity	Organisations still do not understand the evolutionary requirements of the supply chain and the impact of AM Reduction in lead time Print at point of consumption Focus on true demand and agility Reduction in inventory and obsolete spares Reduction in complexity of supply chain Reduction in warehouse space Components will be saved as an e-file and not as a physical component any more
Ecosystem	South African ecosystem still fragmented Participants do not understand how to unlock the real value of the ecosystem Some role players act as bureaus, but they should focus on the academic development of AM Support sustainability strategies

Themes	Expert feedback
Change to business models	Business models will change New business models will require a systemic focus Business models will be based on economy of scope with focus on added value of the system New business models will require agility and customer focus Users do not understand the business impact of AM Organisations are still silo-based AM is a business philosophy and not only a disruptive technology Agility OEMs protect turf
	Holistic and systemic understanding of network or ecosystem E-warehouse will be linked to ecosystem and maintenance strategies
Business risk	Users are risk-averse Linear traditional view of risk Lack of top management adoption of AM as a business strategy Lack of skills to implement AM Change management Clear understanding of AM requirements on business risks Culture will change New leadership models Lack of standards Repeatability and quality control of components Material availability Organisational structure will change IP protection will require new models IP can be violated by design changes to components

	OEMs continue with linear models instead of network integration and development AM is growing at a rapid rate for prototyping and other components, but business risks for spare part adoption must be defined and understood to breakthrough traditional paradigms. Innovation skills required Systemic understanding of business process integration Business models will require new innovative paradigms
DfAM and paradigms	Traditional paradigms entrenched Focus is predominantly on prototyping No clear understanding of the true value of AM Functional focus vs a system focus Leadership adoption as novel strategy Implement use cases to define true value of AM Change to dynamic new paradigms of how to improve total system Paradigm shift from supply chain to ecosystem integration and participation Business models will require new innovative paradigms Innovation, creativity Design for AM skills Resilience Adoption is slow for spare part provisioning due to traditional paradigms and leadership adoption Designers must understand the systemic value of AM to unlock the true value of system optimisation and part consolidation

This section answers research question 2.2:

What is the view of the ecosystem role players in South Africa regarding the barriersto the slow adoption of AM in spare part provisioning?

The information that was obtained from the informal discussions with the ecosystem role players enriched the data collected from the literature review and confirmed the reasons for the slow adoption of AM that were derived from the literature review. This confirms that the reasons identified for the slow adoption of AM from the literature review can be applicable to South Africa.

4.3 Researcher's experience (PDP 3) (3)

During the research, the researcher started to create awareness regarding the adoption of AM inthe working environment where the researcher was employed. Some projects were identified to replace original components with AM-produced components. The experience of the researcher regarding the adoption of AM is captured against the themes, as indicated in Figure17 and Table 20.

Table 20: Researcher's experience.

Theme	Researcher's experience
1. Change to business models	Business models will need to accommodate requirements of AM Agility is a key requirement since AM requires print on demand Change focus from focus on product to focus on value add Business models must incorporate the ecosystem OEMs require new business models to align with spare part provisioning through AM
2. Supply chain complexity	E-warehousing Print at point of consumption Extend end-of-life of equipment Reduce redundant spares Produce on demand Manage agility required for AM provisioning system
3. Ecosystem	Understand role players in ecosystem Co-innovation in ecosystem
4. Business risk	Lack of systemic understanding Linear business processes Lack of standards Focus on supply and not real demand of end customer IP of new designs Lack of understanding how to integrate networks and ecosystem
5. DfAM and paradigms	Traditional manufacturing design thinking Part consolidation Material replacement Improve reliability of operations

This section answers research question 2.3:

According to the experience of the researcher, what are the reasons for the slowadoption of AM in spare part provisioning in South Africa?

The researcher experienced a low level of understanding in the industry where the researcher was employed, of the systemic nature ofAM and the resistance to adopt new business paradigms that can contribute significantly to the slow adoption of AM for spare part provisioning in South Africa.

4.4 Triangulation of different data sets (PDP 4) (4)

Triangulation is a method where the output from various sources of information is analysed to derive at a common theme or themes and to verify the credibility of the output (Heale & Forbes, 2013; Carugi, 2010). Source triangulation was used in stage 4, whereby the following sources ofinformation and data were used:

(a) Summary of concepts from the literature review – Table 16

(b) Thematic analysis of expert feedback – Table 19

(c) Researcher's own experience – Table 20

The triangulated data is presented in Table 21.

Table 21:Triangulation of literature review, expert opinion and researcher’s experience.

	Literature review	Expert opinion	Researcher’sexperience
1. Change to business models	Understanding the impact on business models Require comprehensive understanding of business Impact New business models based on service and value Lower barriers to market entry Maintenance strategies Economy of scale vs economy of scope End-of-life equipment Agility Focus on supplying solutions	Business models will change New business models will require a systemic focus Business models will be based on economy of scope with focus on added value of the system New business models will require agility and customer focus Users do not understand the business impact of AM Organisations are still silo-based AM is a business philosophy and not only a disruptive technology Agility OEMs protect turf	Business models will need to accommodate requirements of AM Agility is a key requirement since AM requires print on demand Change focus from focus on product to focus on value-add Business models must incorporate the ecosystem OEMs require new business models to align with spare part provisioning through AM
2. Supply chain complexity	Understanding change to supply chain and provisioning systems Evolutionary path of provisioning system	Organisations still do not understand the evolutionary requirements of the supply chain and the impact of AM	E-warehousing Print at point of consumption Extend end-of-life of equipment
	Point of consumption Low volume batch size one On demand manufacturing Reduction in lead time Provisioning system agility Reduction of complexity in supply chain Reduction in inventory Reduction in obsolete parts E-warehousing	Reduction in lead time Print at point of consumption Focus on true demand and agility Reduction in inventory and obsolete spares Reduction in complexity of supply chain Reduction in warehouse space	Reduce redundant spares Produce on demand Manage agility required for AM provisioning system

	Literature review	Expert opinion	Researcher'sexperience
1. Change to business models	Understanding the impact on business models Require comprehensive understanding of business Impact New business models based on service and value Lower barriers to market entry Maintenance strategies Economy of scale vs economy of scope End-of-life equipment Agility Focus on supplying solutions	Business models will change New business models will require a systemic focus Business models will be based on economy of scope with focus on added value of the system New business models will require agility and customer focus Users do not understand the business impact of AM Organisations are still silo-based AM is a business philosophy and not only a disruptive technology Agility OEMs protect turf	Business models will need to accommodate requirements of AM Agility is a key requirement since AM requires print on demand Change focus from focus on product to focus on value-add Business models must incorporate the ecosystem OEMs require new business models to align with spare part provisioning through AM
	Flexibility Key requirements for supply chain in 4IR	Components will be saved as an e-file and not as a physical component any more	
3. Ecosystem	Sustainability as a key requirement for 4IR Co-innovation in network Total cost of ownership (TCO) Distributed manufacturing in ecosystem Ecosystem role players Circular economy and recycling of components Integration in ecosystem Network relationships Makers community	South Africa ecosystem still fragmented Participants do not understand how to unlock real value of the ecosystem Some role players act as bureaus, but they should focus on the academic development of AM Support sustainability strategies Holistic and systemic understanding of network or ecosystem E-warehouse will be linked to ecosystem and maintenance strategies	Understand role players in ecosystem Co-innovation in ecosystem

4. Business risk	Skills and knowledge required Not understanding the systemic impact of the business risks Lack of visibility of key requirements for AM implementation Business culture change Disruptive innovative technologies Risk identification and management Intellectual property Leadership adoption Standards to manufacture components Repeatability of printed components Skills Traditional design and risk paradigms Understanding ecosystem requirements	Users are risk-averse Linear, traditional view of risk Lack of top management adoption of AM as a business strategy Lack of skills to implement AM Change management Clear understanding of AM requirements on business risks Culture will change New leadership models Lack of standards Repeatability and quality control of components Material availability Organisational structure will change IP protection will require new models IP can be violated by design changes to components OEMs continue with linear models instead of network integration and development	Lack of systemic understanding Linear business processes Lack of standards Focus on supply and not real demand of end customer IP of new designs Lack of understanding how to integrate networks and ecosystem
		AM is growing at a rapid rate for prototyping and other components, but business risks for spare part adoption must be defined and understood to break through traditional paradigms Innovation skills required Systemic understanding of business process integration	

5. DfAM and paradigms	Entrenched paradigms – linear vs systemic Customisation of components to customer requirements Design flexibility DfM vs DfAM Parts consolidation Change manufacturing paradigm Weight reduction of components Innovation Systems and design thinking	Traditional paradigms entrenched Focus is predominantly on prototyping No clear understanding of the true value of AM Functional focus vs a systemic focus Leadership adoption as new strategy Implement use cases to define true value of AM	Traditional manufacturing design thinking Part consolidation Material replacement Improve reliability of operations
	Resilience View adoption of AM ascomplex	Change to dynamic new paradigms of how to improve total system Paradigm shift from supply chain to ecosystem integration and participation Business models will require new innovative paradigms Innovation, creativity Design for AM skills Resilience Adoption is slow for sparepart provisioning due to traditional paradigms andleadership adoption Designers must understand the systemic value of AM to unlock the true value of system optimisation and part consolidation	

Daytner (2006) states that the results of a triangulation exercise must accurately reflect the phenomenon at hand. The phenomenon at hand is the slow adoption of AM in spare part provisioning in South Africa. To guide the credibility of the data, the themes according to the literature review (Figure 19) were used throughout the triangulation exercise to group the data.

The triangulation exercise confirms the credibility of the three data sources since similar data was recorded against each of the themes. The five themes were condensed to three themes. Themes 1, 2 and 3 relate to the requirement for a change in business models, a reduction in thecomplexity of the supply chain as well as an understanding of the ecosystem. Since this research is based on the provisioning system, theme 2 regarding the supply chain complexity and theme 3 relating to the ecosystem can be combined with theme 1, that leads to:

a) **The adoption of AM in spare part provisioning has a profound impact on the supply chain or provisioning system and will require a new business model.**

Theme 4 relates to the understanding of the business risks:

b) **A clear understanding of the business risks can enhance the adoption of AM.**

Theme 5 relates to the design requirements for AM (DfAM) and the required change in paradigms:

c) **The design requirements of AM require an adjustment to the current paradigmsthat can improve the adoption of AM in spare part provisioning.**

This section answers research question 2.4:

What are the themes that influence the adoption of AM in spare part provisioning?

This section started with five themes that were derived from a thematic analysis of the literature review and were used as a basis in the expert discussions to elicit feedback from the selected South African experts as well as the feedback from the researcher's own experience. The five themes were also used to group the data in the triangulation exercises to determine the credibilityof the data as well as to enrich the data sets.

Both the thematic analysis and the triangulation exercise were required to summarise and groupthe data to prepare the data for the grounded theory formulation.

4.5 Grounded theory (PDP 5) (5)

Grounded theory attempts to generate new theories or conceptual propositions from the phenomenon (Glaser & Strauss, 1967). Grounded theory defines (1) where the findings are derived from, (2) how concepts were elicited and (3) how empirical links among concepts were achieved (Bak, 2000).

The need to combine many data collection methods in grounded theory has been well documented (Glaser, 1978; Strauss & Corbin, 1998). The process of data generation requires the researcher to collect, code and analyse the data iteratively (Tavakol *et al*., 2006). This is an evolutionary process to provide richer data. The stated aim of grounded theory is the discovery of themes applicable to the formation of the new theory (Tavakol *et al*., 2006). According to Glaser (1978), the researcher is responsible to search and define the different groups and trends in the data from where the main themes can be derived.

The data sources for the problem definition stage of the eADR model have been (1) literature research (chapter 2) (PDP 1), (2) informal discussions with South African ecosystem experts (PDP 2) and (3) the researcher's own experience (PDP 3). According to Bak (2000), the ability to incorporate the unique insights during a research study is one of the benefits of a grounded theory research approach and that was achieved through the inputs from the ecosystem experts, and the researcher's own experience.

AM is described as a disruptive innovation, and adoption of such a disruptive innovation can require a paradigm shift (Ismail *et al*., 2014). Grounded theory allows researchers to follow leadsthat they find in the data they research and then to construct evolutionary new concepts following on each other (Charmaz, 2014).

The grounded theory in Figure 23 was derived from the three themes at the end of section 4.5

Theme 1: The adoption of AM in spare part provisioning has a profound impact on thesupply chain or provisioning system and will require a new business model**.**

GT1 – Understanding of the business model evolution from supply chain to a business model based on the key requirements for 4IR can lead to improved AM adoption

Theme 2: A clear understanding of the business risks can enhance the adoption of AM

GT2 ‐ Understanding of the integrated nature of the key business risks when adopting AM can lead to improved AM adoption

Theme 3: The design requirements of AM require an adjustment to the current paradigms that can improve the adoption of AM in spare part provisioning

GT3 – Systems thinking can assist in changing the key business paradigms and can lead to improved AM adoption

Figure 23 is a summary of the derived grounded theory at the end of the problem diagnosing stage.

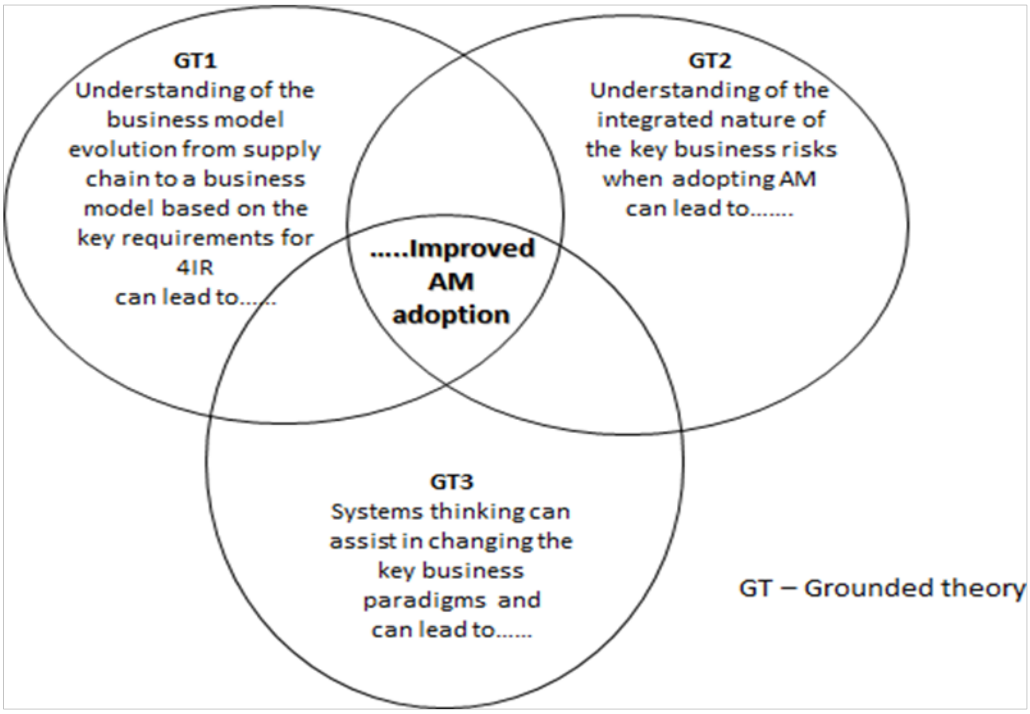

Figure 22:Summary of grounded theory derived from the problem diagnosing stage.

The developed grounded theory was used to do additional research presented in research papersthat will be discussed in chapter 5. The theory was used as the foundation for the design of the maturity model to develop a visible tool that can assist with the adoption of AM (de Carolis *et al*.,2017; Schniederjans, 2017).

4.6 Summary

Chapter 4 concludes the problem diagnosing stage of the research model. A thematic analysis was used to analyse the literature review, informal discussions with the ecosystem experts and the researcher's experience. Triangulation was applied to evaluate the themes that were used as the foundation for the compilation of the grounded theory.

The grounded theory derived at the end of the problem diagnosing stage was used to develop three theories that were further explored and developed. The findings were included in three research papers that were presented and discussed at three different research conferences.

Chapter 5 will contain a summary of the research papers that were derived from each of the grounded theories compiled in chapter 4.

CHAPTER 5: CONCEPT DESIGN STAGE

The concept design stage will address the following research questions:

Research question 3.1	What are the key requirements for a spare part provisioning system in 4IR?
Research question 3.2	What are the evolutionary stages of the spare part provisioning system?
Research question 4.1	What are the key business risks involved when adopting AM in spare part provisioning?
Research question 5.1	What are the key paradigms affecting the adoption of AM in spare part provisioning?

5.1 Introduction

Once the problem diagnosing stage (PDS) (chapter 4) was completed, the concept design stage(CDS) could commence. Figure 24 positions CDS as part of the eADR model.

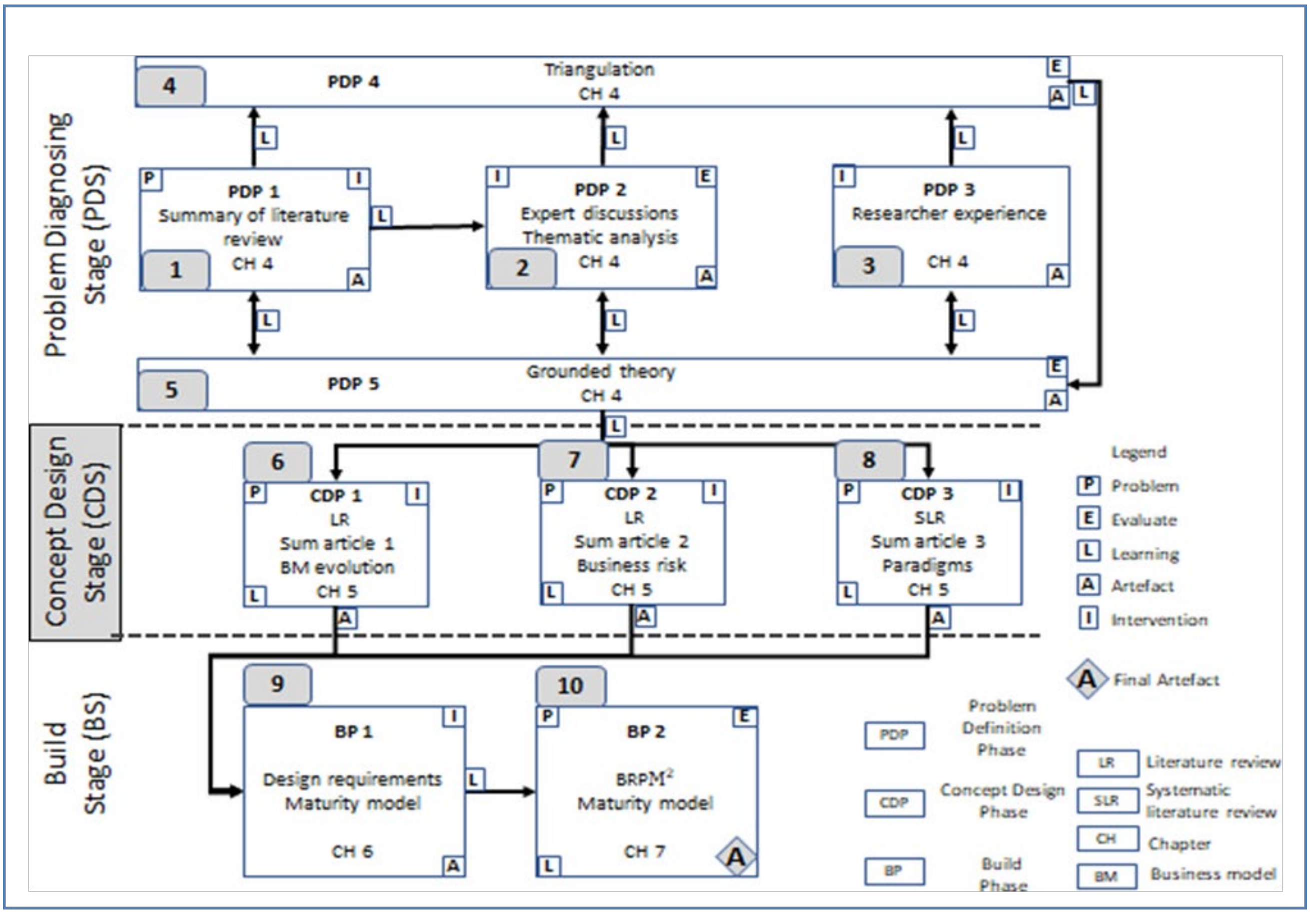

Figure 23: *eADR method concept design stage (CDS)*

A summary of the three theories that were investigated and published as research papers is discussed in chapter 5. The full-length papers are presented in annexure A, B and C.

5.2 Concept design phase 1 (CDP 1) (6)

5.2.1 Grounded theory 1

The first grounded theory states:

Understanding of the business model evolution from a supply chain to a business modelas the key requirements for 4IR can lead to improved adoption of AM.

5.2.2 Research paper

Harmse, H. and Holm, J. F. (2019) 'The evolution of business models from supply chain to agiledemand networks through additive manufacturing', paper presented at the *30th Annual Southern African Institute for Industrial Engineering (SAIIE) 2019*, Port Elizabeth, pp. 779–793, https://conferences.sun.ac.za/index.php/SAIIENeXXXt/SAIIENeXXXt/paper/viewFile /4323/624

This research paper is included in this thesis as annexure A.

5.2.3 Background

The world has experienced several significant step changes referred to as industrial revolutions. Technology has been a key driver during these industrial revolutions as well as in the evolution of the supply chain or provisioning system business model for spare parts. During this supply chain evolution, customers became more demanding because of the availability of real-time information and their integration into multiple global networks.

The 4IR is also shaped by new disruptive technologies. Additive manufacturing (AM) has been indicated as the most disruptive technology of 4IR. To mitigate the impact of the disruption that these technologies will cause, companies need to understand the true requirements of aprovisioning business model for 4IR as well as the evolutionary steps of the provisioning business model from supply chain to a new business model that will enable the effective adoption of AM.

5.2.4 Research aim

The aim of this part of the research was to:

- Research the business model evolution
- Define the requirements for success in the fourth Industrial Revolution (4IR)
- Define an industrial component supply business model based on the defined requirements for success in 4IR
- Define the role of AM in shaping the new business model

5.2.5 Findings

The business model evolution involves many elements of an organisation and its success relies on the support and execution of an array of functions. Due to the disruptive nature of 4IR, business models will have to change and need to be aligned with the key requirements for functioning as part of 4IR. This will require an evolution from linear business models to innovative, non-linear business models.

Figure 25 is a graphical presentation of the business model evolution process.

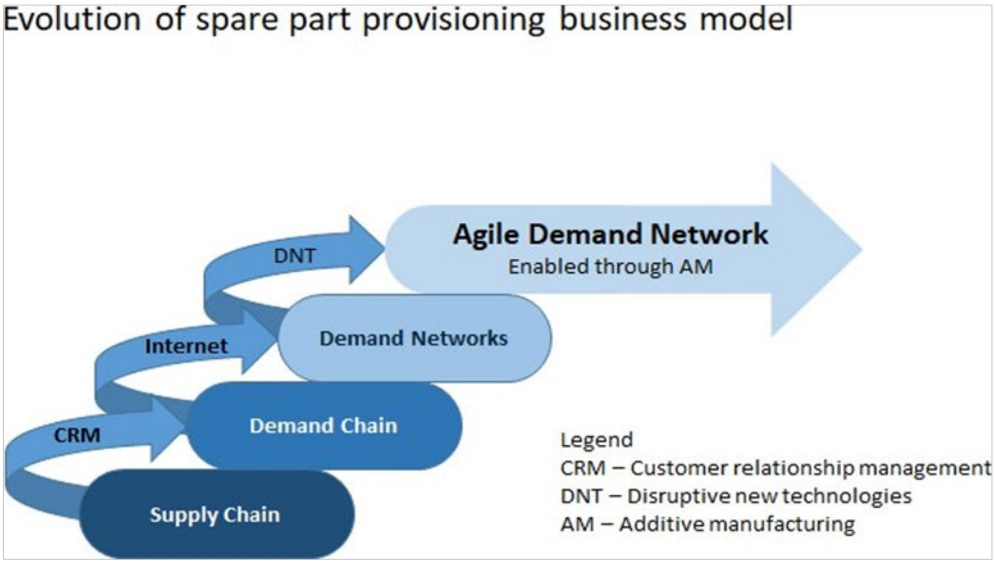

Figure 24:Evolution of spare part provisioning model (Harmse & Holm, 2019).

The first provisioning business model is based on the supply of products in a linear chain format called supply chain. The focus started to move closer to the customer to understand the demand better and therefore to improve the supply of products. With the implementation of customer relationship management software, companies could create improved visibility on the demand ofthe business and the business model was called demand chain management. Although the focus shifted from supply to demand, the business model was still based on a linear chain concept.

The internet allowed organisations to link many different chains together in a network. This integration improved the visibility of the customer demand. This business model was based on anon-linear network structure and was called demand networks. The disruptive new technologies of 4IR required organisations to become agile. The disruptive new technologies are linked together in a network and allow for real-time availability of information for decision-making. Therefore, agility has to be included as part of the spare part provisioning business model that leads to the creation of agile demand networks.

The key requirements for success in 4IR will be the real-time visibility of the customer demand integrated into the ecosystem or networks based on agility to manage the dynamics of the business environment. Since additive manufacturing is a disruptive technology, the adoption of additive manufacturing will not only disrupt the provisioning of spare parts but will also disrupt many parts of the organisation. Hence, additive manufacturing is not simply a disruptive technology but a disruptive, innovative and strategic game changer that an agile demand networkbusiness model must embrace.

CDP 1 answers the following research questions:

Research question 3.1:

What are the key requirements for a spare part provisioning system to operate in 4IR?

A real-time focus on customer demand integrated into the ecosystemor networks based on agility is the key requirement for a spare part provisioning systemto operate in 4IR. This spare part provisioning system will evolve from supply chain to an agile demand network based on the key requirements for success in 4IR

Research question 3.2:

What are the evolutionary stages of the spare part provisioning system?

The evolutionary stages, as discussed in section 5.2.5 and depictedin Figure 25, are the evolutionary stages required for a spare part provisioning system. The evolutionary stages are:

(a) Supply Chain to Supply Network to Demand network to Agile Demand Network.

5.3 Concept design phase 2 (CDP 2) (7)

5.3.1 Grounded theory 2

The second grounded theory states:

Understanding of the integrated nature of the key business risks when adopting AM canlead to improved AM adoption.

5.3.2 Research Paper

Harmse, H. 2019. The business impact of adopting additive manufacturing in spare part provisioning. *Proceedings of the 20th Annual International RAPDASA Conference,* 06–08 November 2019, Bloemfontein, pp. 180–189, ISBN nr: 978-0-6398390-0-4 RAPDASA 2019 Conference Proceedings eBook

This research paper is included in annexure B of this thesis.

5.3.3 Background

The business impact of AM is poorly understood. AM is seen as a disruptive technology although it is a disruptive strategic business intervention that needs to be driven by the CEO. For a business to understand and implement AM successfully, it is important that an integrated model exists indicating all the relationships of the key business activities that will be affected when adopting AM and the importance of alignment between them.

5.3.4 Research aim

The aim of this research paper was to compile an integrated list of all the key business components that will be influenced when adopting AM as part of spare part provisioning.

5.3.5 Findings

Figure 26 is a graphical representation of the key components that will be influenced when adopting AM.

Figure 25:Additive manufacturing business impact (Harmse, 2019)

The current focus of most of the literature is on the production of AM components and less on the impact of AM on the rest of the organisation. Figure 26 indicates that leadership buy-in is key to the successful adoption of AM. Although all the activities are equally important, AM will require new processes, a culture change, new structures in the organisation and an integration and participation in the ecosystem. The business activities can be defined as business risks becauseeach activity poses a risk to the organisation if the systemic effect that each activity has on the other activities is not understood and managed.

This research paper answers research question 4.1:

What are the key business risks involved when adopting AM in spare partprovisioning?

The key business risks are identified and presented in Figure 26. Ashort discussion of the business risks was conducted in section 5.3.5.

5.4 Concept design phase 3 (CDP3) (8)

5.4.1 Grounded theory 3

The third grounded theory states:

Systems thinking can assist in changing the key business paradigms that can lead to improved AM adoption.

5.4.2 Research paper

Harmse, H. and Coetzee, R. 2020. Investigating how systems thinking can assist with the adoption of additive manufacturing in spare part provisioning. Paper presented at the virtual *31th Annual Southern African Institute for Industrial Engineering (SAIIE) 2020*. https://conferences.sun.ac.za/index.php/SAIIENeXXXt/SAIIENeXXXt/paper/viewFile /4323/624.

This research paper is included in annexure C of this thesis.

5.4.3 Background

Although the adoption of additive manufacturing (AM) in various industries is accelerating, the adoption of AM for industrial spare parts provisioning remains slow. AM is indicated as one of the most disruptive innovations of Industry 4.0 (4IR). When adopting a disruptive innovation, the reason for the disruption needs to be understood. An innovation is defined as disruptive when it changes the way the current industry operates. This disruptive innovation challenges the status quo and some of the business paradigms required for adoption of this innovation.

5.4.4 Research aim

This aim of this research is to indicate how the concept of systems thinking can assist organisations that would like to adopt AM in spare part provisioning to resolve the key business paradigms that prolongs the adoption of AM in spare part provisioning.

5.4.5 Findings

The adoption of AM in spare part provisioning will not only require new paradigms for the provisioning system but also how the organisation perceives and manages risks as well as the paradigm of managing complexity. Participation in the global ecosystem will introduce complexityinto the organisation if the systemic interrelationship between the different business risks as wellas the new provisioning system requirements are not well defined and understood. Risk management, complexity management and the provisioning system need to transcend from a linear paradigm to a non-linear paradigm that can accommodate the requirement for agility in 4IR. Systems thinking can assist organisations to understand the required change in these paradigmsand to promote the adoption of AM as part of spare part provisioning.

Figure 27 is a summary of the three areas from where the paradigms have been identified that an affect the adoption of AM.

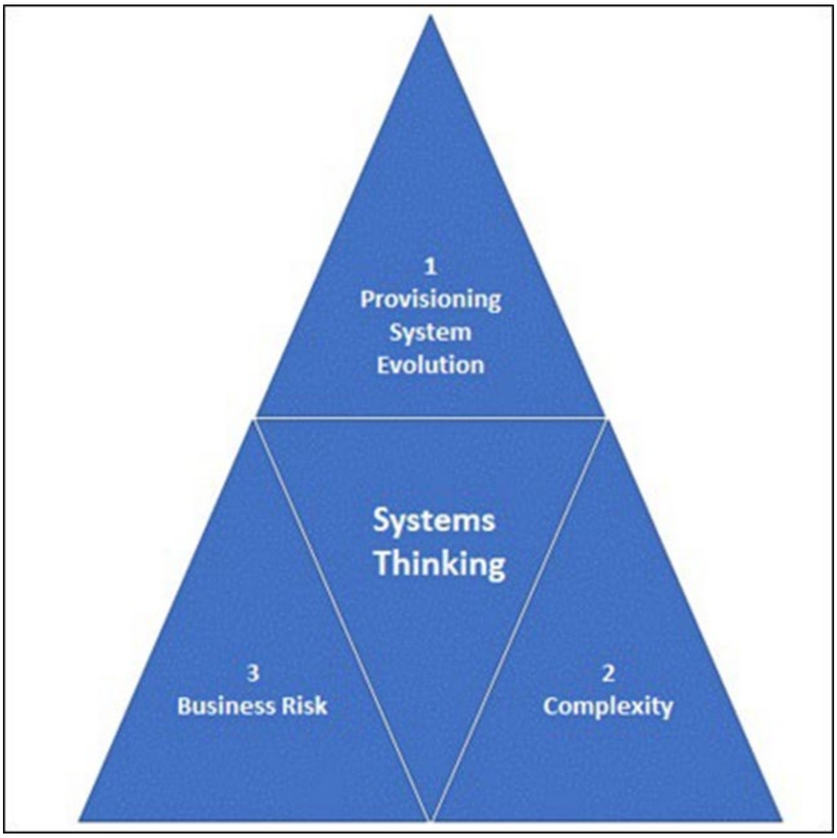

Figure 26:The role of systems thinking in the adoption of AM (Harmse & Coetzee, 2020).

CD 3 addresses the research question 5.1:

What are the key paradigms affecting the adoption of AM in spare partprovisioning?

The key paradigms that were addressed in the research papers can be summarised as follow:

(a) A paradigm that shifts from a focus on efficiency to a focus on effectiveness

(b) A paradigm that shifts from focusing on linear, complicated processes to network-based complex processes

(c) A paradigm that shifts from linear risk management to systemic, non-linear risk management

5.5 Summary

The three phases of the concept design stage will be used in the design of the maturity model asthe final artefact for this research and to assist in solving the research problem. Figure 28 indicates how the grounded theories were used in the development of the maturity model.

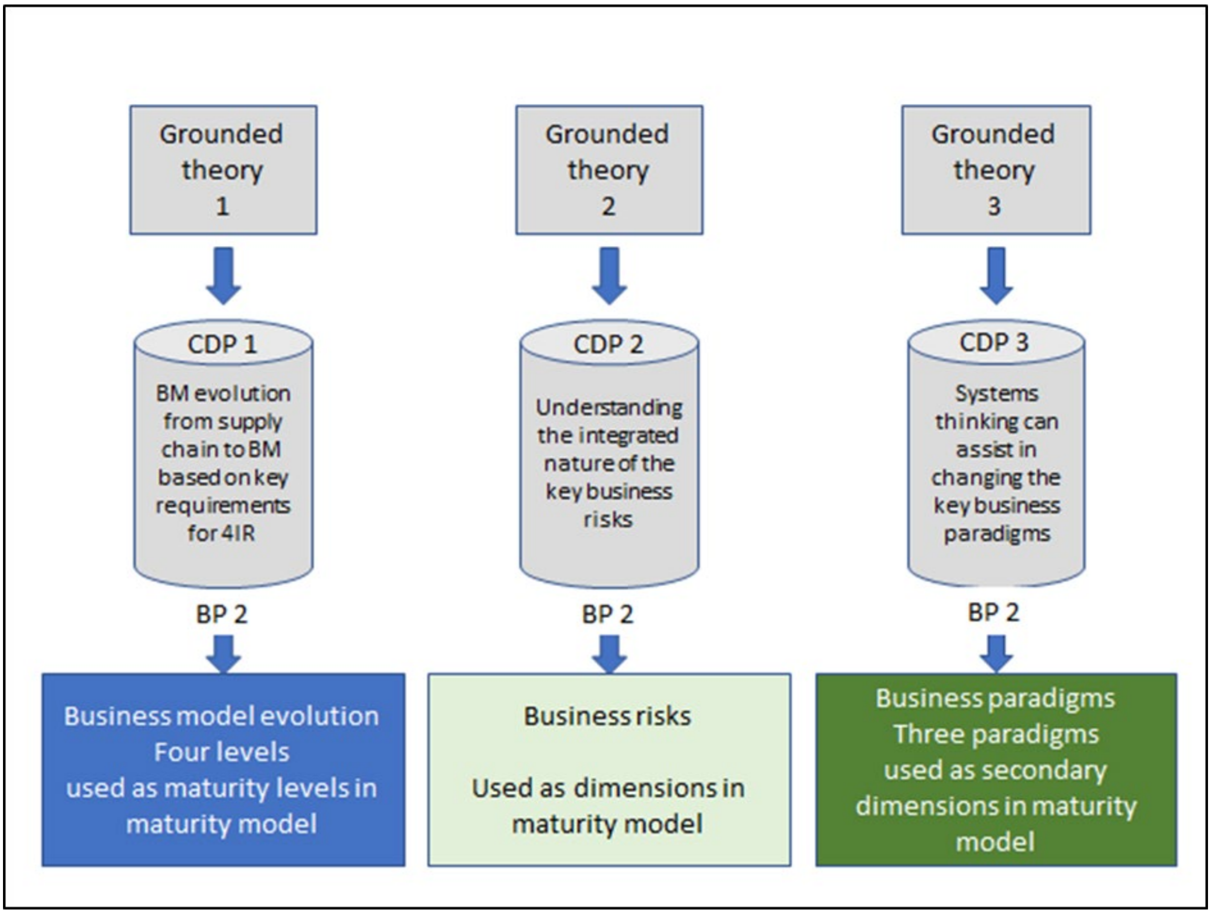

Figure 27: Use of grounded theories to develop input for maturity model

CHAPTER 6: DESIGN REQUIREMENTS AND PARAMETERS FOR THE DEVELOPMENT OF A MATURITY MODEL

Chapter 6 clarifies the design requirements of the new model and the importance of a structured approach to compile the model.

Research question 5.1:	What are the design requirements for the model that will enhance the adoption of AMin spare part provisioning?
Research question 5.2:	What are the key design parameters for a maturity model?

Introduction

Chapter 6 (BP 1) defines the design requirements and key parameters required for the development of such a maturity model. Figure 29 indicates the position of chapter 6 in the eADR framework.

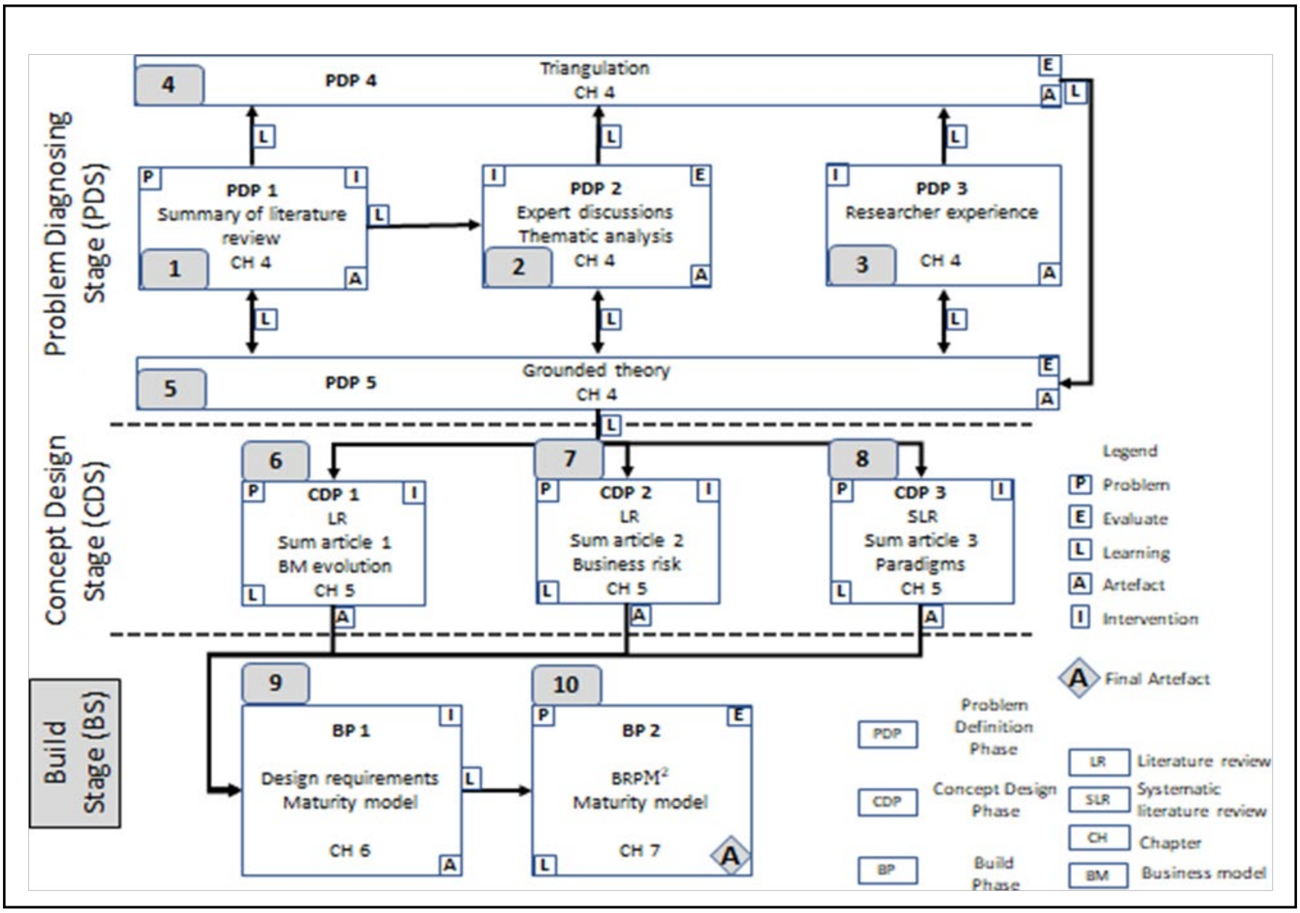

Figure 28: eADR method Build stage (BS).

6.2 Design requirements and design parameter inputs

Figure 28 presents the construction of the grounded theory that was used as the input for the build stage (BS 1) of the eADR model.

The following inputs were used to determine the design requirements for the BRPM^2 model.

(a) The evolutionary stages of the provisioning business model – developed in researcharticle CDP 1

(b) The business risks – identified in research article CDP 2

(c) The paradigms influencing the adoption of AM – identified in research article CDP 3

Literature on the design of maturity models, maturity grids and maturity frameworks (chapter 2) summarised in the design requirements traceability matrix (Table 22).

Table 22: Design requirements traceability matrix for the BRPM2 model.

Design requirements traceability matrix for the BRPM² model				
Design requirements (DR)	**Provisioning business model evolution**	**Business risk identification**	**Business paradigms**	**Literature on design of maturity models, maturity grids and maturity frameworks**
	a	**b**	**c**	**d**
1. Structure				
a) The model should be basic in design				**X**
b) There should be coherence between the different elements in the model				**X**
c) Maturity levels should follow an evolutionary path	**X**			
d) Dimensions of the model should indicatethe key business risks		**X**		
e) The elements must be clear and easy to understand				**X**

2. Usability				
a) The audience should be anyone in the organisation that would like to adopt AM forspare part provisioning				X
b) The model must define the as-is status ofthe organisation				X
c) The model can be used to create a roadmap for future improvement				X
3. **Effectiveness**				
a) An understanding of the key business risks and how they evolve will assist in theadoption of AM		X		
b) The provisioning evolution must be fromsupply to demand	X			
c) The linear (chain) philosophy must evolve to a systemic network philosophy			X	
d) Agility is a key requirement for successful interaction in the ecosystem	X			
e) An understanding of the systemic relationship between the key risks whenadopting AM can improve the adoption			X	

Table 22 summarises the design requirements applicable for the design of the required model to address the research questions and this summary concludes the following research question and will be discussed in chapter 6.

Research question 5.1: **What are the design requirements for the model that will enhance the adoption of AM in spare part provisioning?**

6.2.1 Provisioning business model evolution

King and Kraemer (1984) postulate that maturity models should not focus on a sequence of levelstowards a pre-defined end state but on factors driving evolution and change.

The maturity levels for the maturity model are based on the evolutionary stages of the provisioning business model defined in CDP 1, chapter 5, and are presented in Figure 30.

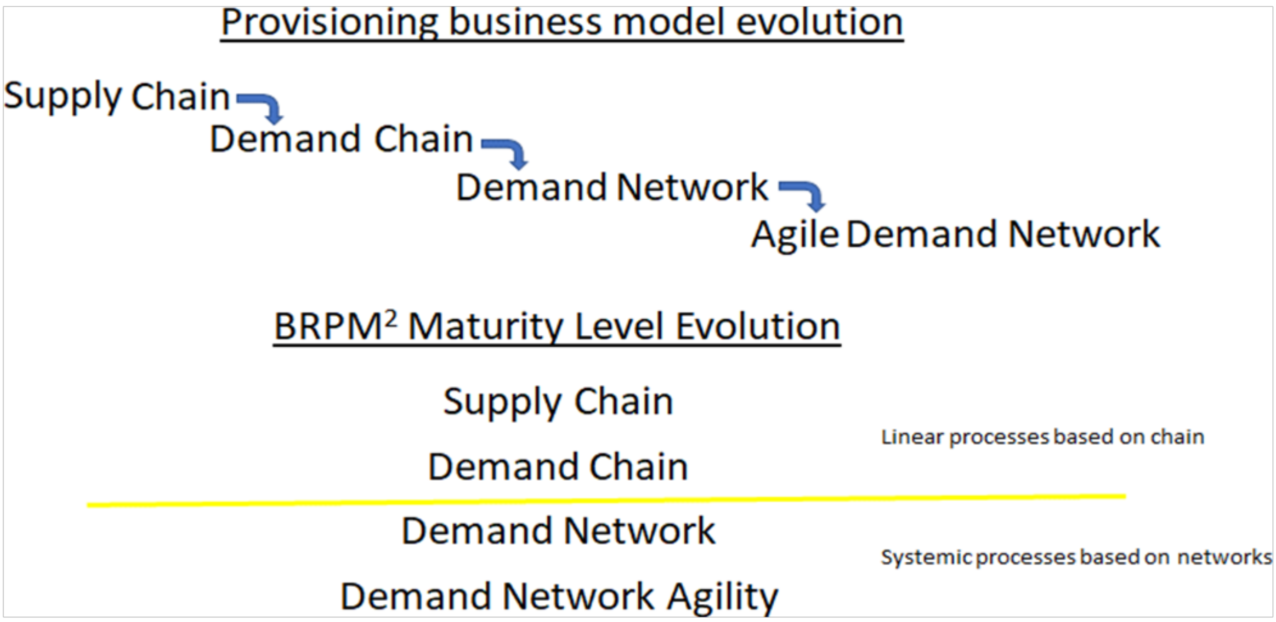

Figure 29:BRPM^2 maturity level evolution

The provisioning business model follows an evolutionary path from supply chain to an agile demand network. The maturity level evolution follows a similar evolutionary path from supply chain to demand network agility that constitutes the highest level of maturity that should be based on agility as a core activity.

The concepts in figure 30 addresses the following design requirements:

a) **Design requirement 1(c)** – Maturity levels should follow an evolutionary path
b) **Design requirement 3(b)** – The provisioning evolution must be from supply to demand
c) **Design requirement 3(d)** – Agility is a key requirement for successful interaction in the ecosystem

6.2.2 Business risks identification

The business risks have been defined in CDP 2 of chapter 5. Since this is an evolutionary process,using the additional experience from the researcher, a final list of business risks has been compiled that was used for the design of the maturity model and was included as the dimensionsof the model. Table 23 is a summary of the business risks included in the BRPM^2 model.

Column a represents the initial risks identified in the research paper on business risks (CDP 2).Column b represents the updated list after adding the researcher's experience.
Column c indicates if the risk was included in the final list.
Column d indicates if the risk was excluded from the final list.
Column e provides a reason for the inclusion or exclusion of the particular risk.

Table 23:Business risks included in the $BRPM^2$ model.

a Risk from research paper	b Risk updated withresearcher's experience	c Included final	d Excluded final	e Reason fordeviation
Culture	Culture	X		
Leadership	Leadership	X		
Processes	Processes	X		
Structure	Structure	X		
Finance	Finance	X		
IP/Legal	IP/Legal	X		
IT	IT	X		
Safety	Safety	X		
Environmental	Environmental	X		
Risk management	Risk management	X		
Maintenance strategy	Maintenance philosophy	X		Focus on change ofparadigm
Design philosophy	Design philosophy	X		
Quality assurance	Quality assurance	X		
Procurement	Procurement/Suppliers	X		Interaction with suppliers to develop AMcapabilities in the ecosystem
HR/Structures			X	HR is embedded in all the processes
Supply chain			X	Focus must be on demand. Focus is onkey components
Asset strategy			X	Divided in three spares philosophies
Sales strategy			X	Focus is on provisioning and supplying of solutions, not on sales

a Risk from research paper	b Risk updated withresearcher's experience	c Included final	d Excluded final	e Reason fordeviation
Ecosystem			X	Ecosystem embeddedin all the risk areas
	Change			New paradigm required
	Customer focus			Focus on demandinstead of sales
	Storage			Impact of AM on e-warehousing
	Inventory			Effect-provisioningsystem
	Spares philosophy – OEM (Original equipment manufacturer)			New strategies required
	Spares philosophy – EOL (End-of-life)			Systemic approach to new design and assetreplacement
	Spares philosophy – Warranty			Effect on warranty when AM adoption
	Skills			New skill sets requiredfor AM

Table 23 addresses the following design requirements

Design requirement 1(d) ·Dimensions of the model should indicate the key business risks

There might be other business risks that require attention, but the business risks listed in Table 23were the most pertinent risks applicable to this research. Due to the evolutionary nature of the model, new risks can be included by the individual users that are applicable to their area of application or specific industry.

6.2.3 Business paradigms

According to Christensen (1997), the adoption of a disruptive and strategic intervention requires new paradigms (Ismail *et al*., 2014). The key paradigms according to the research conducted in CDP 3 that influences the adoption of AM and should be included in the design of the maturity model are:

(a) A paradigm that shifts from the focus on efficiency to a focus on effectiveness

(b) A paradigm that shifts from focussing on linear, complicated processes to network-based complex processes

(c) A paradigm that shifts from linear risk management to systemic, non-linear risk management

These paradigms were included as a secondary dimension in the maturity model.This addresses the following design requirements:

Design requirement 3(c) – The linear (chain) philosophy must evolve to a systemic network philosophy

Design requirement 3(e) – An understanding of the systemic relationship between the key business risks when adopting AM can improve the adoption

6.2.4 Design framework for maturity model design and parameter

Due to the magnitude of establishing AM, users see the adoption process as complex and this notion slows down the adoption (Gress & Kalafsky, 2015). The purpose of this research is to develop a maturity model that will assist in the adoption of AM for spare part provisioning; therefore, the model needs to be basic in design and can be used by anyone in the organisation that wants to adopt AM for spare part provisioning. The model needs to be able to define the as-is status in the organisation for a selected dimension against a maturity level. This model must allow the users to create a roadmap for future improvement as well as a description of the evolutionary steps to maturity. Maturity grids (a subset of maturity models) can assist in designing a model that can adhere to these requirements (refer chapter 2 for the discussion).

A maturity grid will allow for a less complex model design that can assist with adoption. Since thedesign requirements have been set, a design framework is required to ensure that the design of the model is guided along a structured route.

The design parameters that Becker *et al*. (2009) propose and the research design framework from Mettler (2011) in Table 15 (Chapter 2) were used for this research (Table 24). Furthermore, literature regarding the design of maturity models (chapter 2) will also be applied during the design of the BRPM^2 model to further populate the development framework in chapter 7.

Table 24: Maturity model development framework derived from Mettler (2011) and Becker et al. (2009).

1	Define the problem for which the model needs to be developed					
Develop maturity model						
Phase	**Design parameter**		**Characteristics**			
2 Definescope	2.1	Focus/breadth	General issue		Specific issue	
	2.2	Level of analysis/depth	Group decision-making	Organisational considerations	Inter-org considerations	Global and societal considerations
	2.3	Novelty	Emerging	Pacing	Disruptive	Mature
	2.4	Audience	Management	Technology	Inter-organisational	Ecosystem
	2.5	Dissemination	Open		Exclusive	
3 DesignModel	3.1	Compare existing maturity models				
	3.2	Design direction	Top-Down		Bottom-Up	
	3.3	Maturity definition	Process-focused	Object-focused	People-focused	Combination
	3.4	Goal function	One-dimensional		Multidimensional	
	3.5	Design process	Theory-driven	Practitioner-based		Combination
	3.6	Formulate cell text	Descriptive	Prescriptive		Comparative
	3.7	Design product	Textual description of form	Textual description of form and function		Instantiation (assessmenttool)
	3.8	Application method	Self-assessment	Third-party assisted		Certified professionals
	3.9	Respondents	Management	Staff	Business partners	Combination
4 Evaluatedesign	4.1	Method of evaluation and communication	Delphi online	Manual forms		Delphi work groups
	4.2	Subject of evaluation	Design process	Design product		Both
	4.3	Timeframe	Ex-ante	Ex-post		Both
	4.4	Evaluation method	Naturalistic		Artificial	

The following steps were added to the maturity model design framework (Table 15) of Mettler (2011) to create a more comprehensive maturity framework and to ensure that all the important steps required for the development of a maturity model/maturity grid are condensed in one framework.

Step 1 – Define the reason for the development of the maturity model since that will guide the design decisions in the framework.

Step 3.1 – The comparison of existing maturity models for the domain under research is particularly important since this will allow the researcher to define (1) if this development is goingto be a novel artefact and not a duplication, (2) what are the maturity levels and dimensions considered for the domain of research and used in other maturity models and (3) what type of design has been followed by other researchers.

Step 3.2 – The design direction will guide the type of maturity model that will be developed, especially when the new model is a maturity grid.

Step 3.6 – The description of the cell text influences the type of maturity model as well as a decision on the formulation of the text for the elements. This will allow the differentiation between a maturity model and a maturity grid.

Step 4.1 – The method of evaluation and communication was added to include the Delphi method as part of the evaluation methods.

Adapting the maturity development framework ensures the following design requirements are met:

(a)	**Design requirement 1(a)**	–	The model should be basic in design
(b)	**Design requirement 1(b)**	–	There should be coherence between the different elements in the model
(c)	**Design requirement 1(e)**	–	The elements must be clear and easy to understand
(d)	**Design requirement 2(a)**	–	The audience should be anyone in the organisation that would like to adopt AM for spare part provisioning
(e)	**Design requirement 2(b)**	–	The model must define the as-is status of the organisation
(f)	**Design requirement 2(c)**	–	The model can be used to create a roadmap for future improvement
(e)	**Design requirement 3(a)**	–	An understanding of the key business risks and how they evolve will assist in the adoption of AM

Chapter 6 is synthesised in section 6.2.4, which answers the following research question:

Research question 5.2: **What are the key design parameters for a maturity model?**

6.3 Summary

This chapter explained the method for obtaining the design requirements of the BRPM^2 model. The maturity model for this research will be designed along the guidelines of the design requirements (Table 22) and the maturity model development framework (Table 24) developed for this research in chapter 6. The BRPM^2 model that was designed along these requirements and parameters will be presented in chapter 7.

CHAPTER 7: BUSINESS RISK PROVISIONING MATURITY MODEL(BRPM^2)

Chapter 7 presents the design and final version of the BRPM^2 model. Chapter 6 constructed a structured approach for the design of the new maturity model. In chapter 7 the design structure will be applied to the construction of the BRPM^2 maturity model

7.1 Introduction

In chapter 6 the key design requirements and parameters for the design of the BRPM² maturity model have been defined. In chapter 7, these requirements and parameters will be used to build the BRPM² model. Figure 31 indicates where this activity is positioned in the overall research design (10).

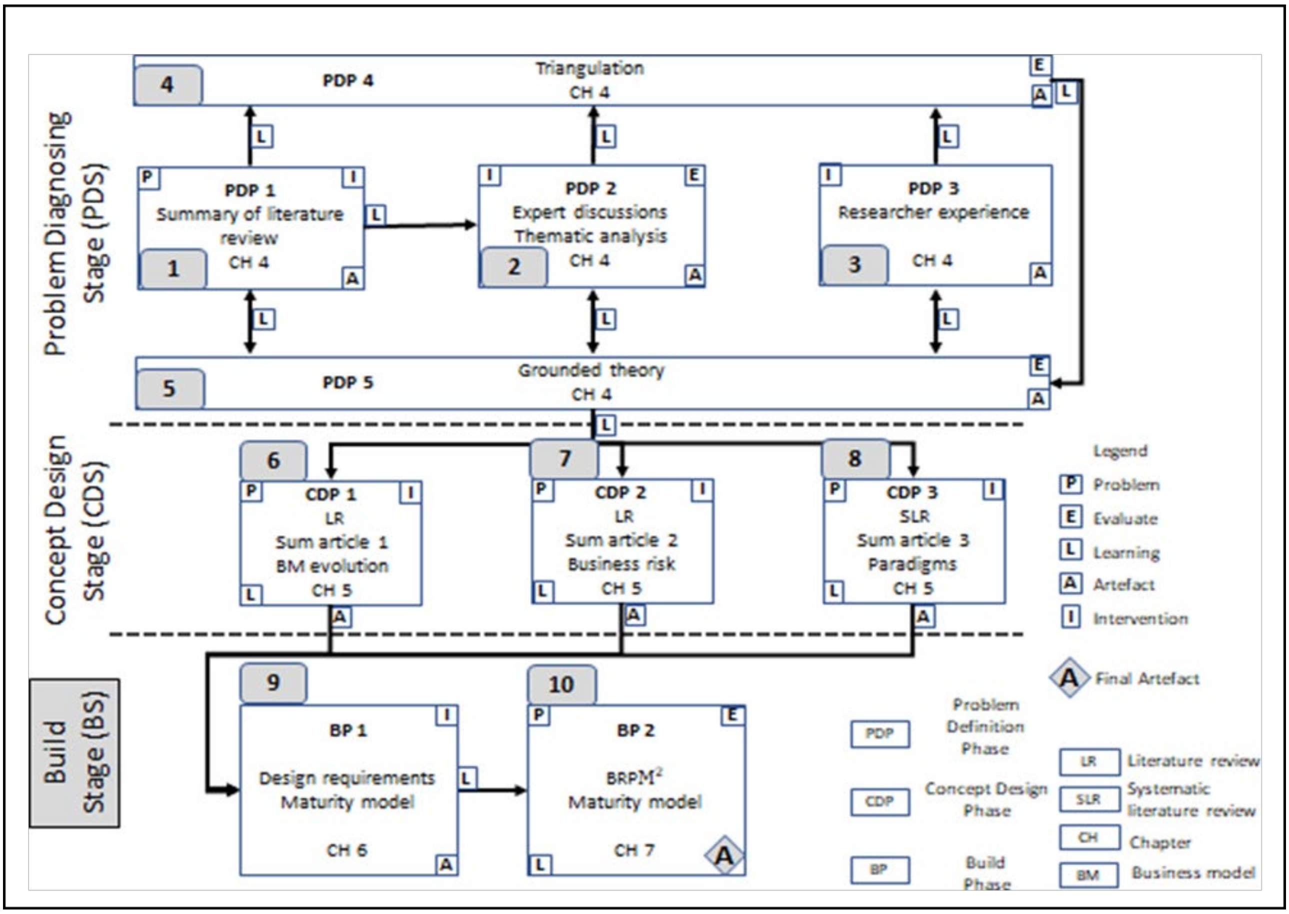

Figure 30:Research design of business risk provisioning maturity model in eADR model (10).

The business risk provisioning maturity model (BRPM²)

The purpose of the BRPM² model is to solve the research aim defined in chapter 1.

The aim of this research is to develop a maturity model that can be used as a concise business roadmap when adopting AM for spare part provisioning. The maturity model should allow organisations to understand (1) the systemic relationship between the evolutionary requirements of the provisioning system as well as (2) the complex systemic relationship between the key business risks when adopting AM as part of spare part provisioning

7.2 Constructs used in the BRPM² model for adoption of AM in spare part provisioning

The following sections elaborate on the different constructs used to develop the BRPM² model.

7.2.1 Overview of the BRPM² model

The BRPM² model is a multidimensional model that consists of maturity levels, two different dimensions and the elements as depicted in Figure 32.

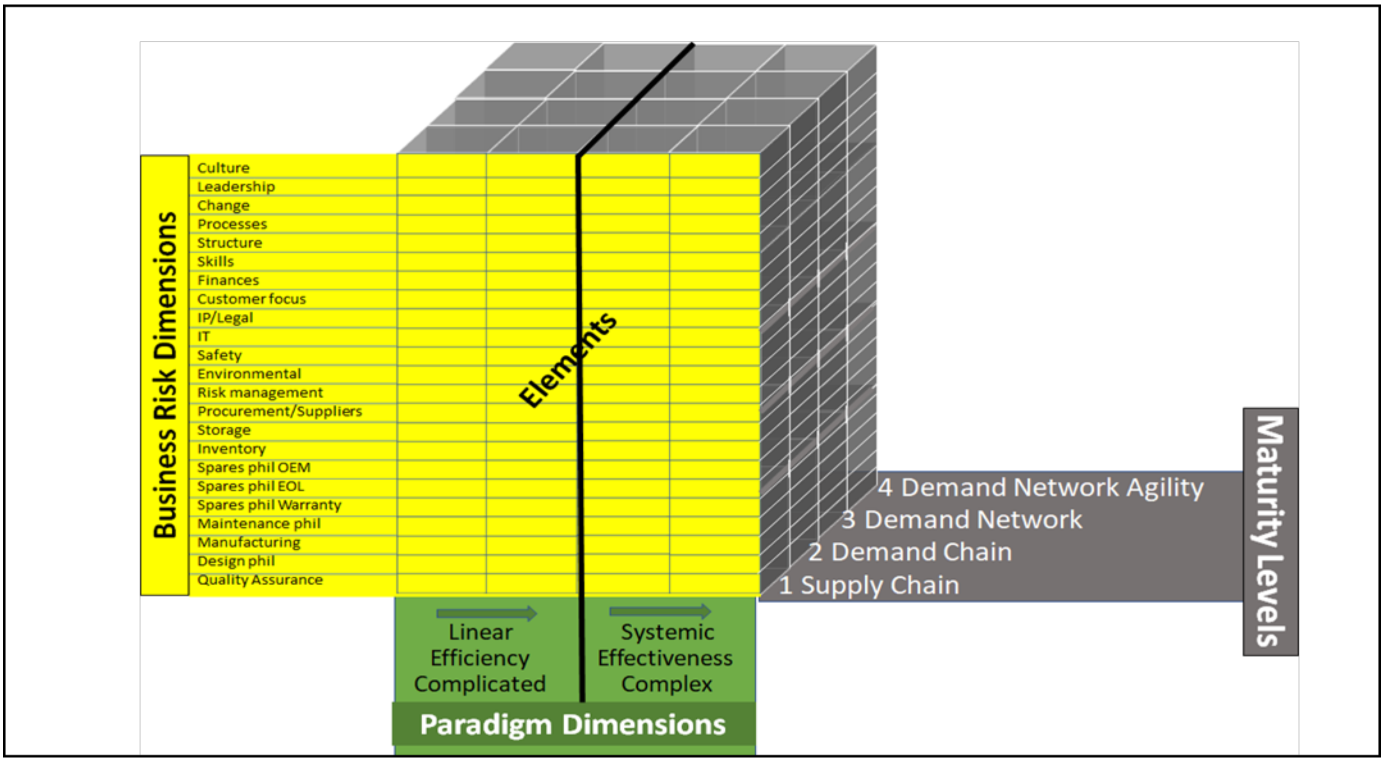

Figure 31:The BRPM² model

The next section will discuss the structured development approach of the BRPM² model (in figure 32) along the guideline of the maturity model development framework compiled for this research.

7.3 Maturity model development framework

The maturity model development framework in Table 25 will be used as the basis for the design since it provides a structured way of developing a maturity model based on the ADR principles. The applicable decision parameters for the BRPM² model have been highlighted in blue in Table25. This indicates the relevant characteristics against the design parameters that will be applied in the development of the BRPM² model applicable for phases 1 to 4.

Table 25: Maturity model development framework adopted from table 24 for model development framework.

Phases	**Maturity model development framework**				
1 Problem definition	**Define the problem for which the model needs to be developed**				
	Develop maturity model				
	Design parameter	**Characteristics**			
2 Definescope	2.1 Focus/breadth	General issue		Specific issue	
	2.2 Level of analysis/depth	Group decision-making	Organisational considerations	Inter-org considerations	Global and societal considerations
	2.3 Novelty	Emerging	Pacing	Disruptive	Mature
	2.4 Audience	Management	Technology	Inter-organisational	Ecosystem
	2.5 Dissemination	Open		Exclusive	
3 DesignModel	3.1 Compare existing maturity models				
	3.2 Design direction	Top-Down		Bottom-Up	
	3.3 Maturity definition	Process-focussed	Object-focussed	People-focussed	Combination
	3.4 Goal function	One-dimensional		Multidimensional	
	3.5 Design process	Theory-driven	Practitioner-based		Combination
	3.6 Formulate cell text	Descriptive	Prescriptive		Comparative
	3.7 Design product	Textual description of form	cription of form andfunction		Instantiation (assessment tool)
	3.8 Application method	Self-assessment	Third-party assisted		Certified professionals
	3.9 Respondents	Management	Staff	Business partners	Combination
4	4.1 Method of evaluation and communication	Delphi online	Manual forms		Delphi work groups

Evaluatedesign	4.2 Subject of evaluation	Design process	Design product	Both
	4.3 Timeframe	Ex-ante	Ex-post	Both
	4.4 Evaluation method	Naturalistic		Artificial

7.3.1 Define the problem

The research problem has been defined in paragraph 1.2 as:

The slow adoption rate of AM as part of spare part provisioning in South Africa is causedby a lack of a concise understanding of the evolutionary requirements of the provisioning system and the systemic relationship between the key business risks applicable when adopting AM as part of spare part provisioning. It is therefore required that a concise model be constructed that will assist with the adoption of AM in spare part provisioning in SouthAfrica.

7.3.2 Define the scope of the maturity model7.4.2.1 Focus of the model The focus of the maturity model for this research is of a specific nature. The reason for this can be found in the problem definition where the requirement is to design a maturity model for the adoption of AM in spare part provisioning. It will be a condensed model that will create systemic visibility of the key business risks along the provisioning evolution.

7.4.2.2 Level of analysis/depth

The level of analysis/depth is inter-organisational since the same spare parts can be used in multiple plants of the organisation. It can also be designed as global and societal considerations since components can be redesigned so that they can be utilised in multiple plants across multiple industries. A single e-file will be linked to all the equipment where this item is used. This will be applicable at the highest maturity level of the model where maintenance can be rendered as a service and becomes predictive in nature.

The societal impact is part of the circular economy where components are designed to be recycledand therefore reduce the waste factor significantly.

7.4.2.3 Novelty

According to the *Oxford Dictionary* (Simpson and Weiner, 1989), novelty can be defined as “the quality of being new, different and interesting”. Novelty indicates what will be the contribution of this model. There are 4 levels as indicated in table 25 i.e. emerging, pacing, disruptive or mature. The maturity model for this research is designed to improve the adoption of AM. Since AM is a disruptive and innovative technology, the purpose of this model is to create awareness of the systemic impact of AM on the identified key business risks. The model will allow organisations to create an as-is status relating to the key business risks and then to develop a roadmap for the adoption of AM aspart of spare part provisioning. The novelty of the model will be discussed in chapter 8 where the BRPM2 model is designed according to these structured parameters of the maturity model development framework.

7.4.2.4 Audience

The audience for this model will be inter-organisational and the ecosystem since the adoption ofAM creates a culture of co-innovation that applies to all levels in the organisation as well as the interaction of the ecosystem. The model needs to create the awareness and understanding of theevolutionary maturity development applicable when adopting AM.

7.4.2.5 Dissemination

The model must be an open design since it needs to be available to all levels in the organisation and due to the evolutionary nature of the model it can be adjusted as and when additional dimensions are identified that can add value to the model.

7.3.3 Design of the BRPM^2 model

7.4.3.1 Compare existing maturity models

The comparison of existing maturity models ensures that there is no duplication and that the new design remains a novel design that will fulfil the specific requirement as stated in paragraph 7.4.2.1. Since the maturity model in this research is based on the provisioning system of AM in spare part provisioning in 4IR, comparison of maturity models should take place using the following search criteria: additive manufacturing, smart manufacturing, supply chain and 4IR. Smart manufacturing (SM) is included since there is an important relationship between the adoption of smart manufacturing and the adoption of AM.

Table 26 is a comparison between 4IR, AM and supply chain management (SCM) maturitymodels.

Table 26:Comparison of 4IR, AM and SCM maturity models.

Element	I4.0 MM	AM–MM	SCMM
Objectives	To provide a maturity model that addresses operations and supply chain management (OSCM) structured by several dimensions to measure the digitisation score in manufacturing organisations and their supply chains to develop a self-assessmenttool to support the transition towards I4.0 in the OSCM domain	To create an integrative, conceptual framework using distinct innovation process models and manufacturing systems to provide multi-domain perspectives on AM	To identify a company's position within a framework of supply chain integration activities
Focus	Operations and supply chain digital implementation	Determine organisational maturity through the measurement of AM technology adoption	Benchmark supply chain processes to identify gaps between current processes and industry benchmarks
Analysis dimensions	Customer, logistics, supplier, integration, planning and production control (PPC), quality, maintenance	Product development Production support Parts production	Chassis engine
Processareas	Customer relationship, segmentation and satisfaction as well as marketing and sales strategies Logistics refer to delivery, transportation, distribution, asset and inventory Supplier refers to supply network coordination, supplier relationship management and flexibility Integration refers to advances in the level of integration of physical and computational technologies Quality control systems Maintenance refers to reliability improvement.	Product prototyping Product complexity Advanced materials Production set-up and agility	Process view Process-structured Process jobs Customer-focused Process value beliefs Process measurement and management system Best practices

Maturitylevels	5 (0–4)	4 Non-user Outsourcing In-house In-house and outsourcing	5 (Ad hoc) Defined Linked Integrated Extended
Inspiring framework	CMM	Chasm model Moore (1991)	Crosby quality framework and CMMI, Supply Chain Council
Model purpose	Descriptive and prescriptive	Descriptive	Descriptive and benchmark, roadmap

Caiado *et al*. (2020) developed the I4.0 MM model to create guidelines for digitisation of smart operations and supply chain management (OSCM) in 4IR. They argue that 4IR maturity models (MM's) that explicitly address OSCM in a generalised, comprehensive and detailed manner are rare. The model is designed with five maturity levels based on CMM and three dimensions with seven sub-elements. The elements include provisioning related activities as well as integration inthe ecosystem. This model focusses on certain activities that will be affected during the adoption of the digitisation of smart manufacturing but do not include specific activities that can enhance the adoption of the 4IR technologies.

Blichfeldt *et al*. (2019) developed the AM–MM model to assess the maturity of organisations relating to their adoption of AM technologies. The model is designed from the chasm model of Moore (1991). Four maturity levels linking to the levels of the chasm model that is based on the diffusion of innovation are defined. One of the goals of the model is to create awareness of the multidisciplinary impact of AM in the adopting organisation.

McCormack (2001) created the supply chain maturity assessment SCM MM model. This assessment can be used to create a roadmap for key supply chain processes and an action planof what is required to reach the desired level of maturity. The model uses various models as the basis for the design and differs from the normal CMM or CMMI maturity models by a visual roadmap with key measurements indicating the maturity.

De Carolis *et al*. (2017) completed a comparison between three maturity models relating to smart manufacturing. Their finding was that the three maturity models, i.e. the digital readiness assessment maturity model (DREAMY), the smart manufacturing readiness level (SMSRL) and the manufacturing operations management/capability maturity model (MOM) complemented eachother. Table 27 is a summary of the three SM maturity models.

Table 27:Comparison of smart manufacturing maturity models (de Carolis et al., 2017).

Element	DREAMY	SMSRL	MOM
Objectives	To assess a manufacturing company readiness level for startingthe digital transformation process To identify strengths and weaknesses and related opportunities manufacturers can gather from the digital transformation, with the final aim tohelp them in defining a roadmap for prioritising investments	To assess a manufacturing company'sreadiness to employ data-intensive technologies forits performance management	To determine the level of an organisation's capability to have mature,robust and repeatable manufacturing operations
Focus	Manufacturing company/product andfactory lifecycles	Maturity of performance improvement tasks/processes, availability of software supports, maturity of information sharing capability and availability of responsible personnel	Manufacturing OperationsManagement (MOM) processes
Analysis dimensions	Process/Execution, monitoring andcontrol, organisation, technology	Organisation, IT, performance management(process execution) and information connectivity	Process/Execution
Process Areas	Product and asset design andengineering Production management Quality management Maintenance managementLogistics management Digital backbone	(Change) Requirement developments Basic rough design of a new or change requirements Detail design and test	Production operations management Inventory managementQuality test operations management Maintenance operations management
Maturity Levels	5 (1–5)	6 (0–5)	6 (0–5)
Inspiring framework	CMMI	Factory design and improvement activity model	ISA-95 Enterprise Controlactivities
Model purpose	Descriptive and prescriptive	Descriptive and comparative	Descriptive and comparative

The comparison of de Carolis *et al*. (2017), Table 27, of the three maturity models relating to SM creates a basis for organisations to understand what is required when they consider embarking on the digitalisation journey. This summary indicates that several capabilities are required in terms of the organisation, process execution and technology. Organisations embarking on the digitilisation journey should at least include all the dimensions included in these models as part of their maturity models (de Carolis *et al*., 2017). These models are mainly descriptive of nature and allow organisations to use them for creating a roadmap for future improvement.

It is important to note that the maturity models developed for SM used more dimensions to measure the maturity of the organisation than the models developed for SCM. The reason for this relates to the complexity involved when adopting SM and therefore more activities are involved in the adoption process. Maturity models measuring adoption of AM are limited since the currentfocus regarding AM is more on the technologies and the adoption of the specific technologies than on the organisational aspect that can be seen in a more mature environment like SM.

From the maturity model comparison, no maturity model could be found that was based on the provisioning system evolution. Most of the supply chain related maturity models used the normal CMM or CMMI maturity levels that varied between four to six maturity levels. The 4IR, AM and SM maturity models could be used to assess which of the dimensions were important to incorporate in the model design. Since AM is defined as disruptive in 4IR and SM technology, both these areas added perspective on the dimensions that are important to measure.

Mettler (2011) stated that when focusing on emerging innovations the definition of maturity maybe extremely uncertain, and that can affect the available maturity models.

7.4.3.2 Design Direction

The design direction for this model is a top-down design since the maturity levels were defined first, then the dimensions and lastly the elements that will follow the evolutionary process of the model, see chapter 2 for discussion.

7.4.3.3 Maturity definition

The progression of maturity will be based on a transition from efficiency to effectiveness and will therefore have a profound impact on the improvement in processes and business practices. According to Mettler (2011), when the focus of the progression in maturity is on an efficiency improvement, then the definition of maturity will have a process focus. The adoption of innovationand disruptive business practices will also require a change in skills of the participants and how they integrate into the ecosystem, therefore the focus will not only be on processes but will also be on people and the role they play in the maturity evolution.

7.4.3.4 Goal function

The maturity model is a multidimensional model. Figure 32 is a representation of this multidimensional model.

One dimension focusses on the key business risks, which is a combination between the business risks adopted from Harmse (2019) (CDP 2) and the researchers personal experience, and the other dimension focusses on the paradigms that influence the adoption of AM and that has been adopted from Harmse and Coetzee (2020) (CDP 3) and is included in chapter 5.

7.4.3.5 Design process

Mettler (2011) states that the decision on the design process will have a profound influence on the choice of research methods to be used. eADR was the underlying methodology since action research creates an innovative artefact. The design of the model was based on the research objectives defined in paragraph 1.5 and the design requirements and design parameters for maturity models as stipulated in chapter 6. The design is a combination of literature, practical experience from the researcher and inputs from experts in the ecosystem in South Africa.

7.4.3.6 Formulate cell text

The cell text or elements will be descriptive and will follow an evolutionary maturity path. There is coherence amongst all the elements in the model. See chapter 2 for the literature review of the elements.

7.4.3.7 Design product

Gregor and Hevner (2013) state that an invention is a radical breakthrough and will require new paradigms for adoption. The development process can be defined as an investigative search over a complex problem space that requires specific skills, imagination, creativity, insight and knowledge across multiple areas of investigation to find a feasible solution (Gregor & Hevner, 2013).

The maturity model, developed during this research can be used as a roadmap that will assist organisations to define the as-is scenario relating to the defined business risks and provisioning evolution. The roadmap will act as a systemic tool considering the interrelationship between all defined key business risks. After the decision regarding the required maturity levels has been taken, the necessary actions from the maturity model can be derived and a strategic roadmap can be compiled. This roadmap will then assist organisations and teams in the understanding of the systemic relationship between the defined elements in the model. Saritas and Oner (2004) argue that the quality of the roadmapwill improve as more participants from diverse environments participate to create the roadmap. The maturity model will therefore be a textual description of form and function. The design should be basic so that it can create a concise overview, and the roadmap should be visible on a singleA4 sheet with no subsequent layers.

The research papers contributed to the maturity model in the following way:

Research paper 1: Provisioning system evolutionary stages were used as the maturity levels

Research paper 2: Business risks were used as the dimensions of the model

Research paper 3: Business paradigms were used as the secondary dimension in the model.These

three research papers will be discussed in the following sections.

7.4.3.7.1 Maturity level

Maturity levels can vary between four to six and will be fixed for a top-down maturity model as discussed in paragraph 2.2.8.5. It has been decided that for this model there will be four maturity levels since it avoids the central tendency and provides greater differentiation between levels (Caiado *et al*., 2020).

The focus of this maturity model is the adoption of AM in the provisioning of spare parts. The definition of the different maturity levels can be seen in Table 28.

Table 28: Definition of maturity levels.

Maturity level	Definition
Supply chain	Structured, linear processes based on a push philosophy and a hierarchical silo business model. Organisation seen as a collection of functions. Creativity and innovation limited. Focus on doing the right thing according to set procedures. Complicated processes visible in the organisation with focus on efficiency – doing the right things.
Demand chain	Structured, linear processes based on a pull philosophy with closer contact to customer requirements. More internal and external customer focus. Improve efficiency of the organisation. (Doing the right things – benchmarking against others).
Demand network	Non-linear processes based on integrated network requirements from the global network, built on dynamic team structures more capable to manage the increased uncertainty, complexity and change as part of the global network. Organisation seen as an integration of different processes. Break-through from focusing on efficiency to effectiveness. (Doing the right things right – internal innovation).
Demand networkagility	Agile processes based on an agile, systemic philosophy integrated into the global ecosystem where creativity and innovation become the differentiator across the ecosystem. (Create co-innovative and agile processes that provide a dynamic and competitive edge). Use agility to combat and alleviate complexity and change it to a competitive edge. Focus on effectiveness of the organisation as part of the ecosystem or global network.

The maturity levels as indicated in Table 28 (definition of maturity levels) have concise descriptorsand there is a logical progression from supply to demand and from chain to networks. The rationalefor the maturity levels is based on the evolutionary requirements of the provisioning requirements through the four industrial revolutions. This is based on the article by Harmse and Holm (2019) where they researched the evolution of business models from supply chain to agile demand networks. A summary of this article is included in chapter 5.

Figure 30 presents the maturity level evolution. This evolution includes the following:

(a) Evolution from supply to demand

(b) Evolution from linear chain to systemic network

(c) Inclusion of agility as a key component for the highest level of maturity

This also corresponds with the literature research in chapter 2 regarding the importance of agilitywhen adopting AM and operating in 4IR. The maturity levels relate to provisioning systems that focus on the demand of the customer or the ecosystem/network.

There are four maturity levels:

Level 1 – Supply chain

Level 2 – Demand chain

Level 3 – Demand network

Level 4 – Demand network agility

Figure 33 indicates the maturity levels as part of the BRPM^2 model. There are four maturity levelsto avoid the central phenomenon. The maturity levels allow the users to change their paradigm supply to demand and from linear chains to systemic networks as part of the ecosystem.

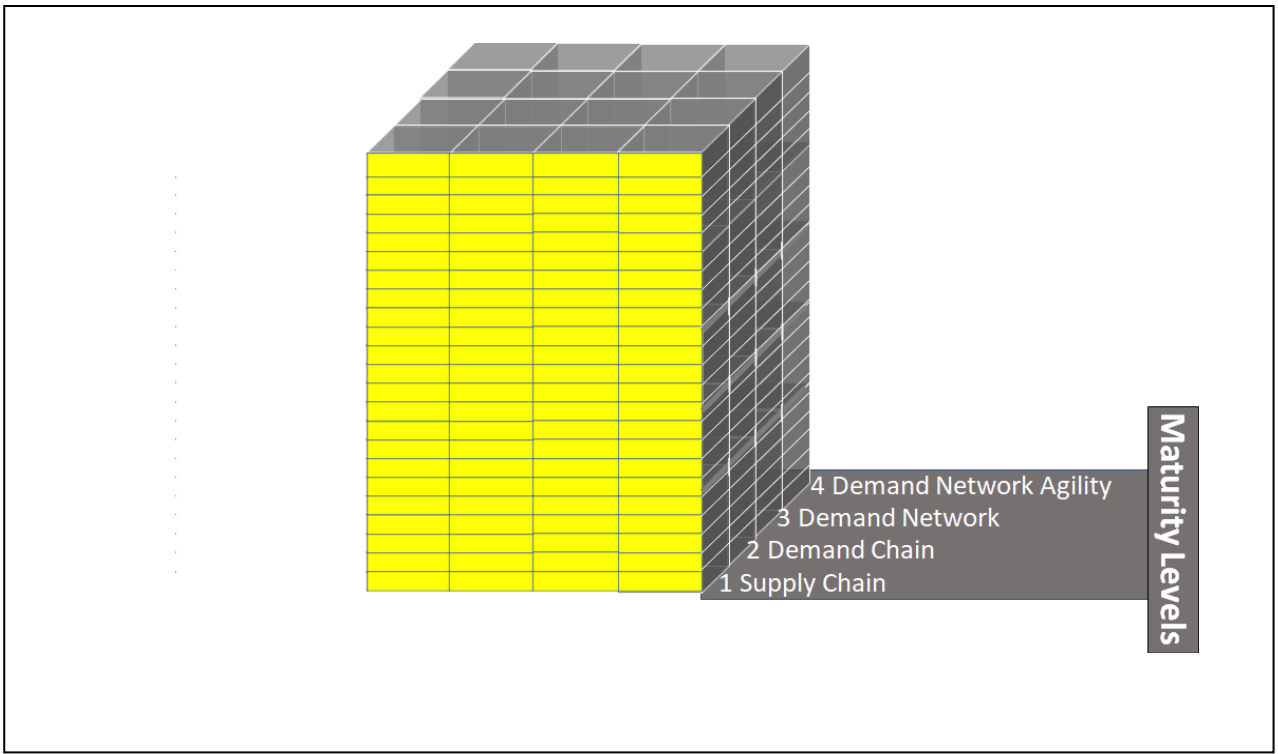

Figure 33 : Maturity levels of the BRPM² model

7.4.3.7.2 Dimensions

The final list of dimensions that are included in the BRPM² model has been compiled in Figure 34.This list is a combination of the key business risks and can be seen in Figure 34. There are 23 dimensions. The model is an evolutionary model and when new or additional dimensions are identified, it can be added to the model. There are two levels of dimensions. The one level represents the key business risks identified for use in this research (CDP 2). The second level is based on the key business paradigms that require adjustment to facilitate successful adoption of AM in spare part provisioning defined as part of this research (CDP 3).

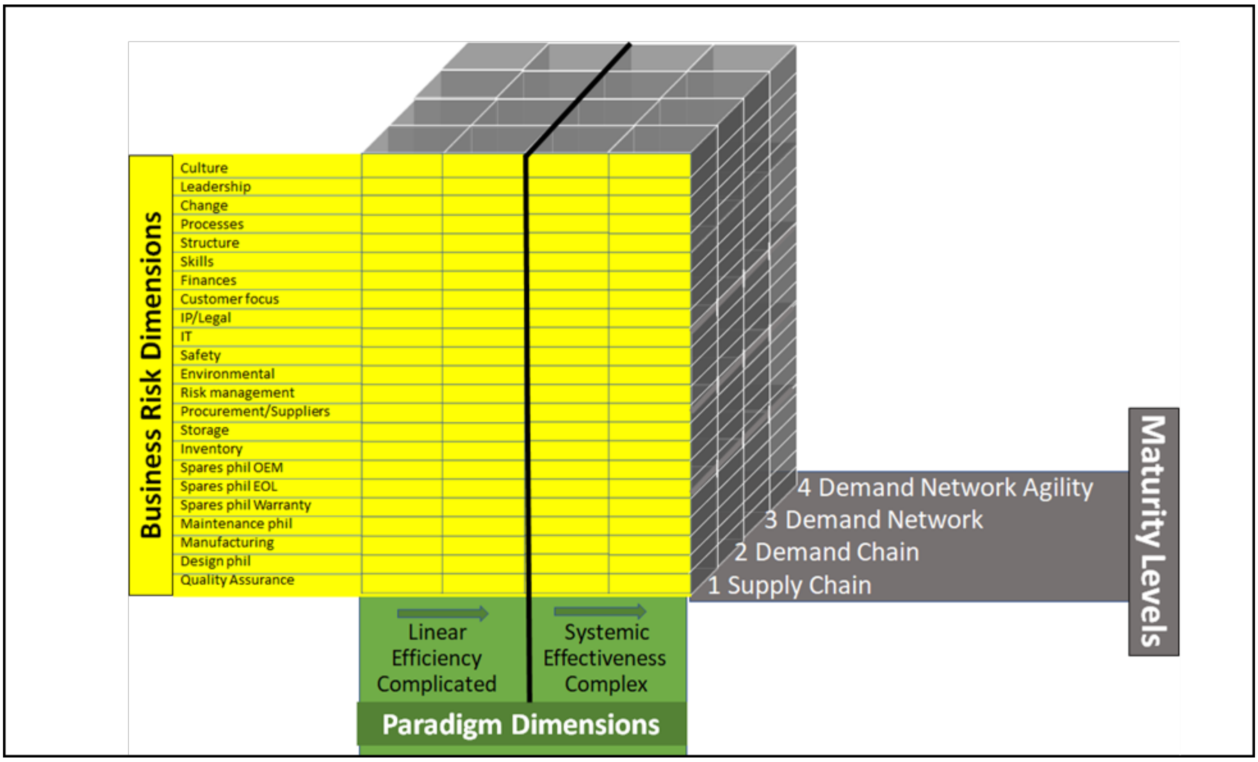

Figure 324:Dimensions of the BRPM^2 model

There is a systemic relationship between the dimensions in the model, see Figure 35. The understanding of the systemic impact between the different dimensions will influence the progression of the team that adopts AM as part of spare part provisioning on their journey to maturity. The systemic relationship between the culture of the organisation and the adoption of innovative design principles can have a significant influence on the adoption of AM. This will thenbe influenced by the leadership style and will also have an influence on the inventory management. See Figure 35 for the systemic relationship map of the example.

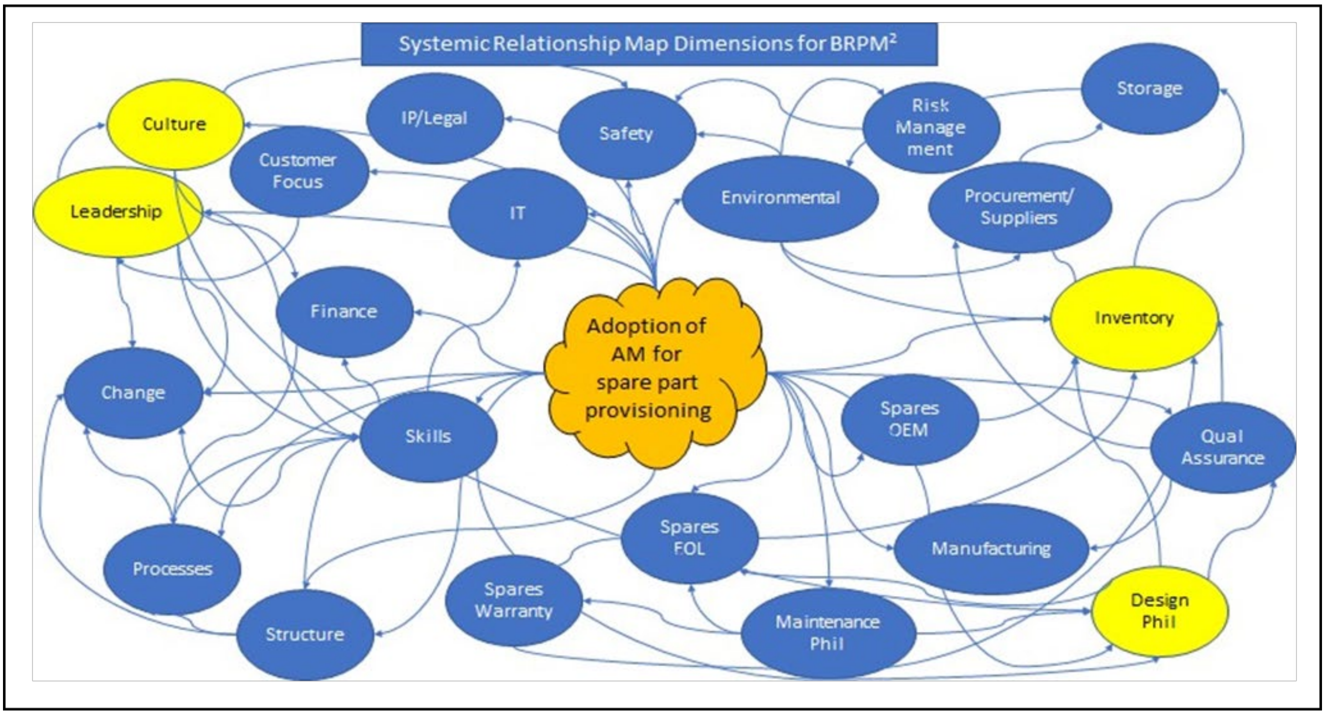

Figure 35:Systematic relationship between dimensions for the BRPM^2 model (Author's own work)

The second dimension is the paradigm dimension. This dimension consists of three paradigms that have been defined in CDP 3 and are displayed in Figure 34. As the maturity level in the model increases, so does the requirement for a paradigm change of these three paradigms. Systems thinking and an understanding of the systemic nature of the risk dimensions will allow the required paradigm shifts to take place.

7.4.3.7.3 Elements

The research on the elements for a maturity model has been completed in chapter two and this section refers to section 2.2.8.6.3. The elements for a disruptive innovation can be compiled by defining the elements for the lowest level of maturity first and then the highest level of maturity (Maier *et al*., 2009). The elements in between can then be completed and aligned with the evolutionary nature of the maturity level and the applicable dimension. There must be coherence between the elements. The elements can be defined through literature reviews, expert inputs or researcher experience.The elements for the BRPM^2 model have been defined accordingly from the literature research in chapter 2, the expert discussions and researchers experience in chapter 4 (Maier *et al*., 2009). Figure 36 indicates the position of the elements in the model and their relationship to the maturity levels and dimensions.

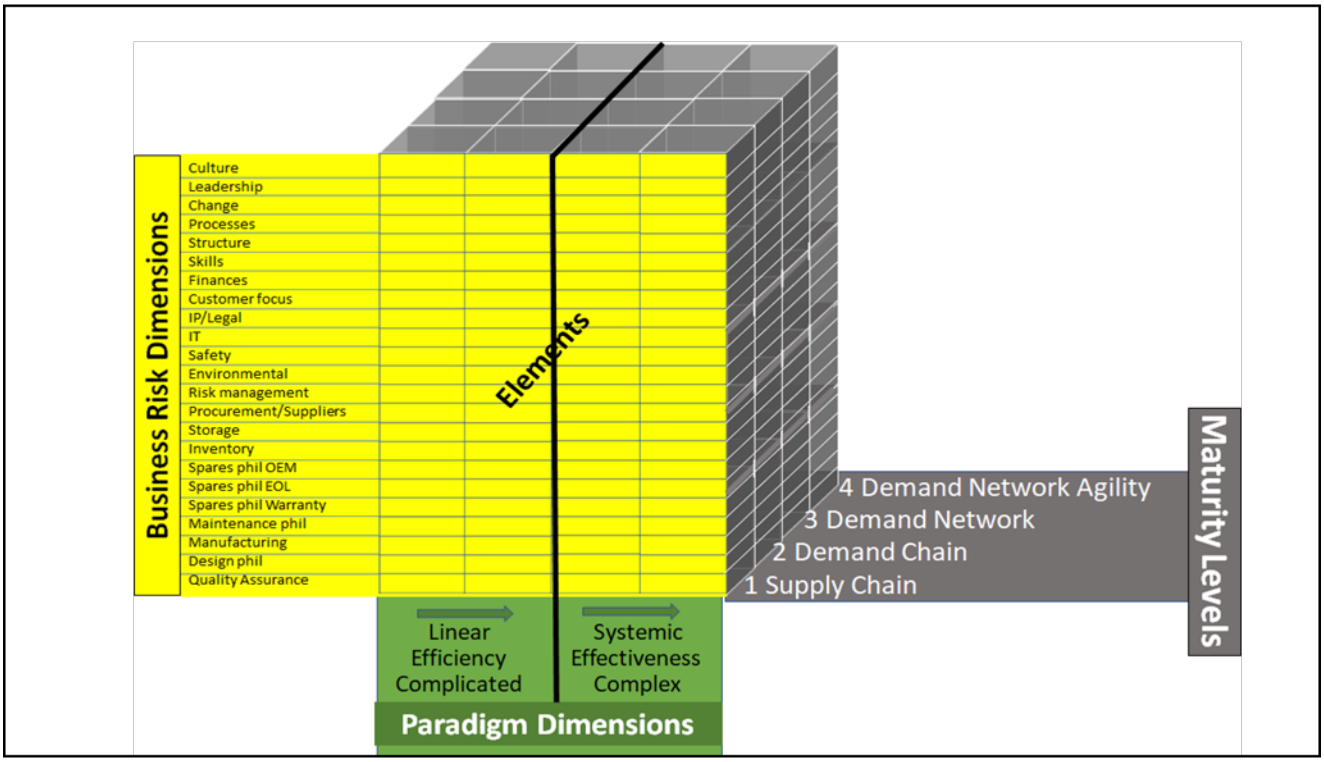

Figure 336:Position of elements in the BRPM2 model

Figure 37 is a list of all the elements per dimension and maturity level for the BRPM^2 model. The elements are descriptive since the definition will guide the user to the requirements but will not provide any specific measurements for the element against a dimension at a specific maturity level.

	Dimensions	ELEMENTS			
Business Risk Dimensions	**Culture**	Consistency, compliance with existing rules, need to know basis, accepting status quo, driven by cost and efficiency, adversarial, mutual mistrust, accountable for actions	Self interest, internal, some cross-functional interaction to solve problems	Challenge status quo move from internal silo focus to integrated network focus	Co-sensing, co-creation, transparency, co-innovation, creativity, accountable for outcome of actions, agility, adaptive, learning organisation
	Leadership	Autocratic, leader makes the decision, push decisions to team, task-orientated, egocentric (Power of position), extended decision process, keep business as stable as possible, do not respond well to criticism	Hierarchical, encourage input from team, focused on own business success, decisions based on senior leadership input, allow some criticism	Participative, network, team-based, focus on value of business to the network, decisions based on internal team input and some input form external network, criticism used to improve business	Co-creating, co-sensing, co-inspiring, context creating, people orientated, *ecocentric* (power of influence), agile leadership, nimble decision process, understand and navigate complexity, encourage criticism
	Change	Top-down, when required, individualistic, silo-based, change mindset and what people think	Consultation, focus not only on internal satisfaction but more on customer requirements	Cross-functional team inclusion, process-orientated, process metrics tied to individual and team performance	Agile adoption, continuous and largely self-organising through group, change behavior and what people do
	Processes	Linear, push-based, static business processes, inter-department focused	Linear, pull-based, limited cross-functional, often manual and one-time efforts	Network integrated, end-to-end focus, commitment to continuous improvement	Agile, eco-dynamic interaction, enterprise and partners are organized around processes
	Structure	Functional silos	Cross functional silos	Team-based	Agile, eco networks, inter-enterprise process teams
	Skills	Subject matter experts	Analytical and sensing	Networking, create value through others, creativity, interpret network dynamics	Innovative, eco co-creation, on demand, agile, add intelligence to external stimuli
	Finance	Lowest cost	Cost to serve	TCO (Total cost of Ownership)	TCE (Total Cost of Ecosystem)
	Customer focus	Push, product-centric.	Pull, product-centric	Pull, demand-driven	Interactive demand, customer-centric
	IP/Legal	IP internal	IP Internal	IP Internal, external	IP ecosystem
	IT	ERP systems, pockets of optimisation within functions, IT plays a significant role in the roll out and implementation of technologies	Focus on maintenance support systems, IT leads cross-functional initiative (systems-focused)	Some 4IR technologies, team identify requirements and take ownership of required technologies.	Integrate technologies of eco system and real time monitoring
	Safety	Enforce, top-down	Enforce, ownership at source	Individual ownership, engineer safety in	Way of life, creative solutions
	Environmental	Compliance	Cradle-to-grave	Cradle-to-grave with some recycling	Circular management
	Risk management	Linear-based risk assessment, break risk down into components, reductionist, risk-averse.	Linear risk management, investigate interaction of risk elements	Integrated risk management, cross-functional interaction	Non-linear, systemic eco risk management, involve external and internal entities, align risk management with innovation culture
	Procurement/Suppliers	Category managed at arm's length	Focused supply base, forecast to suppliers, improved interaction	Network-managed, integrate suppliers	Eco-procurement, suppliers become valued business partners, co-creation of parts
	Storage	Multiple warehouse	Warehouse, Vendor managed inventory	Some AM parts in e-warehouse	Conventional, e-warehousing
	Inventory	Obsolescence, excess stock, long tail of slow-moving stock, not all stock visible on ERP system, some items not linked to BOM and functional locations, functional view of inventory	Obsolescence, MRP, more items linked to BOMs and functional locations	MRP, reduced stock levels, improved granularity on safety stock, manage use in multiple locations centrally, reducing long tail of slow moving parts with AM	Critical stock, balance on demand, all items linked to BOM and functional location, integrated holistic view of inventory
	Spares philosophy - OEM	Procure from OEM	Procure from OEM	Discuss introduction of AM, print monitoring sensors into AM parts	Procure AM parts or AM e-file to print local with accredited bureau, OEM manages spare requirements globally and advise when replacement is
	Spares philosophy - End-of-life equipment	Declare redundant and discard	Declare redundant and discard, investigate possibility of AM to obtain spares	Redesign and print some components with AM.	Extend equipment life cycle and efficiency with improved component design through AM
	Spares philosophy - Warranty	Warranty on OEM parts	Warranty on OEM parts	Warranty on OEM parts - conventional and AM	OEM sell e-file, warranty dictates that component must be printed on specific equipment and standards
	Maintenance philosophy	Reactive, run to failure	Preventative, time-based	Predictive, condition-based	Prescriptive, EAIM (Eco Asset integrity management), based on sensors and AI
	Manufacturing	Conventional	Conventional, AM prototype	Basic AM parts, conventional	AM, conventional
	Design philosophy	Design for manufacturing, DfM, avoid complexity	Design for manufacturability, complexity is expensive	Design for maintainability, introduce some complexity, standardisation of components across network	Design for functionality and personification, DfAM (Design for Additive Manufacturing), design to optimize TCE, complexity can be accommodated
	Quality assurance	Adhere to set standards, inspect quality in	Adhere to set standards, inspect quality in	Adhere to set standards, build quality in	Adhere to set standards, imbed quality in process, create new standards

Figure 347:Elements of the BRPM² model.

Figure 37 indicates the evolution of the elements for the BRPM² model. Section 6.2.2 discussed the requirements for the development of these elements. The elements for this model were developed through research on the lowest level of maturity, i.e. supply chain and the requirementfor the South African dimension in 4IR and with AM. The two levels in-between were derived from the literature review, expert discussions or own experience. The elements are clear to understand and evolutionary.

The following element is an own creation from abductive reasoning: total cost of ecosystem (TCE)vs total cost of ownership (TCO). It is important to ensure that there is a total understanding of allcosts that will affect the business and how to manage the costs across the ecosystem. Figure 37 presents a comprehensive list of all the elements per dimension and maturity level.

7.4.3.8 Application method

The maturity model will be used as a self-assessment instrument creating an as-is status of the current maturity level against the dimensions. Once the desired state is identified on the maturity model, the two markers – the-as is and the to-be - per dimension can be linked and this will create a roadmap for the organization towards their desired state see figure 41. The linear, single dimension models based on CMMI and other maturity models indicatethat maturity can only be reached by an organisation if all the requirements for that maturity levelhave been met.

Since this model is a multidimensional model based on the adoption of AM for spare part provisioning, the maturity level of the organisation for AM adoption as part of the provisioning system will be at the maturity level where the organisation has achieved most of the dimensions.The red circles in Figure 38 indicate the current maturity level per risk dimension of the organization and is only used as an example.

Not all the dimensions will be at the same maturity level. The maturity level of the organisation will be determined by the number of dimensions that are linked with a marker to that particular maturity level. The maturity level with the highest number of markers, as indicated in Figure 38, isthe as-is maturity level.

		BRPM^2 Maturity level						
		Supply Chain		Demand Chain		Demand Network		Demand Network Agility
DIMENSIONS		ELEMENTS						
Culture	x	Consistency, compliance with existing rules, need to know basis, accepting status quo, driven by cost and efficiency, adversarial, mutual mistrust, accountable for actions		Self interest, internal, some cross-functional interaction to solve problems		Challenge status quo move from internal silo focus to integrated network focus		Co-sensing, co-creation, transparency, co-innovation, creativity, accountable for outcome of actions, agility, adaptive, learning organisation
Leadership		Autocratic, leader makes the decision, push decisions to team, task-orientated, egocentric (Power of position), extended decision process, keep business as stable as possible, do not respond well to criticism	x	Hierarchical, encourage input from team, focused on own business success, decisions based on senior leadership input, allow some criticism		Participative, network, team-based, focus on value of business to the network, decisions based on internal team input and some input form external network, criticism used to improve business		Co-creating, co-sensing, co-inspiring, context creating, people orientated, *ecocentric* (power of influence), agile leadership, nimble decision process, understand and navigate complexity, encourage criticism
Change		Top-down, when required, individualistic, silo-based, change mindset and what people think	x	Consultation, focus not only on internal satisfaction but more on customer requirements		Cross-functional team inclusion, process-orientated, process metrics tied to individual and team performance		Agile adoption, continuous and largely self-organising through group, change behavior and what people do
Processes		Linear, push-based, static business processes, inter-department focused	x	Linear, pull-based, limited cross-functional, often manual and one-time efforts		Network integrated, end-to-end focus, commitment to continuous improvement		Agile, eco-dynamic interaction, enterprise and partners are organized around processes
Structure	x	Functional silos		Cross functional silos		Team-based		Agile, eco networks, inter-enterprise process teams
Skills		Subject matter experts	x	Analytical and sensing		Networking, create value through others, creativity, interpret network dynamics		Innovative, eco co-creation, on demand, agile, add intelligence to external stimuli
Finance	x	Lowest cost		Cost to serve		TCO (Total cost of Ownership)		TCE (Total Cost of Ecosystem)
Customer focus		Push, product-centric.		Pull, product-centric	x	Pull, demand-driven		Interactive demand, customer-centric
IP/Legal		IP internal	x	IP Internal		IP Internal, external		IP ecosystem
IT	x	ERP systems, pockets of optimisation within functions, IT plays a significant role in the roll out and implementation of technologies		Focus on maintenance support systems, IT leads cross-functional initiative (systems-focused)		Some 4IR technologies, team identify requirements and take ownership of required technologies.		Integrate technologies of eco system and real time monitoring
Safety		Enforce, top-down	x	Enforce, ownership at source		Individual ownership, engineer safety in		Way of life, creative solutions
Environmental	x	Compliance		Cradle-to-grave		Cradle-to-grave with some recycling		Circular management
Risk management	x	Linear-based risk assessment, break risk down into components, reductionist, risk-averse.		Linear risk management, investigate interaction of risk elements		Integrated risk management, cross-functional interaction		Non-linear, systemic eco risk management, involve external and internal entities, align risk management with innovation culture
Procurement/Suppliers	x	Category managed at arm's length		Focused supply base, forecast to suppliers, improved interaction		Network-managed, integrate suppliers		Eco-procurement, suppliers become valued business partners, co-creation of parts
Storage		Multiple warehouse	x	Warehouse, Vendor managed inventory		Some AM parts in e-warehouse		Conventional, e-warehousing
Inventory		Obsolescence, excess stock, long tail of slow-moving stock, not all stock visible on ERP system, some items not linked to BOM and functional locations, functional view of inventory	x	Obsolescence, MRP, more items linked to BOMs and functional locations		MRP, reduced stock levels, improved granularity on safety stock, manage use in multiple locations centrally, reducing long tail of slow moving parts with AM		Critical stock, balance on demand, all items linked to BOM and functional location, integrated holistic view of inventory
Spares philosophy - OEM		Procure from OEM	x	Procure from OEM		Discuss introduction of AM, print monitoring sensors into AM parts		Procure AM parts or AM e-file to print local with accredited bureau, OEM manages spare requirements globally and advise when replacement is required
Spares philosophy - End-of-life equipment	x	Declare redundant and discard		Declare redundant and discard, investigate possibility of AM to obtain spares		Redesign and print some components with AM.		Extend equipment life cycle and efficiency with improved component design through AM
Spares philosophy - Warranty		Warranty on OEM parts	x	Warranty on OEM parts		Warranty on OEM parts - conventional and AM		OEM sell e-file, warranty dictates that component must be printed on specific equipment and standards
Maintenance philosophy		Reactive, run to failure	x	Preventative, time-based		Predictive, condition-based		Prescriptive, EAIM (Eco Asset integrity management), based on sensors and AI
Manufacturing	x	Conventional		Conventional, AM prototype		Basic AM parts, conventional		AM, conventional
Design philosophy		Design for manufacturing, DfM, avoid complexity	x	Design for manufacturability, complexity is expensive		Design for maintainability, introduce some complexity, standardisation of components across network		Design for functionality and personification, DfAM (Design for Additive Manufacturing), design to optimize TCE, complexity can be accommodated
Quality assurance		Adhere to set standards, inspect quality in	x	Adhere to set standards, inspect quality in		Adhere to set standards, build quality in		Adhere to set standards, imbed quality in process, create new standards
Dimensions per level	9		13		1		0	
Current maturity level:		Supply Chain		Demand Chain		Demand Network		Demand Network Agility

Figure 358:BRPM^2 maturity measurement as is (current level of maturity).

Once the as-is or current maturity level has been determined, an evolutionary roadmap can be defined, as indicated by the light blue arrows in Figure 39. The users might not aspire to reach the highest level of maturity on some of the dimensions, which is shown in Figure 39.

	BRPM² AM adoption road map							
		Supply Chain		**Demand Chain**		**Demand Network**		**Demand Network Agility**
DIMENSIONS				**ELEMENTS**				
Culture	×	Consistency, compliance with existing rules, need to know basis, accepting status quo, driven by cost and efficiency, adversarial, mutual mistrust, accountable for actions		Self interest, internal, some cross-functional interaction to solve problems		Challenge status quo move from internal silo focus to integrated network focus		Co-sensing, co-creation, transparency, co-innovation, creativity, accountable for outcome of actions, agility, adaptive, learning organisation
Leadership		Autocratic, leader makes the decision, push decisions to team, task-orientated, egocentric (Power of position), extended decision process, keep business as stable as possible, do not respond well to criticism	×	Hierarchical, encourage input from team, focused on own business success, decisions based on senior leadership input, allow some criticism		Participative, network, team-based, focus on value of business to the network, decisions based on internal team input and some input form external network, criticism used to improve business		Co-creating, co-sensing, co-inspiring, context creating, people orientated, *ecocentric* (power of influence), agile leadership, nimble decision process, understand and navigate complexity, encourage criticism
Change		Top-down, when required, individualistic, silo-based, change mindset and what people think	×	Consultation, focus not only on internal satisfaction but more on customer requirements		Cross-functional team inclusion, process-orientated, process metrics tied to individual and team performance		Agile adoption, continuous and largely self-organising through group, change behavior and what people do
Processes		Linear, push-based, static business processes, inter-department focused	×	Linear, pull-based, limited cross-functional, often manual and one-time efforts		Network integrated, end-to-end focus, commitment to continuous improvement		Agile, eco-dynamic interaction, enterprise and partners are organized around processes
Structure	×	Functional silos		Cross functional silos		Team-based		Agile, eco networks, inter-enterprise process teams
Skills		Subject matter experts	×	Analytical and sensing		Networking, create value through others, creativity, interpret network dynamics		Innovative, eco co-creation, on demand, agile, add intelligence to external stimuli
Finance	×	Lowest cost		Cost to serve		TCO (Total cost of Ownership)		TCE (Total Cost of Ecosystem)
Customer focus		Push, product-centric.		Pull, product-centric	×	Pull, demand-driven		Interactive demand, customer-centric
IP/Legal		IP internal	×	IP Internal		IP Internal, external		IP ecosystem
IT	×	ERP systems, pockets of optimisation within functions, IT plays a significant role in the roll out and implementation of technologies		Focus on maintenance support systems, IT leads cross-functional initiative (systems-focused)		Some 4IR technologies, team identify requirements and take ownership of required technologies.		Integrate technologies of eco system and real time monitoring
Safety		Enforce, top-down	×	Enforce, ownership at source		Individual ownership, engineer safety in		Way of life, creative solutions
Environmental	×	Compliance		Cradle-to-grave		Cradle-to-grave with some recycling		Circular management
Risk management	×	Linear-based risk assessment, break risk down into components, reductionist, risk-averse.		Linear risk management, investigate interaction of risk elements		Integrated risk management, cross-functional interaction		Non-linear, systemic eco risk management, involve external and internal entities, align risk management with innovation culture
Procurement/Suppliers	×	Category managed at arm's length		Focused supply base, forecast to suppliers, improved interaction		Network-managed, integrate suppliers		Eco-procurement, suppliers become valued business partners, co-creation of parts
Storage		Multiple warehouse	×	Warehouse, Vendor managed inventory		Some AM parts in e-warehouse		Conventional, e-warehousing
Inventory		Obsolescence, excess stock, long tail of slow-moving stock, not all stock visible on ERP system, some items not linked to BOM and functional locations, functional view of inventory	×	Obsolescence, MRP, more items linked to BOMs and functional locations		MRP, reduced stock levels, improved granularity on safety stock, manage use in multiple locations centrally, reducing long tail of slow moving parts with AM		Critical stock, balance on demand, all items linked to BOM and functional location, integrated holistic view of inventory
Spares philosophy - OEM		Procure from OEM	×	Procure from OEM		Discuss introduction of AM, print monitoring sensors into AM parts		Procure AM parts or AM e-file to print local with accredited bureau, OEM manages spare requirements globally and advise when replacement is required
Spares philosophy - End-of-life equipment	×	Declare redundant and discard		Declare redundant and discard, investigate possibility of AM to obtain spares		Redesign and print some components with AM.		Extend equipment life cycle and efficiency with improved component design through AM
Spares philosophy - Warranty		Warranty on OEM parts	×	Warranty on OEM parts		Warranty on OEM parts - conventional and AM		OEM sell e-file, warranty dictates that component must be printed on specific equipment and standards
Maintenance philosophy		Reactive, run to failure	×	Preventative, time-based		Predictive, condition-based		Prescriptive, EAIM (Eco Asset integrity management), based on sensors and AI
Manufacturing	×	Conventional		Conventional, AM prototype		Basic AM parts, conventional		AM, conventional
Design philosophy		Design for manufacturing, DfM, avoid complexity	×	Design for manufacturability, complexity is expensive		Design for maintainability, introduce some complexity, standardisation of components across network		Design for functionality and personification, DfAM (Design for Additive Manufacturing), design to optimize TCE, complexity can be accommodated
Quality assurance		Adhere to set standards, inspect quality in	×	Adhere to set standards, inspect quality in		Adhere to set standards, build quality in		Adhere to set standards, imbed quality in process, create new standards
Dimensions per level:	9		13		1		0	
Current maturity level:		Supply Chain		Demand Chain		Demand Network		Demand Network Agility

Figure 369:The BRPM[2] model maturity roadmap (only an example no real data used).

7.4.3.9 Respondents

The respondents refer to the entities that assisted with the data required to evaluate the model through the Delphi method and will be discussed in section 8.3.

7.4.4 Evaluate design

The evaluation of the design will be done in chapter 8 by means of the Delphi questionnaire.

7.4.5 Reflect evolution

This stage of the design falls outside the scope of this research and will be discussed in chapter11 as part of the recommended future research.

7.5 The final BRPM^2 model

Figure 40 presents the final BRPM^2 model. At the top are the three paradigms influencing the adoption of AM. Below the paradigms are the maturity levels and an indication what caused the evolution as well as a concise description of each maturity level. The column on the left representsthe risk dimensions. The rows reflect the elements against each maturity level and risk as well as paradigm dimension.

As presented in chapter 7, the BRPM^2 model is a concise model based on a maturity grid designthat will allow users to measure their as-is maturity level and then to develop a roadmap that adoption process of AM.

Business Risk Provisioning Maturity Model (BRPM²)for adopting AM in spare part provisioning				
	Paradigm dimensions			
	Efficiency → Effectiveness			
	Linear - closed systems → Systemic - open systems			
	Complicated processes → Complex processes			
	MATURITY LEVELS - Provisioning evolution			
	Supply Chain	**Demand Chain**	**Demand Network**	**Demand Network Agility**
Technology reason for evolution	ERP systems	Customer Relationship Management (CRM)	Internet	Disruptive innovative technologies of 4IR/ Internet of things
Provisioning reason for evolution	Supply - Push methodology	Demand - Pull methodology	Demand - Pull methodology	Demand - Dynamic Interactive Pull methodology
Process reason for evolution	Chain - Linear processes	Chain - Linear processes	Network - Systemic non-linear processes	Network Agility - Eco non-linear agile processes
Maturity Level Description	Structured, linear processes based on a push philosophy and a hierarchical silo business model. Organisation seen as a collection of functions. Creativity and innovation limited. Focus on doing the right thing according to set procedures. Complicated processes visible in the organisation with focus on efficiency - doing the right things.	Structured, linear processes based on a pull philosophy with closer contact to customer requirements. More internal and external customer focus. Improve efficiency of the organization. (Doing the right things - benchmarking against others)	Non-linear processes based on integrated network requirements from the global network, built on dynamic team structures more capable to manage the increased uncertainty, complexity and change as part of the global network. Organization seen as an integration of different processes. Break through from focusing on efficiency to effectiveness.(Doing the right things right -	Agile processes based on an agile, systemic philosophy integrated into the global eco-system where creativity and innovation become the differentiator across the eco-system.(Create co-innovative and agile processes that provides a dynamic and competitive edge). Use agility to combat and alleviate complexity and change it to a competitive edge. Focus on effectiveness of the
Dimensions (Business Risk Dimensions)	ELEMENTS			
Culture	Consistency, compliance with existing rules, need to know basis, accepting status quo, driven by cost and efficiency, adversarial, mutual mistrust, accountable for actions	Self interest, internal, some cross-functional interaction to solve problems	Challenge status quo move from internal silo focus to integrated network focus	Co-sensing, co-creation, transparency, co-innovation, creativity, accountable for outcome of actions, agility, adaptive, learning organisation
Leadership	Autocratic, leader makes the decision, push decisions to team, task-orientated, egocentric (Power of position), extended decision process, keep business as stable as possible, do not respond well to criticism	Hierarchical, encourage input from team, focused on own business success, decisions based on senior leadership input, allow some criticism	Participative, network, team-based, focus on value of business to the network, decisions based on internal team input and some input form external network, criticism used to improve business	Co-creating, co-sensing, co-inspiring, context creating, people orientated, *ecocentric* (power of influence), agile leadership, nimble decision process, understand and navigate complexity, encourage criticism
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Processes	Linear, push-based, static business processes, inter-department focused	Linear, pull-based, limited cross-functional, often manual and one-time efforts	Network integrated, end-to-end focus, commitment to continuous improvement	Agile, eco-dynamic interaction, enterprise and partners are organized around processes
Structure	Functional silos	Cross functional silos	Team-based	Agile, eco networks, inter-enterprise process teams
Skills	Subject matter experts	Analytical and sensing	Networking, create value through others, creativity, interpret network dynamics	Innovative, eco co-creation, on demand, agile, add intelligence to external stimuli
Finance	Lowest cost	Cost to serve	TCO (Total cost of Ownership)	TCE (Total Cost of Ecosystem)
Customer focus	Push, product-centric.	Pull, product-centric	Pull, demand-driven	Interactive demand, customer-centric
IP/Legal	IP internal	IP Internal	IP Internal, external	IP ecosystem
IT	ERP systems, pockets of optimisation within functions, IT plays a significant role in the roll out and implementation of technologies	Focus on maintenance support systems, IT leads cross-functional initiative (systems-focused)	Some 4IR technologies, team identify requirements and take ownership of required technologies.	Integrate technologies of eco system and real time monitoring
Safety	Enforce, top-down	Enforce, ownership at source	Individual ownership, engineer safety in	Way of life, creative solutions
Environmental	Compliance	Cradle-to-grave	Cradle-to-grave with some recycling	Circular management
Risk management	Linear-based risk assessment, break risk down into components, reductionist, risk-averse.	Linear risk management, investigate interaction of risk elements	Integrated risk management, cross-functional interaction	Non-linear, systemic eco risk management, involve external and internal entities, align risk management with innovation culture
Procurement/Suppliers	Category managed at arm's length	Focused supply base, forecast to suppliers, improved interaction	Network-managed, integrate suppliers	Eco-procurement, suppliers become valued business partners, co-creation of parts
Storage	Multiple warehouse	Warehouse, Vendor managed inventory	Some AM parts in e-warehouse	Conventional, e-warehousing
Inventory	Obsolescence, excess stock, long tail of slow-moving stock, not all stock visible on ERP system, some items not linked to BOM and functional locations, functional view of inventory	Obsolescence, MRP, more items linked to BOMs and functional locations	MRP, reduced stock levels, improved granularity on safety stock, manage use in multiple locations centrally, reducing long tail of slow moving parts with AM	Critical stock, balance on demand, all items linked to BOM and functional location, integrated holistic view of inventory
Spares philosophy - OEM	Procure from OEM	Procure from OEM	Discuss introduction of AM, print monitoring sensors into AM parts	Procure AM parts or AM e-file to print local with accredited bureau, OEM manages spare requirements globally and advise when replacement is
Spares philosophy - End-of-life equipment	Declare redundant and discard	Declare redundant and discard, investigate possibility of AM to obtain spares	Redesign and print some components with AM.	Extend equipment life cycle and efficiency with improved component design through AM
Spares philosophy - Warranty	Warranty on OEM parts	Warranty on OEM parts	Warranty on OEM parts - conventional and AM	OEM sell e-file, warranty dictates that component must be printed on specific equipment and standards
Maintenance philosophy	Reactive, run to failure	Preventative, time-based	Predictive, condition-based	Prescriptive, EAIM (Eco Asset integrity management), based on sensors and AI
Manufacturing	Conventional	Conventional, AM prototype	Basic AM parts, conventional	AM, conventional
Design philosophy	Design for manufacturing, DfM, avoid complexity	Design for manufacturability, complexity is expensive	Design for maintainability, introduce some complexity, standardisation of components across network	Design for functionality and personification, DfAM (Design for Additive Manufacturing), design to optimize TCE, complexity can be accommodated
Quality assurance	Adhere to set standards, inspect quality in	Adhere to set standards, inspect quality in	Adhere to set standards, build quality in	Adhere to set standards, imbed quality in process, create new standards

Figure 40 :The complete BRPM² model

Figure 41 is an example of how the maturity model works. The selected risk dimension is culture at the demand chain maturity level. The applicable paradigm dimension is linear, complex and focusses on efficiency. The element description is:

Self-interest/Internal. Some cross-functional interaction to solve problems.

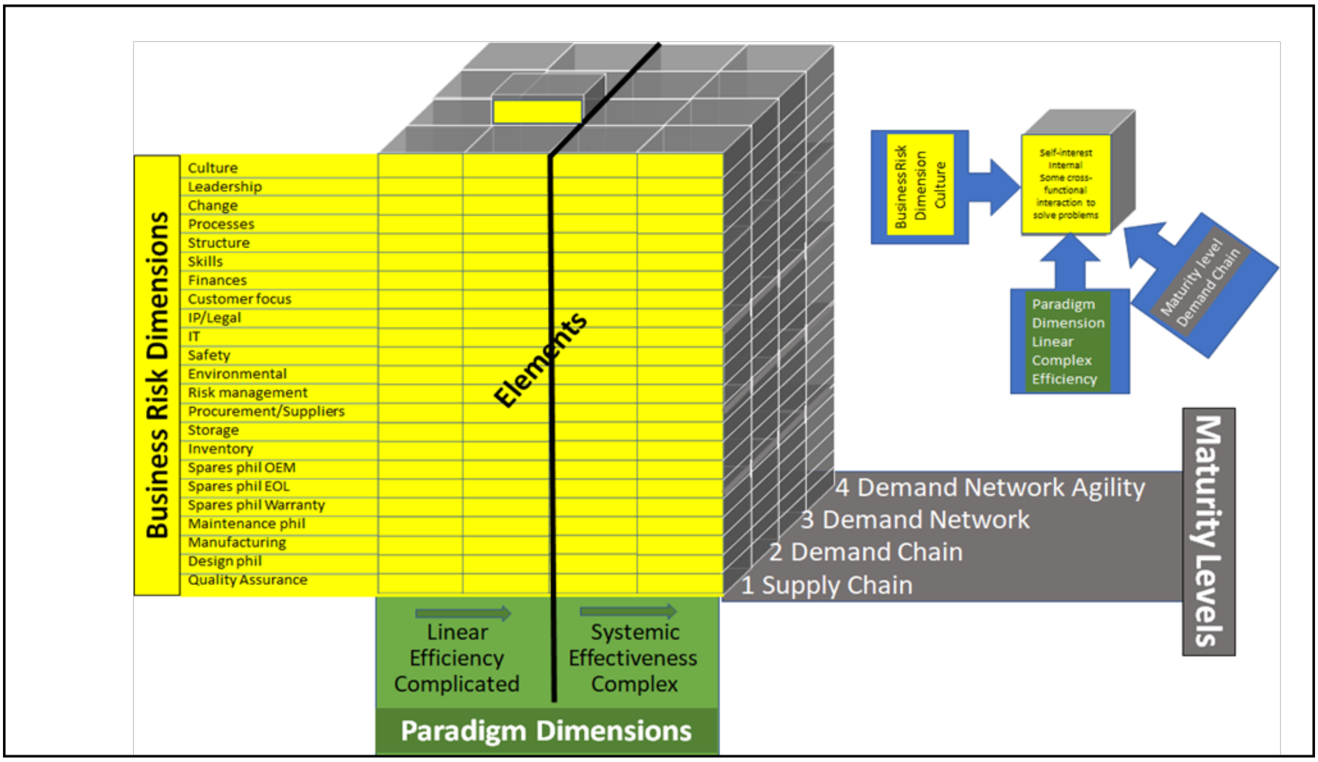

Figure 371: A BRPM² model maturity example.

7.6 Conclusion

This chapter elaborated on the design of the BRPM² model. As per phase 4 of the maturity model development framework, the model needs to be evaluated. A Delphi process (chapter 8) was conducted to verify (chapter 9) the design of the model and to validate the model (chapter 10).

CHAPTER 8: DELPHI QUESTIONNAIRE

This chapter explains how the Delphi process was used to verify and validate the business risk provisioning maturity model (BRPM^2). The purpose of the Delphi technique was to determine if there is consensus and to verify and validate the business risk provisioning maturity model.

8.1 Introduction

The BRPM^2 model was developed in chapter 7. Chapter 8 explains the Delphi technique that wasapplied to verify and validate the BRPM^2 model. Skulmoski and Hartman (2007) state that the Delphi method works well when there is incomplete knowledge about a problem or phenomenon.

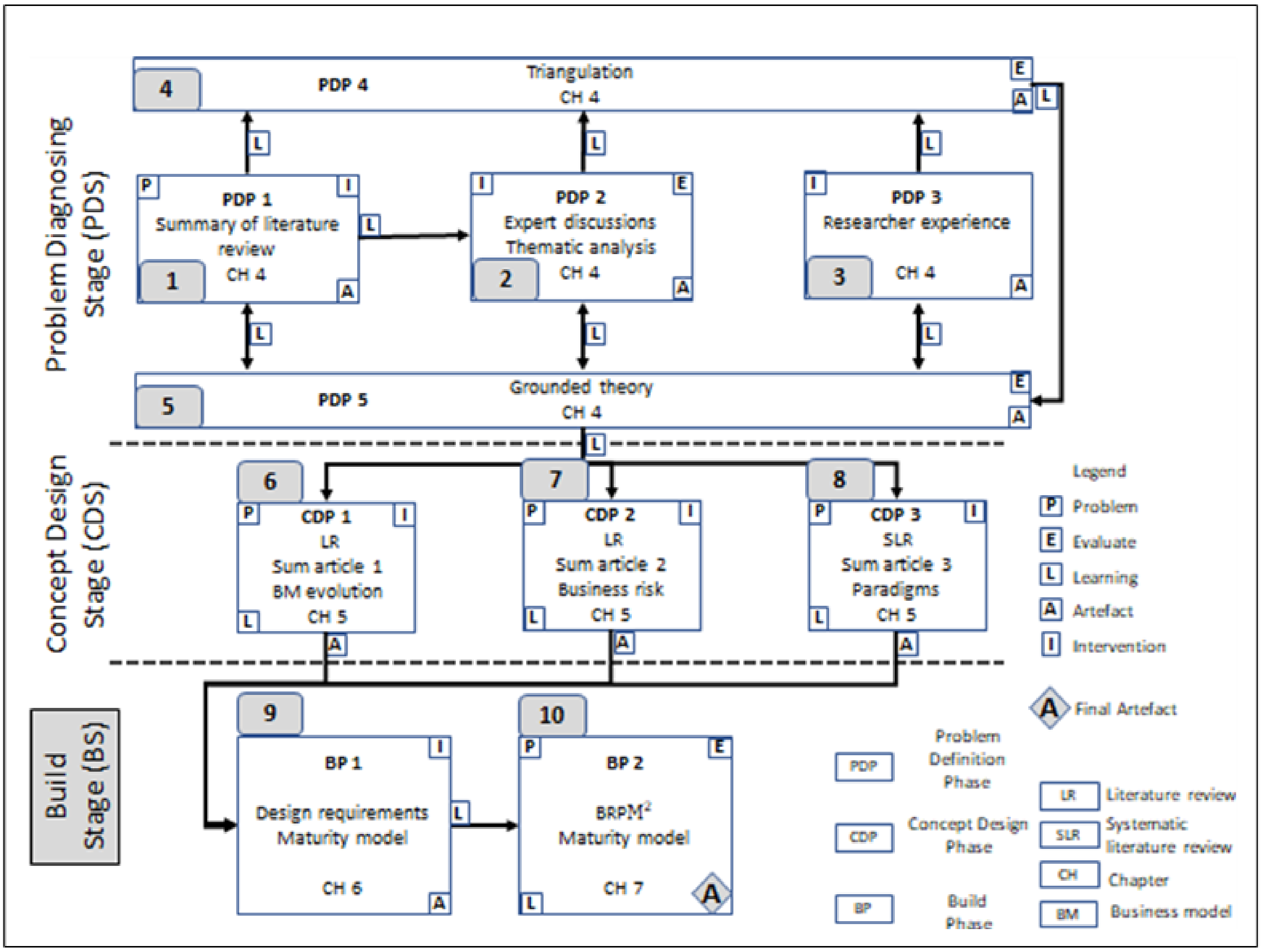

Figure 382: Delphi questionnaire – evaluation of final artefact (E)(BP 2).

Figure 42 indicates where the Delphi technique fits into the overall research design. The Delphi technique was used as the evaluation (E) for the second build phase that comprises the BRPM^2 model BP2 (10).

8.2 Delphi process

The Delphi process was used to verify and validate the BRPM^2 model. A Google forms questionnaire was compiled from the design requirements defined in chapter 6. Participants were selected according to their participation in the South African AM ecosystem. When a person participates in the AM ecosystem, the assumption can be made that the person will have a certain level of knowledge and interest of AM in South-Africa. The questionnaire was distributed electronically to the participants. Feedback was received electronically, and onceconsensus had been reached amongst the participants as defined in section 8.4, the questionnaire was closed and the data was analysed.

8.3 Selection of experts The selection of experts was done according to their role in the AM ecosystem as indicated in Figure 43. According to Skulmoski and Hartman, (2007), the selection of experts should comply with the following criteria:

(a) They should have knowledge and experience regarding the matter underinvestigation.

This requirement was addressed by purposefully selecting the participants according to their rolein the South African AM ecosystem. Snowball sampling was also used by asking these participants to forward the questionnaire to other potential participants.

Okoli and Pawlowski (2004) state that a group of heterogeneous participants provided more diverse feedback than a homogeneous group providing they:

(b) Have the capacity and willingness to participate.

All the participants were contacted individually and requested if they would and can participate in the research.

(c) Have enough time to participate.

Some participants completed the Delphi questionnaire quickly, but some participantshad to be reminded but eventually participated. The time for completion of the questionnaires was eight weeks. The longer than usual time delay was due to the impact of COVID-19 on the business environment and the availability of the participants.

(d) Have effective communication skills.

The request for effective communication skills is more applicable when the Delphi process is conducted as part of a meeting. The participation for this research was conducted via an online electronic questionnaire in Google forms.

Figure 43 is a graphical representation of the selected participants.

The number can be defined as follow:

First set - (01) AM participation group: 01 – 04

Second set – (01-01) Key group represented within the AM participation group:

Third set – (01-01-01) Sector represented within the key group: 01–07

Fourth set – number in brackets – denoted the number of participants per sector.

Example:

01 – Technology users and industry

01 – Industry

02 – Railway

(2) – Two participants from the railway

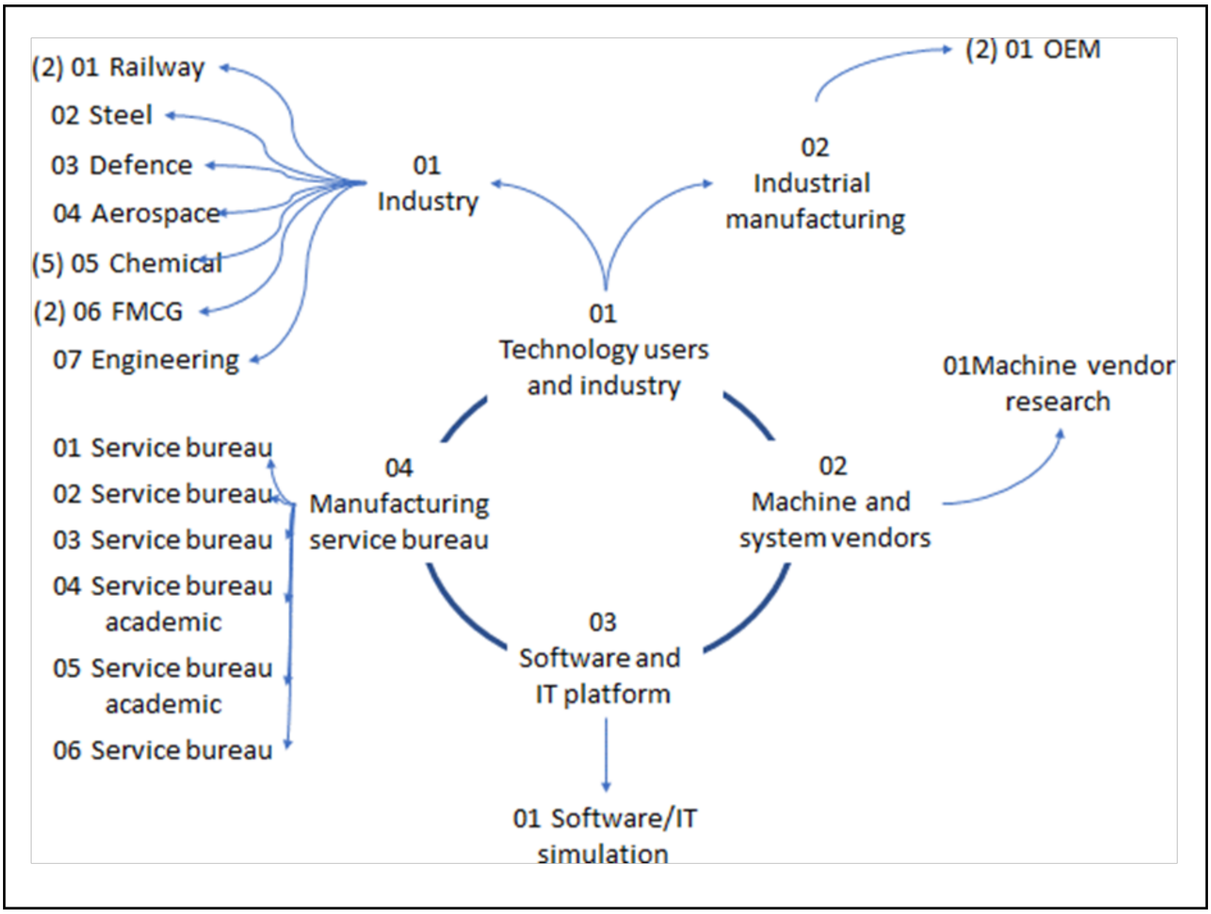

Figure 393:Selection of experts according to their role in the AM ecosystem.

The participants represent a heterogeneous group with expertise across various industries and functions in the ecosystem pertaining to the provisioning and applying AM for spare parts. Twenty-four participants were selected and 23 participated in the Delphi study that represents a responserate of 96%. According to Hasson *et al (*2000), the reliability of the Delphi method is based upon the assumption of safety in numbers indicating that several people are less likely to arrive at a wrong decision. The high participation in this Delphi questionnaire as well as the high response rate adds to the reliability of the Delphi questionnaire used for this research.

Figure 44 is a graphical display of the experience distribution of the selected experts extracted from the Google forms questionnaire. While 34.7% of the respondents have zero to three years of experience in AM, 65.3% have more than three years of experience.

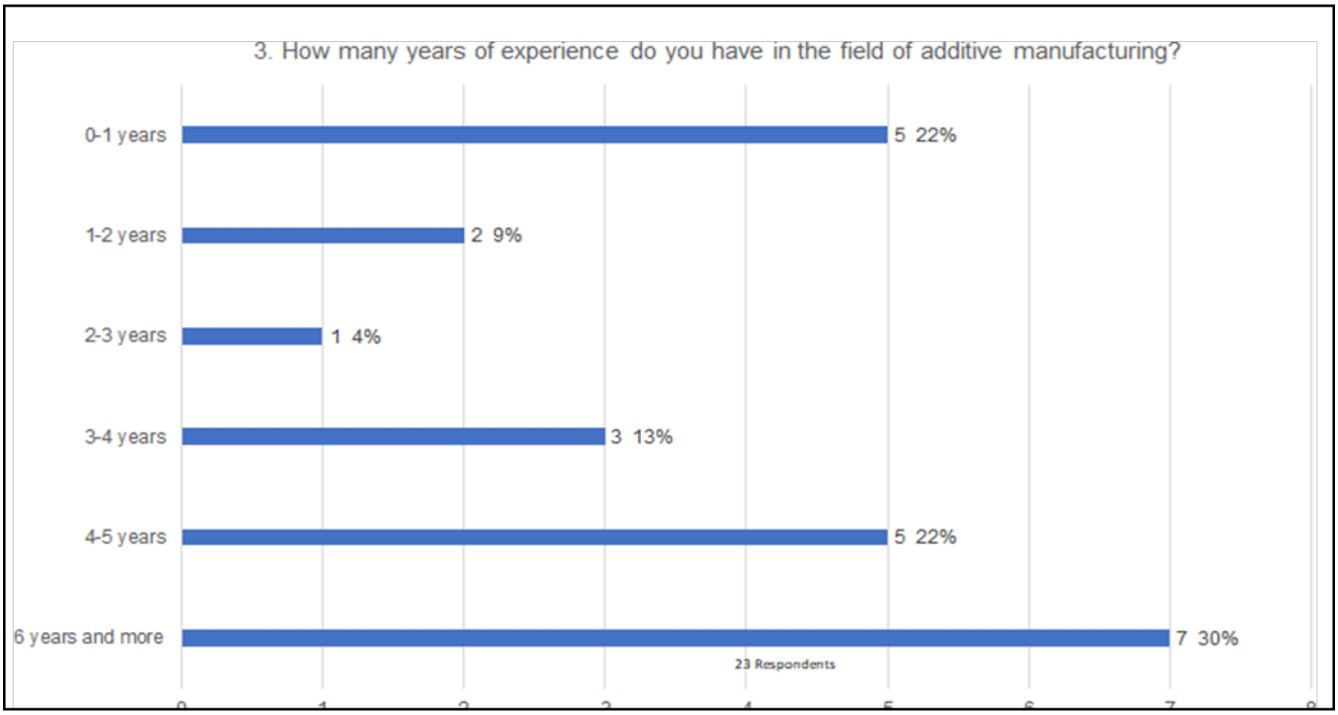

Figure 404:Experience of expert panel from Google forms questionnaire.

Figure 45 is a representation of the role that the selected experts perform in the AM ecosystem. Some of the participants are involved in multiple nodes of the ecosystem. An example of the multiple roles is the academic participants who are not only involved in research but also participate as bureaus supplying parts to the industry.

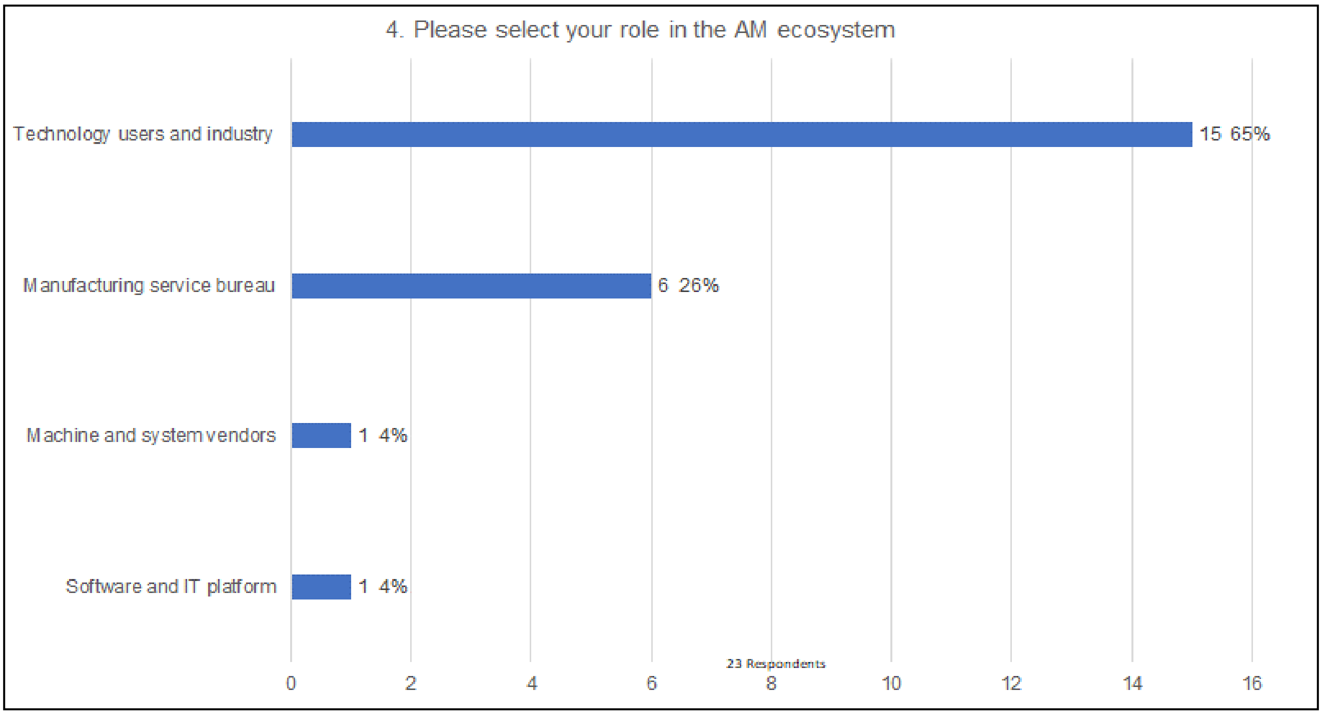

Figure 415: Role of experts in AM ecosystem

Figure 46 shows the industries that the participants represent. Some of the participants service multiple industries.

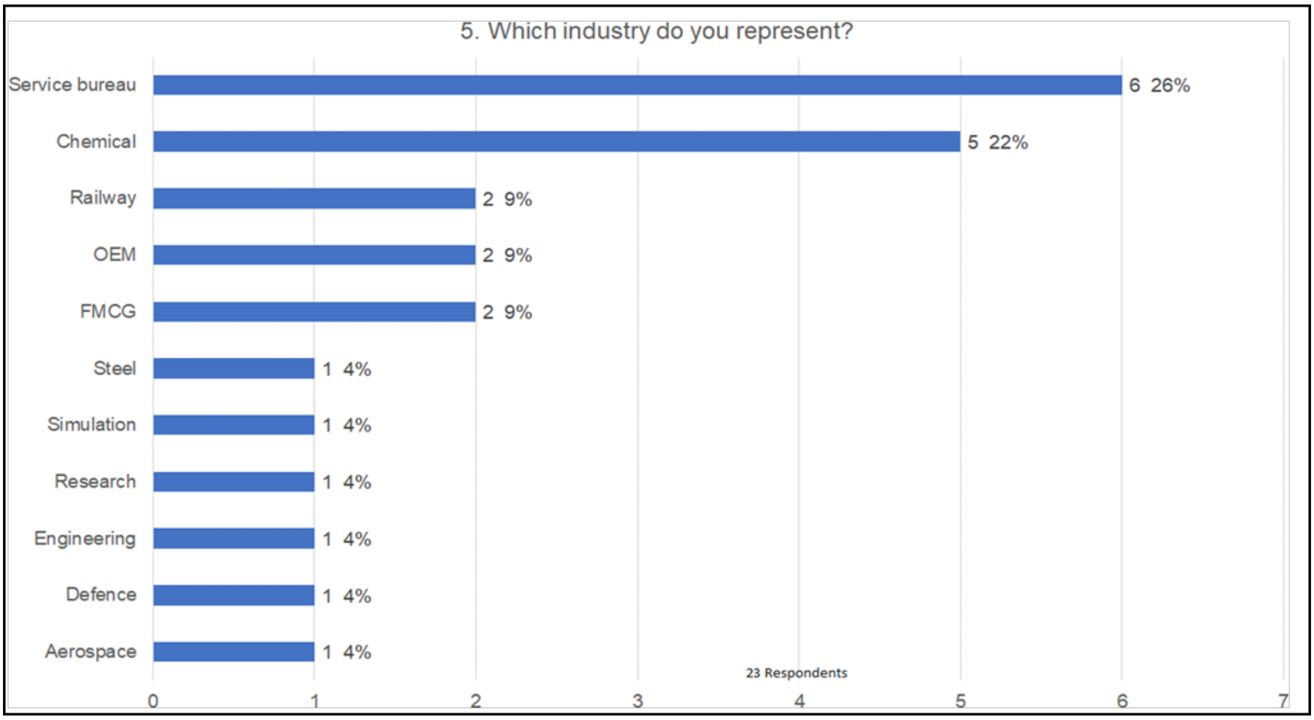

Figure 426: Industry represented.

8.4 Defining consensus

There is no universal proportion in the Delphi technique that defines consensus. Consensus between the experts needs to be defined case by case and according to the complexity of the research (Hasson *et al*., 2000). Consensus for a disruptive innovation will be lower amongst participants due to the maturity level and duration of exposure to the disruptive innovation by the participants (Belsky, 2015). One of the dominant barriers to the adoption of AM remains the lackof sophisticated know-how and the maturity of the industry ecosystem (Jirsak & Brunet-Thornton,2019). Consensus can be reached when 51% of the defined group agrees on a topic (Loughlin & Moore, 1979). Therefore, for this study and the complexity of the research, consensus was defined when an average rating of above three (60% on a 5-point Likert scale) was achieved for a specific item in the questionnaire (van Bracht *et al*., 2016).

8.5 First round questions

The questions were designed as open-ended questions to allow participants to express their view according to a 5-point Likert scale:

Strongly disagree, disagree, neutral, agree and strongly agree.

At the end of each section, the participants could also provide open-ended qualitative feedback.The first-round questionnaire was developed by identifying pertinent factors relating to:

(a) **Verification** – Questions were aimed at verifying that the model adhered to the initial design requirements.

(b) **Validation** – Questions were aimed at proving that a valid research problem had been identified and that the $BRPM^2$ model is a valid solution to address the stated research problem.

The compilation of the questionnaire is discussed in the next section and the completequestionnaire is available in Annexure D. The $BRPM^2$ model and the road map was included as part of the complete questionnaire for participants to answer the questions accurately.

8.5.1 Verification questions

The design requirements (specified in chapter 6 and 7) were converted into questions that were used for the compilation of the Delphi questionnaire. The numbers in the Table represent the number in the design requirement traceability matrix.

8.5.1.1 Structure

Table 29:Structure design requirements and Delphi questions.

Design requirements	Questionnaire statement
1a) The model should be basic in design	The model is basic in design
1b) There should be coherence between the different elements of the model	There is coherence (systematic and logical connection) amongst all the elements in the model
1c) Maturity levels must relate to provisioning systems	The maturity levels relate to provisioning systems
1d) Dimensions of the model must indicate the key business risks	The dimensions of the model indicate the key business risks
1e) The elements must be clear and easy to understand	The elements in the risk/provision matrix are clear and easy to understand

8.5.1.2 Usability

Table 30:Usability design requirements and Delphi questions.

Design requirements	Questionnaire statement
2a) The audience should be anyone in the organisation that would like to adopt AM for spare part provisioning	The model can be used by people on any level in the organisation whowants to adopt AM as part of spare part provisioning
2b) The model must define the as-is status of the organisation	The model assists in creating an as-is status relating to the key business risks
2c) The model can be used to create a roadmap for future improvement	The model assists in creating a basic roadmap towards provisioning maturity

8.5.1.3 Effectiveness

Table 31:Effective design requirements and Delphi questions.

Design requirement	Questionnaire statement
3a) An understanding of the key business risks and how they evolve will assist in the adoption of AM	An understanding of the evolutionary role of the key business risks identified in the model will assist in an improved adoption of AM
3b) The provisioning evolution must be from supply to demand	There is a clear evolution from supply to demand
3c) The linear (chain) philosophy must evolve to a systemic network philosophy	There is a clear evolution from the linear (chain) philosophy to a systemic network philosophy
3d) Agility is a key requirement for successful interaction in the ecosystem	Agility is a key requirement for success in the dynamic eco-network
3e) An understanding of the systemic relationship between the key risks when adopting AM can improvethe adoption	An improved understanding of the systemic relationship between the model dimensions (risks) can improve the adoption of AM in spare part provisioning

8.5.2 Validation questions: research problem

The validity of the research problem was tested with specific questions relating to the research problem, see Table 32.

Table 32:Validation questions regarding the research problem.

Stated research problem	Questionnaire statement
The adoption rate of AM as part of spare part provisioning in South Africa is slow because of a lack of a concise understanding of the evolutionary requirements of the provisioning system and the systemic relationship between the key business risks	The adoption of AM as part of spare part provisioning is slow in South Africa
	The adoption of AM in spare part provisioning is low because of a lack of understanding of the systematicimpact on the key business risks when adopting AM
applicable when adopting AM as part of spare part provisioning	The linear provisioning paradigms slow down the adoption of AM in spare part provisioning

8.5.3 Validation question: research output

Validation is the degree to which a maturity model is an accurate representation of the real world from the perspective of the intended uses of the model (Mettler, 2011). The validity of the BRPM^{2}model was determined by including specific questions in the Delphi questionnaire (see Table 33).

Table 33:Validation questions regarding the research output.

Validation requirement	Questionnaire statement
The artefact should address the research problem	The BRPM^2 model could assist in increasing the adoption of AM in spare part provisioning in South Africa
The model should have an original design	To the best of your knowledge, would you consider the construction of the BRPM^2 model as an original design (as opposed to just a duplication of other previous work)

8.6 Administering and analysing round 1 questionnaire

An e-mail was sent to all the participants with a link to the Google forms questionnaire. The e- mail requested them to complete the online questionnaire and to submit the results electronically.

A reminder e-mail was sent if no response had been received after 14 working days. After eight weeks, the results were analysed by combining the qualitative and quantitative feedback.

The Delphi method needs to be conducted in multiple rounds or till consensus as defined in section 8.4 is reached. According to Skulmoski and Hartman, (2007), the process stops when the research question is answered: for example, when consensus is reached, theoretical saturation is achieved, or when sufficient information has been exchanged. According to Hasson *et al*. (2000) the reliability of the Delphi technique is based upon the assumption of safety in numbers that leads to the notion that several people are less likely to arrive at a wrong decision.

The validity of the study is improved when participants have knowledge and an interest in the topic researched and the validity can also be affected by the response rate of the participants (Hasson *et al*., 2000).

8.7 Results

The minimum percentage for agreement on an item was set to 60%. Therefore, consensus was achieved with an average rating of above three (60% of a 5-point Likert scale) achieved for each item on the questionnaire and no more rounds of the Delphi process was required since theoretical saturation had been reached after round 1. The quantitative results of the Delphi survey are summarised in Table 34 and discussed in section 8.7. The numbers in the first column represent the corresponding number in the questionnaire. An average above three was achieved for all the questions. Consensus was therefore reached after the first round of the Delphi questionnaire. The results of these questions are available in annexure D. Followed by the qualitative feedback in annexure E and the quantitative feedback in annexure F.

Table 34:Summary of results from the Delphi questionnaire.

	Question	Results
	Research problem	
6a	The adoption of AM as part of spare part provisioning is slow in South Africa	4.4
6b	The adoption of AM in spare part provisioning is low because of a lack of understanding of the systemic impact on the key business risks when adopting AM	4.0
6c	The linear provisioning paradigms slow down the adoption of AM in spare part provisioning	3.8
	Design requirements	
	Structure of the model	
8a	The model is basic in design	3.2
8b	There is coherence (systemic is logical connection) amongst all the elements in the model	4.0
	Maturity levels	
10a	The maturity levels relate to provisioning systems	3.9
10b	The maturity levels follow an evolutionary path	4.0
	Dimensions	
12a	The dimensions of the model indicate the key business risks	4.1
	Elements	
14a	The elements in the risk/provision matrix are clear and easy to understand	4.1
	Usability	
16a	The model can be used by people on any level in the organisation who wants to adopt AM as part of spare part provisioning	3.2
16b	The model assists in creating an as-is status relating to the key business risks	3.8
16c	The model assists in creating a basic roadmap towards provisioning maturity	4.0
	Effectiveness	
	Key business risks	
18a	An understanding of the evolutionary role of the key business risks identified in the model will assist in an improved adoption of AM	3.8
	Evolution of provisioning system	

	Question	Results
20a	There is a clear evolution from supply to demand	4.1
20b	There is a clear evolution from the linear (chain) philosophy to a systemic network philosophy	4.0
20c	Agility is a key requirement for success in the dynamic eco-network	4.5
	Systemic relationships	
22a	An improved understanding of the systemic relationship between the model dimensions (risks) can improve the adoption of AM in spare part provisioning.	4.2
	Research output	
24	To the best of your knowledge, would you consider the construction of the $BRPM^2$ model as an original design (as opposed to just a duplication of other previous work)	4.1
26	The $BRPM^2$ model could assist in increasing the adoption of AM in spare part provisioning in South Africa	3.9

The qualitative and quantitative results are discussed in the following sections.

8.8 Discussion of Delphi results

The quantitative results indicated that there was consensus regarding the validity of the research problem. All the participants agreed that the adoption of AM for spare part provisioning in South Africa is slow. The question regarding the linear provisioning paradigms achieved the lowest average score of 3.8 in this section. This is an indication that the participants did not clearly understand how linear paradigms can slow down innovative thinking required for the adoption of AM in spare part provisioning. A summary of the quantitative results is included in annexure F.

8.8.1 Research problem

The qualitative feedback indicated that the current economic climate could cause a slowdown in adoption since potential users do not want to adopt a perceived risk when struggling with the current business. One of the responses indicated that the OEMs have a monopoly over spares. This is a clear indication that the true all-inclusive value of AM is not understood, and traditional paradigms still prevail. The focus remains on the cost of the specific component and not on the total cost of the ecosystem.

(a) “Most South African manufacturers are under severe financial strain currently and are focused on staying afloat in the short term” (participant 01–01–02).

(b) "The technology is sometimes overwhelming, and the market does not trust the technology yet. Sometimes the cost of AM is also a drawback". (participant 01–01–07)

(c) "In South Africa at the current moment there are bureaucratic supplier qualification processes that excludes many suppliers. Even when the supplier qualifies, he still gets disqualified due to preferential treatment of other suppliers. A business needs long term supply agreements to survive and thrive. At the current moment it is too risky for new AM suppliers to enter the market as there is no long-term vision and support. The capital requirements for AM are high and investment can only be done on solid supply agreements. Linear provisioning paradigms are the excuse that gets used when there is no real commitment to supplier development" (participant 04–03).

(d) "Slow adoption is also attributed to the following:

(e) Awareness (This is more geared toward the capabilities of utilising the AM technologyto produce functional parts. Currently, the technology and the parts created are still considered "Prototyping or Rapid Prototyping" mainly due to its initial introduction to the industry and a tool specific to prototyping. This is slowly changing, but only those that are involved know about it)

I. Design for AM (DfAM) rules and techniques (This falls under skills and knowledge). Traditional design for manufacturing and assembly methods (CNC, injection moulding, cutting, grinding, and so forth) cannot be applied directly to AM parts. All parts that are produced using AM must be designed specific to that printing technology and not designed to be a replica of the part it intends to replace. Understanding the design process and matching it to the AM process to produce functional 3D-printed parts addsto the skills and knowledge challenge, which results in a slow adoption.

II. "Spare part requirements (If mass production is required, AM may not be a beneficialoption; however, this would largely depend on the part itself and the available AM process). Spare parts, in most instances, would be a part that was initially produced using traditional manufacturing. When using AM (and to use it to its full benefit), the partwould need to follow new design changes to allow it to be printed and be functional (fit for purpose)" (participant 01–01–01–01)

(a) "The slow adoption of AM in the industry is also due to the cost associated with the fabrication of parts. It becomes important to categorise which spare parts will benefit from AM, e.g. low stock, long lead time components" (participant 01–01–01–02)

(b) "AM is widely adopted in SOUTH AFRICA. One big issue is the OEM monopoly over spares" (participant 01–01–06–02)

8.8.2 Structure – design requirements

The qualitative results indicated that the average for the design requirement to create a model that is basic in design is 3.2. This can be attributed to the novelty of AM and that the model is based on the maturity levels that represent the provisioning evolution. With the current focus of most discussions on the technological aspects of AM, participants do not understand the role that the business aspects play in the slow adoption of AM and therefore have a lower appreciation for the value of the model.

Qualitative feedback indicated that the model provides a natural flow, and this adds to the evolutionary nature of the model. One of the participants indicated that this is a well-balanced model and can even be used outside of South Africa in the wider spare part provisioning ecosystem.

(a) "The model shows a natural flow is possible with many added benefits" (01–01–07)

"I would just like to qualify my answers to the above: The model does indeed seem basicin its design when taken at face value. However, I have no previous experience with such maturity models and hence very little context from which to make this type of judgement" (03–01)

(b) "Understandable model with key element changes as the adoption of AM progresses"(04–02)

(c) "Too complex. Yes, a big organisation needs to look at all these aspects, but I believeyou need to define the one single factor that is stopping the adoption of AM. AM has been proven. Technically there are no obstacles. So, what is stopping its adoption?" (04–03)

(d) "The model is well portraying the picture of current status of AM not only in South Africa"(04–06)

(e) "Some factors may need to be looked into and how they may interact with your dimensions:

I. Material handling corresponding to the AM process (From raw material to AM readymaterial – This is important in achieving reliable, functional spare parts).

II. Technology type for AM". (01–01–01–01)

8.8.3 Structure – maturity levels

The average quantitative feedback for the questions relating to the maturity levels is 3.9. This indicates that participants understand the evolutionary nature of the maturity levels and that the maturity levels are based on the provisioning system.

The model is designed as a maturity grid and maturity can be managed individually per dimension.The maturity level that represents the most areas of compliance is the current maturity level of the organisation.

(a) "With the potential of AM clusters being setup, a group of companies may jump fromvery immature to a mature adopter of AM in a short time span" (04–02)

(b) "Maturity levels stagnates a business. Its ability to adopt to change, specifically in identifying and empowering good new suppliers, get hampered by bureaucracy andprocess. Current suppliers will do ANYTHING to maintain their supplier status and exclude new suppliers" (04–03)

(c) "Some factors may need to be looked into and how they may interact with yourdimensions:

I. Material handling corresponding to the AM process (From raw material to AM readymaterial – This is important in achieving reliable, functional spare parts).

II. Technology type for AM.

Part production and delivery processes (logics – either in-house manufacturing or external service providers).

III. Identification process of parts (spare parts) that could actually be manufactured using3D printing. Not all parts in all industries could benefit from AM, which is why the identification process is important. Just replicating parts that were made from traditional manufacturing processes to AM without utilising the benefits of the technology has no benefit.

IV. Identification process of printed spare parts (Once mass production or production scale-up is achieved)" (01–01–01–01)

V. "The AM technology especially in South Africa is still very much in the pre-developmentphases and focused on niche materials and applications" (01–01–05–02)

8.8.4 Structure – dimensions

The average for this section is 4.1. The dimensions in the model represent the key business risksand not all the risks applicable to the adoption of AM that included technological risks as well. The feedback from the participants is valid, but the risks identified for this model are, according to their research, the most pertinent business risks. The linear paradigms prevailing in business causes people not to see the systemic interaction between the different dimensions.

Changes in the market will be addressed by a proper understanding of the ecosystem and a definition of the role players. The paradigm shifts from what the market can offer to what the organisation can offer to the market through innovation.

(a) "The adoption of AM and benefits thereof by direct competitors can be viewed as a potential risk if an organisation is slow to adapt" (01–01–02)

(b) "How does the model support a business to address changes in market perception/industry requirements, or industry-driven technology requirements? I missed details with respect to how the business will respond to changes in the market, as a business risk to be managed". (02–01)

(c) "This model looks at the business from a very traditional paradigm. 4IR and Disruptive technologies work in a new paradigm. This model is sufficient for a baseline analysis, but a new model is required that takes into account disruptive change". (04–03)

(d) "Some points on the dimensions:

I. IT – Be mindful that IT is a relatively broad category. When you mention Ecosystem, Iam assuming this would include all levels of technology and software that would fall under spare part provisioning using AM for areas such as:

1. Production (actually producing the 3D printed parts),
2. Monitoring (for 3D printed parts, AM machines, People/customer interactionmanagement, material handling, waste disposal),
3. Safety

II. A dimension of repeatability. Not sure if your model is going to be the benchmark to ensure that this process will ensure consistent repeatability. Some factors that affect the repeatability of 3D printed functional spare parts include:

1. Certification and tracking of raw materials and the final AM material.

2. Specifications and standards (these are for all levels from manufacturing, toquality, to end-of-life).

3. AM technology and printer capabilities.

4. Customer and manufacturer interactions.

5. Quality control (01–01–01–01)

(e) Risk areas rather than risks” (01–01–06–02)

8.8.5 Structure – elements

The average for the section on elements is 4.1. The maturity model is about the adoption of AM as part of the spare part provisioning business model. It seems that some of the participants were unclear how the provisioning maturity, the risk dimensions and the elements interact. There is only one participant that disagreed that the elements are clear and easy to understand.

(a) “You need to create a new model that will take the business into the future” (04–03)

(b) “The elements are clear and easy to understand. However, the maturity levels is difficult to understand” (01–01–01–02)

(c) “Well defined and simplistic to apply” (01–01–05–01)

8.8.6 Use ability of the model

(a) There is consensus amongst the participants, but the consensus is low. This can be attributed tothe novelty of AM and the low adoption rate; people first need to ensure that they understand thekey concepts and the impact on the business. That is where this model will play a crucial part in creating the systemic awareness. Since this model is a roadmap and a descriptive model, the intention is not to provide detailed instructions but to leave it open to individual organisations to compile their own detailed implementation strategies that will align with how aggressive they wantto adopt AM in spare part provisioning. “It certainly shows a clear "pathway" to maturity” (01–01–07)

(b) “Disruption aims to upset traditional models. The model shows the end goal (Demand network agility) and will show the steps that need to be achieved at each level. It needs another dimension of the how. Change management is a management science on its own, but it will define the pathway. This is also a bottom up approach. It needs to be topdown if AM is to succeed. Especially when an organisation has a top-heavy executive level” (04–03)

(c) “The model is complex and will only be understood by subject matter experts especially the maturity level section” (01–01–01–02)

(d) “Shop floor can use model. Provisioning Maturity - some areas/companies may not want to get to that sophisticated” (01–01–06–02)

8.8.7 Effectiveness – key business risks

The key business risks that have been identified through the literature research, expert interactionand the researcher’s own experience forms the basis of these dimensions for the model. These keybusiness risks are part of an evolutionary process to transform the business for AM adoption. Asdiscussed before, the purpose of this model is not to outline all the business risks but the key business risks that will help to create an improved understanding regarding AM adoption for sparepart provisioning and how the adoption of AM will affect the business.

(a) “The model is a definite "head start" towards AM and how it could improve processes”(01–01–07)

(b) “It should be noted that in terms of quality, standards are still being established. So this is also a risk in the adoption of AM. Not all risks have been outlined

(c) Spares is a part of AM - Spares manufacturing will get you to adopt AM – it’s the otherway round” (01–01–06–02)

8.8.8 Effectiveness – evolution of provisioning system

This section tests the understanding of the participants regarding the evolution of the provisioning system from supply to demand and the linear chain to the non-linear network and ecosystem environment. Agility will play an important role as part of this evolution.

(a) “Agility comes with risk. You need to explore and quantify the risk(s) and try to create mitigating processes” (04–03)

8.8.9 Effectiveness – systemic relationship

Twenty-one of the respondents either agreed or strongly agreed that a systemic understanding of the business risks can improve the adoption of AM in spare part provisioning.

(a) “Yes. This is the correct approach. Requires in depth analysis (Delphi model)” (04–03)

8.8.10 Research output – originality of the model

There is consensus that indicates that the model is an original and novel artefact.

(a) "Most definitely an original design that I have never come across before" (01–01–07)

(b) "I am not aware of a similar model, but must also just acknowledge that I have not explicitly searched for a similar model before" (03–01)

(c) "AM needs to operate outside the normal processes (for now). You cannot apply the same paradigm. It needs its own place in the organisation- It needs its own budget and independence, and it needs license to disrupt. You CAN NOT change the institutional bureaucracy that is based around suppliers. AM will disrupt the supply chain and the supply chain will resist. Your model is correct in showing what is required but if you wantto do something ground breaking you will have to address the elephant in the room. Suppliers dominance, supplier agreements, supplier influence" (04–03)

(d) "The model do not need to be original .... it needs to be adapted to industry standards and

(e) market pull' (01–01–05–02)

(f) "First time I have seen it in a combined format. Not sure the content is original. But veryclear depiction thereof" (01–01–05–03)

8.8.11 Research output – contribution to solving the research problem

There is consensus that the model will assist in solving the research problem. The model will assist teams that would like to adopt AM with a tool that could assist them in the adoption process.

(a) "As AM is becoming more known in the local markets people will need more guidance towards adopting the principles. This model could become a great tool to assist with theprocess towards adoption" (01–01–07)

(b) "The model is accurate and correct but cannot be implemented without a proper understand of the financial implications. Which suppliers will benefit and which will fall onthe wayside and what will be the implications of that" (04–03)

(c) "AM is not applicable to all spare parts manufacturing. The model does not assist in understanding which parts will benefit from" AM (01–01–01–02)"The model gives a clear path but does not address lack of industry and trusting of the technology involved in AM" (01–01–05–05)

8.8.12 Final comments

As part of the Delphi questionnaire, participants were asked to share some final comments regarding the model. Below is the feedback that has been received.

(a) "This is indeed a fine piece of work. Indeed ground breaking work from my point of view. Definitely a step in the right direction to promote AM" (01–01–07)

(b) "Good work" (04–03)

(c) "Excellent understanding of current status to lay the foundations for a new paradigm'(04–06)

(d) "All the best" (01–01–01–01)

(e) "Thank you for the work and including me. Good luck with completion! May it bring much growth and improvement!" (01–01–05–03)

(f) "Need to link Additive Manufacturing, AM and spares together. AM is the driver of the above, cost management is the driver of Additive Man & spares supply chain reviews"(01–01–06–02)

(g) "Mad about the model. Well done" (01–01–05–01)

8.9 Conclusion

The Delphi technique reaches consensus among experts. If consensus as defined before the distribution of the questionnaire is reached after the first round, there is no need for any consecutive rounds. Consensus for this research was reached after the first round on all four aspects of the model.

The participants emphasised the important role that an integrated model like $BRPM^2$ can play in creating awareness for the adoption of AM in spare part provisioning in South Africa.

The next two chapters, chapter 9 (verification) and chapter 10 (validation), will summarise and conclude the results of this research study.

CHAPTER 9: VERIFICATION

The purpose of this study was to develop a maturity model that will assist in the adoption of AM in spare part provisioning and that practitioners can use as a roadmap for implementation. The design requirements for the model were discussed in chapter 6 and the $BRPM^2$ model was designed in chapter 7. Chapter 8 was a discussion regarding the results of the Delphi questionnaire.

Chapter 9 will address the following research question:

Research question 6.1:	Does the model adhere to each of the design requirements?

9.1 Verification methodology

The verification process confirms whether the BRPM^2 model adheres to the initial design requirements and design parameters. Verification is the process of determining that the designed maturity model represents the researcher's conceptual description and specifications with sufficient accuracy (Mettler, 2011).

To demonstrate this, there were four inputs to the verification process:

(a) **Design intent** – Section 9.2 provides a retrospective view of the design process, indicating how the design requirements for the BRPM^2 were considered.

(b) **Maturity model development framework** – Section 9.3 summarises compliance with the maturity model development framework that was used to design the maturity model (chapter 7).

(c) **Delphi technique** – Section 9.4 summarises the results of the Delphi technique (explained in chapter 8).

(d) **Checklist** – In section 9.5 a checklist is used to confirm the adherence to design requirements not included in the Delphi questionnaire.

9.2 Design intent

The design requirements and design for the BRPM^2 model were developed in chapter 6 and incorporated during the design of the BRPM^2 model in chapter 7. In this section, each design requirement is considered retrospectively to verify that it was considered as part of the design process.

DR 1a) – **The model should be basic in design**

The design guidelines of the maturity model were followed with the focus on a maturity grid. Research of maturity models also provided input into the requirements for a basic model design. It is only the key business risks that were included as dimensions in the model.

DR 1b) **There should be coherence between the different elements in the model**

The design parameters for maturity models stipulate that the elements must be evolutionary in nature and that there should be a link between subsequent elements.

DR 1c) – Maturity levels should follow an evolutionary path

The maturity levels were based on the research paper by Harmse and Holm (2019) relating to the provisioning business model evolution from supply chain to an agile demand network. The design parameters of a maturity model stipulate that the maturity levels should be evolutionary.

DR 1d) – Dimensions of the model should indicate the key business risks

The key business risks were defined from a research paper by Harmse (2019) as well as inputs from the South African ecosystem experts and the researcher'sown experience. One of the identified problems prohibiting the adoption of AM for spare part provisioning is the availability of a tool that visualises the key business risks that will be affected when adopting AM. The dimensions of the maturity model allow for multiple items to be measured.

DR 1e) – The elements must be clear and easy to understand

The elements relating to each dimension were researched as well as the evolutionary steps. The elements were aligned with the applicable domain for the dimension.

DR 2a) – The audience should be anyone in the organisation that would like toadopt AM for spare part provisioning

The model was designed to be basic according to the design parameters of a maturity model. There are no sublayers in the model and the terminology was kept as basic as possible to relate to a wide audience.

DR 2b) – The model must define the as-is status of the organisation

The model allows any user to identify the current status of the organisation andto mark it on the model This will allow the user to visualise with a single view what the as-is or current status of the organisation is.

DR 2c) – **The model can be used to create a roadmap for future improvement**

Once the as-is status has been defined, the users can decide on the future maturity stage that they prefer to reach and mark that on the model. The link between the as-is status and the future stage will indicate the roadmap for improvement.

DR 3a) – **An understanding of the key business risks and how they evolve will assist in the adoption of AM**

The dimensions of the maturity model are the business risks. The evolution of the business risks is designed as part of the evolution of the elements applicableto the dimensions and the maturity level.

DR 3b) – **The provisioning evolution must be from supply to demand**

The provisioning evolution is based on the research paper by Harmse and Holm (2019) defining the evolution of provisioning business models from supply to demand.

DR 3c) – **The linear chain philosophy must evolve to a systemic network philosophy**

The evolution is based on the research paper of Harmse and Holm (2019) considering the evolution of provisioning business models from a linear supply model to an integrated network philosophy.

DR 3d) – **Agility is a key requirement for successful interaction in the ecosystem**

The literature research as well as the research paper by Harmse and Holm (2019), confirmed that agility is a key requirement for operating in 4IR

DR 3e) – An understanding of the systemic relationship between the key risks whenadopting AM can improve the adoption

The importance of the systemic relationship between the key business risks was confirmed by two research papers. The first research paper from Harmse (2019) confirmed the key business risks and the second one by Harmse and Coetzee (2020) confirmed the role of systems thinking in understanding the systemic relationship between the key business risks.

The above discussions explain how each of the design requirements of the $BRPM^2$ model was addressed during the concept design and building phases of the eADR model. The following section summarises the results from the maturity model development framework that was used to guide the development of the $BRPM^2$ model.

9.3 Maturity model development framework

The maturity model development framework was used in chapter 7 to align the design of the $BRPM^2$ model with standard practices. Table 35 verifies if all the requirements of the development framework were incorporated in the design.

Table 35:Verification – maturity model development framework checklist.

Phase	Design	Design intent	Reference
1	1. Define theproblem	Yes	7.4.1
2	2.1 Focus/breadth	Yes	7.4.2.1
Definescope	2.2 Level of analysis/depth	Yes	7.4.2.2
	2.3 Novelty	Yes	7.4.2.3
	2.4 Audience	Yes	7.4.2.4
	2.5 Dissemination	Yes	7.4.2.5
3	3.1 Compareexisting MMs	Yes	7.4.3.1
	3.2 Designdirection	Yes	7.4.3.2
	3.3 Maturitydefinition	Yes	7.4.3.3
	3.4 Goal function	Yes	7.4.3.4
Designmodel	3.5 Designprocess	Yes	7.4.3.5
	3.6 Formulate celltext	Yes	7.4.3.6
	3.7 Design product	Yes	7.4.3.7
	3.8 Applicationmethod	Yes	7.4.3.8
	3.9 Respondents	Yes	7.4.3.9

4 Evaluatedesign	4.1 Method of evaluation and communication	Yes	Chapter 8 – Delphi questionnaire andfeedback
	4.2 Subject of evaluation	Yes	Design process – design intent matrix Design product – Delphi expert evaluation
	4.3 Timeframe	Yes	Ex-post (after the development of the model)
	4.4 Evaluation method	Yes	Artificial (Delphi questionnaire)

9.4 Delphi technique

The verification of the adherence to the design requirements was partially achieved by means ofthe Delphi technique, as explained in chapter 8. A summary of the quantitative results is providedin Table 36.

Table 36:Results for design requirements from Delphi questionnaire.

Design requirements	Result	Consensus
Structure		
The model is basic in design	3.2	Yes
There is coherence (systemic and logical connection) amongst all the elements in the model	4.0	Yes
Maturity levels		
The maturity levels relate to provisioning systems	3.9	Yes
The maturity levels follow an evolutionary path	4.0	Yes
Dimensions		
The dimensions of the model indicate the key business risks	4.1	Yes
Elements		
The elements in the risk/provision matrix are clear and easy to understand	4.1	Yes
Usability		
The model can be used by people on any level in the organisation who want to adopt AM as part of spare part provisioning	3.2	Yes
The model assists in creating an as-is status relating to the key business risks	3.8	Yes
The model assists in creating a basic roadmap towards provisioning maturity	4.0	Yes
Effectiveness		
Key business risks		
An understanding of the evolutionary role of the key business risks identified in the model will assist in an improved adoption of AM	3.8	Yes
Evolution of provisioning system		
There is a clear evolution from supply to demand	4.1	Yes
There is a clear evolution from the linear (chain) philosophy to a systemic network philosophy	4.0	Yes
Agility is a key requirement for success in the dynamic eco-network	4.5	Yes
Systematic relationships		
An improved understanding of the systemic relationship between the model dimensions (risks) can improve the adoption of AM in spare part provisioning	4.2	Yes

9.5 Summary of cross-verification

Table 37 provides a summary of the three inputs that were used to verify adherence to the design requirements:

(a) Design intent

(b) Maturity model development framework

(c) Delphi technique

The first column indicates the design requirements and columns two to four the adherence by means of each input. The last column indicates the conclusion reached in terms of verifying the adherence to each design requirement.

Table 37:Cross-verification of design requirements.

Design requirements	Reference to intentional design	Development framework	Delphi technique	Verification conclusion
Structure				
The model is basic in design	Maturity model development guidelines	7.4.3.6	Confirmed by question 8(a)	Yes
There is coherence (systemic and logical connection) amongst all the elements in the model	Maturity model development guidelines	7.4.3.2	Confirmed by question 8(b)	Yes
Maturity levels				
The maturity levels relate to provisioning systems	Business model evolution	7.4.3.3	Confirmed by question 10(a)	Yes
The maturity levels follow an evolutionary path	Business model evolution	7.4.3.3	Confirmed by question 10(b)	Yes
Dimensions				
The dimensions of the model indicate the key business risks	Business risk	7.4.3.5	Confirmed by question 11	Yes
Elements				

Design requirements	Reference to intentional design	Development framework	Delphi technique	Verification conclusion
The elements in the risk/provision matrix are clear and easy to understand	Maturity grid designframework	7.4.3.6	Confirmed by question 14	Yes
Usability				
The model can be used by people on any level in the organisation who want to adopt AM as part of spare part provisioning	Maturity model designspecification	7.4.2.4	Confirmed by question 16(a)	Yes
The model assists in creatingan as-is status relating to thekey business risks	Maturity model designspecification	7.4.3.8	Confirmed by question 16(b)	Yes
The model assists in creating abasic roadmap towards provisioning maturity	Maturity model designspecification	7.4.3.9	Confirmed by question 16(c)	Yes
Effectiveness				
Key business risks				
An understanding of the evolutionary role of the key business risks identified in themodel will assist in an improved adoption of AM		n/a	Confirmed by question 18(a)	Yes
Evolution of provisioning system				
There is a clear evolution fromsupply to demand	Business model evolution research paper	n/a	Confirmed by question 20(a)	Yes
There is a clear evolution from the linear (chain) philosophy toa systemic network philosophy	Business model evolution research paper	n/a	Confirmed by question 20(b)	Yes
Agility is a key requirement for success in the dynamic eco- network	Business model evolution research paper	n/a	Confirmed by question 20(c)	Yes
Systematic relationship				
An improved understanding of the systemic relationship between the model dimensions(risks) can improve the adoption of AM in spare part provisioning	Business paradigm research paper and business risk research paper	n/a	Confirmed by question 22 (a)	Yes

9.6 Verification conclusion

The aim of this chapter was to confirm that the $BRPM^2$ model adheres to all the specified designrequirements. This was achieved by means of cross-verification of a retrospective view of the design process, the Delphi technique and the development framework, of which the conclusion is summarised in Table 37. All the design requirements were positively verified by one or more of the methods.

By confirming adherence to all the design requirements, research question 6.1 is answered.

The research question is: “Does the model adhere to all of the design requirements?”

However, the validation of the research question, method and output remain to be proven. This aspect of the research will be covered in chapter 10.

CHAPTER 10: VALIDATION

Validation is the degree to which a maturity model is an accurate representation of the real world fromthe intended use of the model (Mettler, 2011).

Taken the above statement into account, chapter 10 will address the following research questions:

Research question 7.1	Has a valid research problem been identified?
Research question 7.2	Has a valid research design been followed?
Research question 7.3	Does the research output address the research problem as well as thespecific and general limitations to the study?

10.1 Validation methodology

This chapter considers the rigour of the research process and the value of the contribution by means of the following methods:

(a) **Research problem** – In section 10.2, literature and the Delphi technique will be used toprove the validity of the research problem.

(b) **Research design** – In section 10.3, the validity of the research design will be determined by means of the DSR and ADR guidelines and a research validation matrix.

(c) **Research output** – In section 10.4, the validity of the research output will be determined through the feedback from the Delphi technique.

10.2 Validation of research problem

The research problem was stated in chapter 1:

The adoption rate of AM as part of spare part provisioning is slow in South Africa becauseof (1) the lack of a concise understanding of the evolutionary requirements of the provisioning system and (2) the complex systemic relationship between the key businessrisks applicable when adopting AM as part of spare part provisioning.

The validity of the research problem was cross validated by means of the research papers summarised in chapter 5 and the Delphi technique (chapter 8).

10.2.1 Validation of research problem by means of literature

The first part of the research problem relates to an understanding of the evolutionary requirements of the provisioning system when adopting AM for spare part provisioning. AM is an innovative technology and requires evolutionary thinking about the business and provisioning paradigms. This necessitated a paradigm shift and an understanding of the provisioning system evolution from supply to demand, from linear chains to systemic, integrated networks and the inclusion of agility required for successful operations in 4IR. The evolution of the provisioning system was addressed through research on the evolution of business models with emphasis on the provisioning business model discussed in chapter 5.

The second part of the research problem is the understanding of the systemic interaction between the key business risks applicable when adopting AM. The key business risks were identified, anda paradigm shift is required to move from a linear way of managing the risks to a systemic understanding of the risks that will enhance the adoption of AM for spare part provisioning. This was discussed in chapter 5 (CDP 2) A paradigm shift is required when adopting AM and this is addressed by CDP 3.

10.2.2 Validation of research problem by means of Delphi technique

In addition to literature, the validity of the research problem was confirmed by means of specific questions in the Delphi questionnaire (chapter 8). Table 38 shares the results from the Delphi questionnaire. The averages of each of the three questions are above three, indicating that consensus was reached on the validity of the research problem.

Table 38:Results of the research question validation from the Delphi questionnaire.

Delphi questionnaire	Results
This section relates to the research problem addressed by the study	
The adoption of AM as part of the spare part provisioning system remains slow in South Africa	4.4
The adoption of AM in spare part provisioning is low because of a lack of understanding ofthe systemic impact on the key business risks when adopting AM	4.0
The linear provisioning paradigms slows down the adoption of AM in spare part provisioning	3.8

10.3 Validation of the research design

The second part in determining the validity of the research involved confirming the research design that was followed. In other words, are the answers to each research question warranted by the research input and research output. This was achieved by means of the following methods:

(a) The design science research guidelines (section 10.3.1)

(b) The action design research principles (section 10.3.2)

(c) The maturity model development framework (section 10.3.3)

10.3.1 Design science research guidelines

Design science research (DSR) is inherently a problem-solving process. Therefore, building and applying an artefact requires knowledge and understanding of a design problem and its solutions.

To understand these requirements for effective design science research, Hevner *et al*. (2004) developed seven guidelines on DSR to assist researchers (Table 9). Table 39 provides the validation of the research study against the DSR guidelines.

Table 39:Validation against DSR guidelines.

Guideline	**Description**	**Confirmation**	**Chapter reference**
Design as an artefact	DSR must produce a viable artefact in the form of a construct, a model, a method or an instantiation	The BRPM^2 model was designed as an artefact	Chapter 7 – BRPM^2 model
Problem relevance	The objective of DSR is to develop technology-basedsolutions for important and relevant business problems	The BRPM^2 model addresses the relevant business problem of the lowadoption of AM for spare part provisioning	Chapter 7 – BRPM^2 model
Design evaluation	The utility, quality and efficacy of a design artefactmust be rigorously demonstrated using well executed evaluation methods	The Delphi technique was used to verify the usability, effectiveness andapplicability of the BRPM^2 model	Chapter 8 – Delphi technique
Research contributions	Effective DSR must provideclear and verifiable contributions in the areas ofthe design artefact, design foundations and/or design methodologies	The Delphi technique was used to prove that the BRPM^2 model has an original design (as opposed to just a duplication of other previous work). The originality of the new design wasvalidated through the Delphi questionnaire	Chapter 9 – Delphi technique
Research rigor	DSR relies on the applicationof rigorous methods in both the construction and evaluation of the design artefact	During the first and second concept design phase literature reviews were used and during the 3rd concept design phase a systematic literature review was used. The Delphi methodwas used for the evaluation of the model	Chapter 5 – LR (article 1) Chapter 5 – LR (article 2) Chapter 5 – SLR(article 3) Chapter 8 – Delphi technique
Design as a search process	The search for an effective artefact requires utilising available means to reach desired ends while satisfyinglaws in the problem environment	During the problem diagnosing stage,a literature review, informal discussions and the researcher's ownexperience were used to find a possible effective artefact. Grounded theory was applied to define the requirement for the business model evolution	Chapter 2 – literature reviewChapter 4 – problem diagnosing

Guideline	Description	Confirmation	Chapter reference
Communication of research	DSR must be presented effectively both to technology-oriented as wellas management-oriented audiences	The final $BRPM^2$ model has been shared with experts during the Delphistudy. The research is communicated via thethesis and published articles as part of conference proceedings	Chapter 7 – $BRPM^2$ model Thesis document Conference proceedings

10.3.2 Action design research principles

Action design research (ADR) is a research method for generating prescriptive knowledge by building and evaluating artefacts (Sein *et al*., 2011). Table 40 provides verification against ADR principles.

Table 40:Action design research principles (Sein et al., 2011).

Principle	Description	Confirmation	Chapter reference
Practice inspired	The field problem should be viewed as a knowledge-creating opportunity	The problem of the slow adoption of AM as part of spare part provisioning was used for this research	Chapter 2 and chapter 4
Theory ingrained	The artefacts created and evaluated should be informed by theories	The problem definition stage was concluded. Grounded theory was used as input to the concept design stage. During the concept design stage literature reviews and a SLR were used. Multiple other literature resources were considered in the build stage	Chapter 2, 4 and 5
Reciprocal shaping	The artefact and the organisational context should exert inseparable, equal forces	Interactive intervention with experts took place during the problem definition stage. Expert involvement was also created during the Delphi study. The researcher's own experience from the case study organisation was applied	Chapter 4 and 8
Mutually influential roles	Mutual learning should take place among the different project participants	Interactive intervention with experts took place during the problem definition stage. Expert involvement was also created during the Delphi study	Chapter 4 and 8

Authentic and concurrent evaluation	Evaluation should form part of the build stage	The Delphi technique was used for the evaluation during the buildstage	Chapter 8
Guided emergence	The collective artefact should not only reflect the primary design created by the researchers, but also its ongoing shaping by organisational use, perspectives and participants	Interactive intervention with practitioners took place during the exploratory discussions but also during the Delphi technique	Chapter 4 and 8
Generalise the outcomes	Outcomes of the research should be generalised by including the organisational change that took place along with the implementation of the artefact. In other words, it should move from the specific-and-unique to the generic-and-abstract.	The outcomes and conclusions of the research is explained in chapter 11 – conclusions. The model is also designed as an open system with dissemination to a wide audience	Chapter 11 – conclusions

10.4 Validation of research output

Validation is a process during which a judgement is made as to whether an item is fit for purpose (Creswell & Creswell, 2017). The validity of the BRPM^2 model was determined by including specific questions in the Delphi questionnaire. Refer to Table 34 (summary of results from Delphi questionnaire) for these questions and results. An average of above three was achieved for eachquestion, indicating that consensus was reached on:

(a) The BRPM^2 model has a novel design.

(b) The BRPM^2 model will address the research problem.

The summary of the validation questions and results are listed in Table 41.

Table 41:Results of research output validation from the Delphi questionnaire.

This section relates to the validity of the research output	
(a) To the best of your knowledge, would you consider the construction of the BRPM[2] model as an original design as opposed to just a duplication of other previous work?	3.9
(b) The BRPM[2] model could assist in increasing the adoption of AM in spare part provisioning in South Africa.	4.1

10.5 Summary of cross-validation

Table 42 provides a summary of the five inputs that were used to determine the validity of the study and the conclusions. The first column states the validation requirement while columns 2–5 confirm which method(s) was/were used to confirm the validity. The last column states the conclusion that was reached in terms of the validation of the study.

Table 42:Summary of cross-validation results.

Validation requirement	**Research paper literature**	**DSR guidelines**	**ADR principles**	**Maturity model framework**	**Delphi technique**	**Validation conclusion**
Validity of the research problem						
A valid research problem should be identified	Confirmed	n/a	n/a	n/a	Confirmed by question6	Validated
Validity of the research design						
A valid research design should be followed	n/a	Confirmed	Confirmed	Confirmed	n/a	Validated
Validity of the research output						
The model should havean original design	n/a	n/a	n/a	Confirmed	Confirmed by question 24	Validated
The artefactshould address theresearch problem	n/a	n/a	n/a	Confirmed	Confirmed by question 26	Validated

10.6 Validation conclusion

The aim of this chapter was to confirm the validity of the research problem, the research design and the research output. This was achieved by cross-validation of a literature study, using the DSR guidelines, using a maturity model framework and utilising the Delphi technique. The results were summarised in Table 42 (summary of cross-validation results), confirming the validity of the study by answering the following research questions:

(a) **Research question 7.1**: Has a valid research question been identified? – Yes

(b) **Research question 7.2**: Was a valid research design followed? – Yes

(c) **Research question 7.3**: Does the research output address the research problem and the specific and general limitations of the study? – Yes

The validity of the study is therefore confirmed. Chapter 11 will conclude the study.

CHAPTER 11: CONCLUSION

The purpose of this chapter is to conclude the study, indicate how the research solved the central research question as well as the contribution made by the research and make recommendations for further research.

11.1 Introduction

The final chapter contains an overview of the research and the resulting contributions. The chapter also elaborates on the limitations of the study and the recommendations for further research. The conclusion on the study ends the chapter.

11.2 Research overview

The central research question of this research is:

What is required to improve the adoption of AM for spare part provisioning in South Africa?

Despite the growing interest in AM for various other applications, the adoption of AM in spare part provisioning in South Africa remains slow. The purpose of this research was to investigate the reasons for the slow adoption of AM for spare part provisioning in South Africa and to develop an instrument that could assist with the adoption of AM in spare part provisioning. This research is embedded in the design science paradigm that guided the research.Figure 47 is the eADR research design map that was designed for this research.

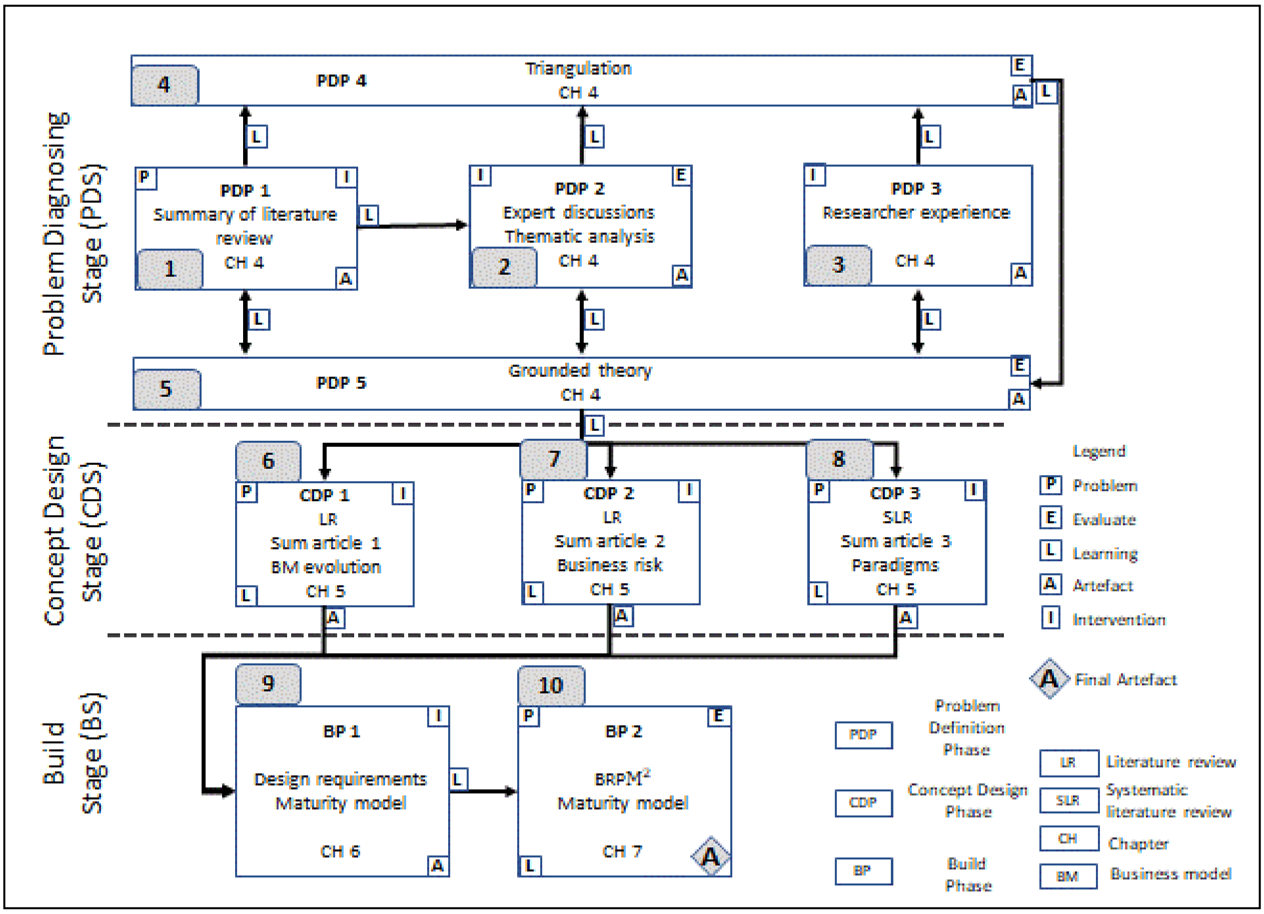

Figure 43:The eADR research design map.

The problem definition stage (PDS) of this research focused on understanding the reasons for the slow adoption AM for spare part provisioning. After a literature review relating to AM and the adoption of AM in various industries, a list of key contributing factors (codes) was compiled and used as guidance for informal discussion with experts from the AM ecosystem in South Africa.

The literature review (PDP 1) and the feedback from the South African ecosystem experts (PDP2) echoed the requirement for visible models to aid in the adoption of AM.

The output from the literature review, experts' feedback and the researcher's experience were triangulated (PDP 4) to determine the validity of the findings. The outcome played an important role in the iterative grounded theory (PDP 5) development to understand the phenomenon of the slow adoption of AM. Creswell (2013) states that the purpose of grounded theory is to develop new theory from the data collected rather than to test and refine existing theory.

The newly developed grounded theories were used as an input for the concept design stage. The three Grounded Theories:

(a) The first theory focused on the evolution of the provisioning business models from a linear supply chain business model to a non-linear business model focusing on the agile integration and participation into the global networks or ecosystem. This was used as the maturity levels in the $BRPM^2$ model.

(b) The second theory was used to research the key business risks that are impacted when adopting AM as part of spare part provisioning. This theory was used to developthe dimensions for the $BRPM^2$ model.

(c) The third theory directed research to the identification of the key paradigms influencing the adoption of AM and the importance of the systemic change required when adopting AM. This was included as a dimension of the $BRPM^2$ model.

These three theories were further researched and presented in different phases. The first phase explained the evolution of business models, the second phase identified the key business risks applicable when adopting AM and the third phase addressed the key paradigms required when adopting AM.

During the design of the new $BRPM^2$ model, several reference models were investigated to assess the possibility of finding a solution for the research problem. It was not possible to find a model that could satisfy the requirements of this research since the model needed to be based onthe evolution of provisioning systems for successful operation in 4IR, and the systemic overviewof the key business risks affected when adopting AM for spare part provisioning.

The evolutionary stages defined from the first phase of the concept design stage, were used as the maturity levels for the model and the key business risks defined in the second phase as the dimensions. The elements were defined as the as-is status per dimension for the current linear provisioning status and the future mature requirements of a non-linear systemic status. This created the basis for the design of the business risk provisioning maturity model or BRPM² (BP 2) Refer section 3.5.2 for a detail discussion on all the elements of this phase. During the evaluation phase of the model (E), a questionnaire was compiled and forwarded to identified

experts from the AM ecosystem in South Africa. The Delphi technique was used to administer the results and consensus was reached on all questions after the first round, thus verifying and validating the BRPM² model. The final artefact from this research is a maturity model where the maturity levels are based on the provisioning system evolution that will allow organisations to move from the linear paradigms of the past to embrace the new eco based paradigms required for AM adoption.

The dimensions of the model creates a view of the key risks that will be impacted when they contemplate to adopt AM for spare part provisioning. The elements link the evolutionary progress required of the provisioning system and business to each dimension and allows organisations not only to understand the current reality relating to each dimension but also to create a future view of what is required when they adopt AM and therefore to create a road map that can contribute to enhance the adoption of AM and assist them on their journey when adopting AM for spare part provisioning.

11.3 Limitations

(a) The flowing limitations were encountered during this research. The ideal way for external validation of the BRPM² model would have been to apply the BRPM² model to a sufficiently large sample of users that want to adopt AM as part of spare part provisioning and monitor the value of the model and the adoption rate of AM in spare part provisioning over a period of a few months or years. This would really indicate if the model contributed to an improved rate of adoption in AM for spare part provisioning. However, the time taken to conduct these evaluations would exceed the timeframe allowed for a typical doctoral study.

(b) Ideally, for the purpose of validation, it is important that the sample of participants that participate in the research is representative of as many of the industries where AM adoption for spare parts is applicable. However, in this study, the participants were selected based on availability and accessibility and the researcher tried to involve as many industries as possible.

11.4 Contribution of research

According to Hevner *et al*. (2004), effective design science research (DSR) should make a clear contribution to the real-world application environment from which the research problem or opportunity is drawn. This latches onto the three-worlds model of Mouton (2001) in Figure 48,

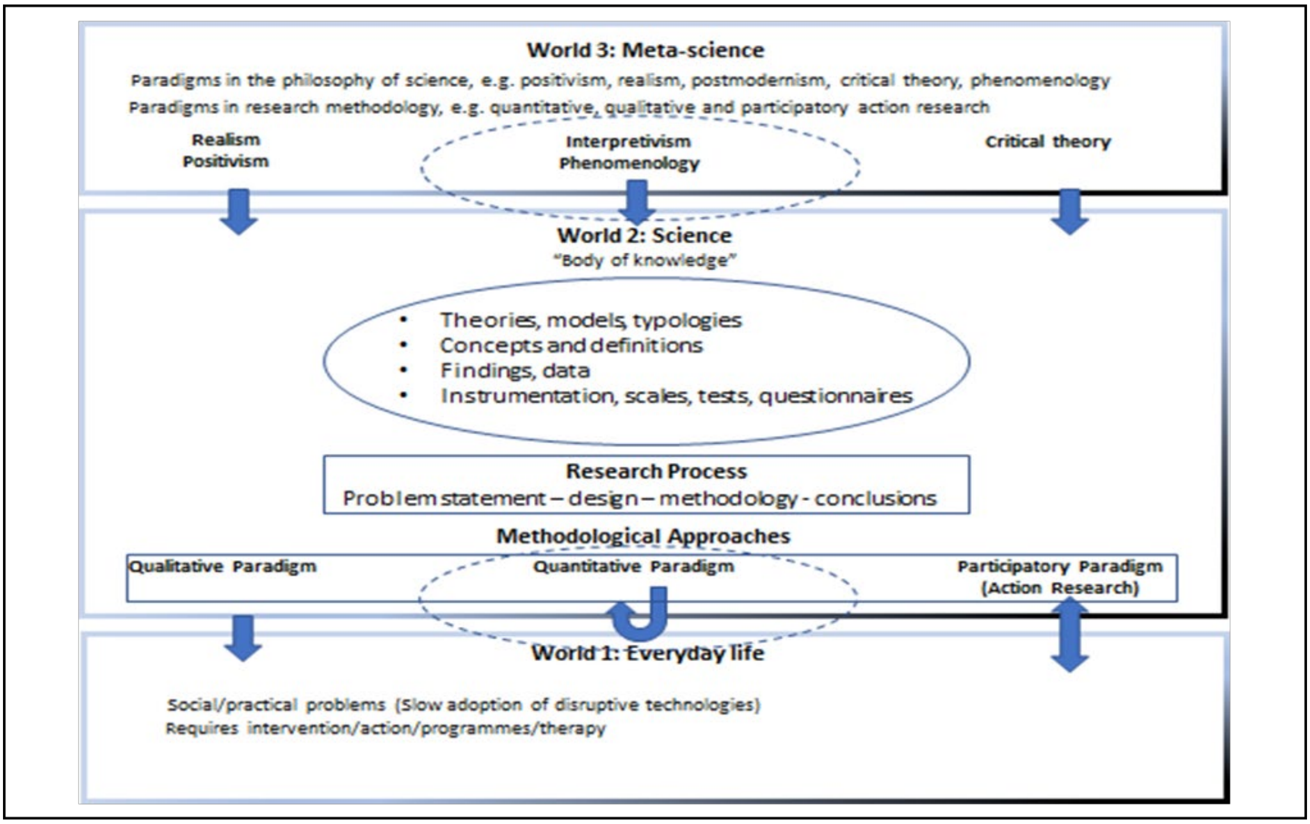

Figure 448:The three-worlds framework adopted from Mouton (2001).

where world 1 represents the real-world application environment. The triangulation of the three world's created the innovative new artefact or the BRPM² model where world 2 represents the research and world 3 the paradigms and grounded theories (Mouton, 2001) The real-world application environment of the BRPM² model is the creation of a tool that will create the required visibility andunderstanding and therefore assists in the improved adoption of AM for spare part provisioning This was confirmed through the maturity model in chapter 7 and the feedback from the real-world application environment through the Delphi questionnaire discussed in chapters 9 and 10.

Gregor and Hevner (2013) state that DSR knowledge can be divided into descriptive knowledge,the "what" knowledge about natural phenomena and prescriptive knowledge and the "how" knowledge of human-build artefacts. The descriptive knowledge can be drawn from various resources where the prescriptive knowledge can come from known artefacts and design theories that have been used to solve the same or similar research problems in the past.

Maturity models as per Table 10 (application specific domains of maturity models) can also be divided according to their application domains in descriptive and prescriptive models. The newly designed BRPM^2 model is a descriptive model and is based on the “what” knowledge of the application world. The descriptive knowledge was drawn from the maturity model design frameworks as well as the DSR guidelines that guided the construction of the maturity model.

Gregor and Hevner (2013) compiled a DSR knowledge contribution framework that allows researchers to determine the knowledge contribution of the designed artefact. This framework can be seen in Figure 49. The BRPM^2 model can be positioned in the ***exaptation*** quadrant since the researcher needed to demonstrate that there is a research opportunity and a knowledge contribution. The feedback from the experts that participated in the Delphi questionnaire attestedto this:

“Excellent understanding of current status to lay the foundations for a new paradigm” (04–06)

“This is indeed a fine piece of work. Indeed ground breaking work from my point of view. Definitelya step in the right direction to promote AM.” (01–01–07)

In the exaptation domain of the knowledge contribution model in Figure 49, the application domain(x-axis) maturity is low. This corresponds with the low maturity of AM adoption as indicated in theresearch problem. The solution maturity (y-axis) is high; therefore, the use of the maturity modelframework or known solution for the construction of the BRPM^2 model assists in defining the contribution of the BRPM^2 model. This provided the research opportunity and knowledge contribution to develop a model that will enhance the adoption of AM for spare part provisioning.

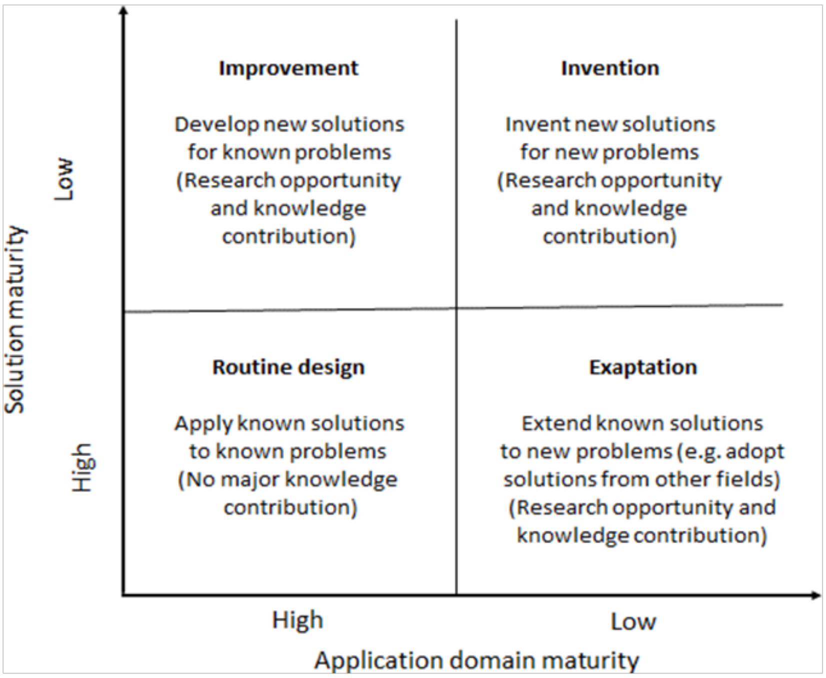

Figure 459:The DSR knowledge contribution framework (Gregor & Hevner, 2013).

Figure 50 is a graphical presentation of the knowledge contribution of the BRPM^2 model as well as an explanation of the contribution of AM to the individual, the organisation and the ecosystemthat will be explained in the next section. Chapter 9 and 10 provides evidence that the model can be applied to the world outside of the research contest. The major contribution of this study is therefore a BRPM^2 model that can be used by organisations for the assessment of their “as-is” status relating to the model and to prepare a road map to plan their journey when they contemplate to adopt AM for spare part provisioning.

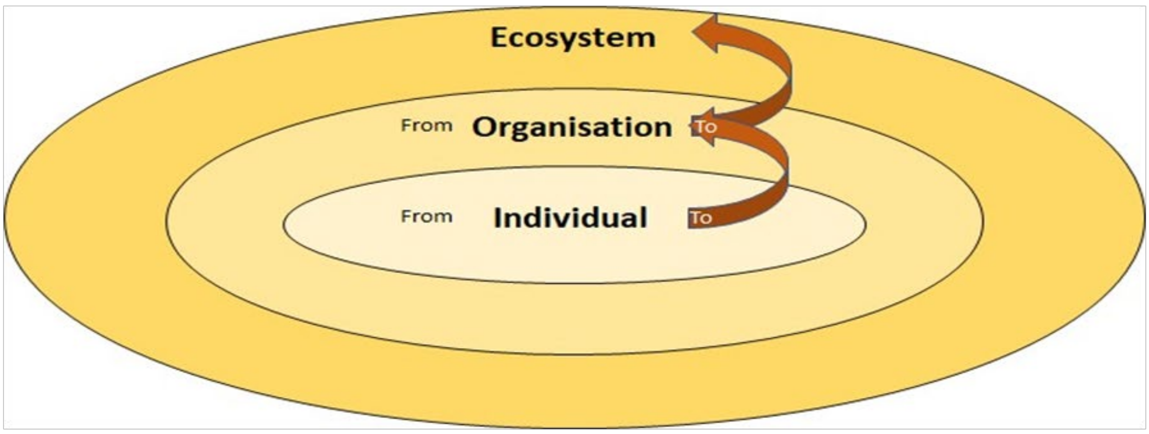

Figure 50: Knowledge contribution of the BRPM^2 model.

11.4.1 Contribution to the individual

An understanding of AM and the change from linear paradigms to non-linear paradigms allows individuals to participate in the culture change that will be required when AM is adopted. The $BRPM^2$ model is a descriptive model and does not provide detailed methodologies of how to implement AM but highlights the key requirements and the systemic interaction between the keyrisks.

The model provides an as-is scenario for individuals and for teams, allowing them to create a roadmap for the adoption of AM in spare part provisioning. This creates ownership of the roadmap and a willingness to drive the innovation and challenge the status quo. When individuals experience the benefits of AM and the real change in their work and business environments, they start to become more creative and think about the total cost of the ecosystem versus only the lowest cost and the functional solving of a localised problem.

The roadmap allows the individuals to focus on the key business requirements and to understandthe systemic relationship between these dimensions. This creates a culture of participation and non-linear thinking where design limitations forced a certain way of thinking in the past regardingthe spare parts and the provisioning system. AM with DfAM changes the scenario and allows innovative, participative and creative thinking of how a person changes the ecosystem to becomea better place versus what's in it for me. This instils self-esteem and a sense of achievement, which requires a culture and leadership change in the organisation.

11.4.2 Contribution to the organisations

Sisca et al (2016) contemplated that organisations will require a higher level of maturity to adopt AM. The provisioning maturity allows organisations to move away from the linear thinking of the supplychain provisioning system to a non-linear, agile network provisioning system. The business risks embedded in the dimensions of the model provide organisations with a guideline of the most important risks that will be impacted when the organisation adopts AM for spare part provisioning. Roos & Fisco (2014) reasoned that the limited understanding of the business risks involved when adopting AM is a contributing factor to the slow adoption of AM This is where the $BRPM^2$ model will play a crucial part in highlighting the business risks in a concise manner.

The adoption of AM is a journey, and therefore the notion of the evolutionary change needs to take place. De Carolis *et al*. (2017) indicated that the adoption of AM requires a roadmap. The $BRPM^2$ model allows users to create a basic roadmap that will assist them to develop a journey to adopt AM. It is not a revolution with a sudden impact but a gradual change that will affect the organisation and the way that the organisation interacts internally, but most importantly how the organisation relates to the ecosystem. AM requires the organisation to utilise the ecosystem for co-innovation and co-creation.

The change needs to start with the leadership of the organisations who needs to understand the impact of AM and embed AM not as a novel technology but as a disruptive strategic intervention.AM will then unleash creativity and innovation in various areas and will change the linear thinkingof the company to non-linear thinking and reset the status quo. The status quo in the organization will never be static again but will evolve to an agile culture embedded in demand, focused on providing solutions to customers in the global ecosystem.

One of the projects that was initiated in a company during this research is the replacement of a stainless-steel agitator with a 3D-printed polymer component. The agitator had to be replaced once a month in the past. Since implementing the polymer component, which took place from August 2019 to February 2021, the production rate was increased three times and none of the polymer components had to be replaced over 18 months. This is an example of the value that can be unlocked when AM is adopted for spare part provisioning.

11.4.3 Contribution to the AM ecosystem

The notion of supply chain embeds the focus on supply of spare parts and the linear chain concept where the linear paradigms dictate the modus operandi. AM requires organisations to participate in the global ecosystem and not to only use selected parts of the ecosystem but also to co- innovate. This will request from the organisation to understand the ecosystem and how to unlockthe value in the ecosystem and thereby ensure that spare part designs are improved and that theend of life of equipment can be prolonged due to new and innovative component designs that canbe created as part of co-innovation in the ecosystem. Thomas-Seal et al (2018) argued that the lack of industry standards can be a contributing factor relating to the slow adoption of AM. The $BRPM^2$ model allows organisations to understand that standards are important but adoption is an evolutionary process and standards will evolve over time through the contribution of the role players in the ecosystem.

The $BRPM^2$ model creates visibility of the key business risks and how AM as a strategic business intervention can assist in managing these risks not only in the organization but also as part of the ecosystem.

11.5 Recommendations for future research

The following topics should receive priority in future research based on the $BRPM^2$ developed in this study

11.5.1 Logitudinal studies

The scope of this study includes the development, verification and internal validation of a maturity model for the adoption of AM in spare part provisioning in South Africa. However, the standard timeframe of a doctoral study does not allow for a completely comprehensive examination into the development, verification, internal validation and external validation of enterprise models, such as maturity models.

The opportunity exists for future work where an “as-is” maturity assessment in an entity where the adoption of AM for spare part provisioning is contemplated and this model can be used as the point of departure. The purpose of such a study would then be to follow the creation of the road map and the implementation of the BRPM^2 roadmap and in doing so, contribute (or not) to the external validity of the BRPM^2.

The implementation of the model is not only applicable to the South African business environment but can be tested in an international realm as well.

11.5.2 Further iterations of the BRPM^2

The BRPM^2 model was designed with input from various sources. Future research would therefore need to include further interactions in the development of the BRPM^2. Specific focus areas are discussed below:

11.5.2.1 Dimensions

The dimensions for the BRPM^2 were compiled from the literature research, expert input and the researchers experience. As the adoption of AM mature, there might be other dimensions that will be more pertinent to the model and therefore the dimensions need to be updated.

The key business risks have been identified to serve as the dimensions for the BRPM^2 model. The suggestions from one participant that can be incorporated into the model is to change the concept of risks to risk areas. The risk areas create the notion of a more encompassing concept.

11.5.2.2 Elements

The elements contained in the model follows an evolutionary path. The evolutionary stages might change over time and needs to be updated to remain relevant regarding the applicable dimension and the evolutionary stage.

11.5.2.3 Descriptive and, prescriptive maturity model

De Bruin *et al.* (2005) explain that a deeper understanding of the “as is” domain situation is firstly achieved by means of the descriptive maturity model which was accomplished in this study. According to De Bruin *et al* (2005), after the maturity model has been applied a sufficient number of times, it can be developed into a prescriptive model. A topic for research is to further develop the BRPM^2 into a prescriptive model.

11.5.2.4 Roadmap

The purpose of the model is to create a basic roadmap that will provide users with an easy-to-understand plan. Some of the feedback during the Delphi feedback indicated that the model seems to be complex. A recommendation for future use could be to train key users in an organisation to use the model and allow them to deploy the model in the organisation. This will allow participants to better understand some of the key concepts as well as to understand the evolution of these concepts.

11.6 Concluding remarks

Since AM is a disruptive, strategic intervention, it requires the buy-in from top management and has to be incorporated into the strategic plan of the organisation. To allow AM to be moved fromthe technology realm where it has been positioned to a strategic business imperative, will require an understanding of the systemic impact of the key business risks areas. The $BRPM^2$ model willassist users to develop the understanding and to create a basic roadmap to guide their journey when adopting AM in spare part provisioning and therefore fulfill the requirement of the key research question ang will enhance the adoption of AM in sparepart provisioning in South Africa.

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ANNEXURES

ANNEXURE A: CD1 THE EVOLUTION OF BUSINESS MODELS FROM SUPPLY CHAIN TO AGILE DEMAND NETWORKS THROUGH ADDITIVE MANUFACTURING

THE EVOLUTION OF BUSINESS MODELS FROM SUPPLY CHAIN TO AGILE DEMAND NETWORKS THROUGH ADDITIVE MANUFACTURING.

ABSTRACT

Disruptive technologies had been the drivers for each of the first 3 industrial revolutions. These technologies shaped the evolution of the supply chain. As customers became more demanding, business models had to adapt from focus on supplying customers with goods, according to forecast, to a demand driven business model. The dynamics required to fulfil customer demand required more dynamic thinking and agility. It was also requested that companies leave behind linear chain thinking and participate in flexible agile networks.

As with all previous industrial revolutions, disruptive technology also plays an important part in shaping 4IR. In order to survive and thrive in 4IR, organizations will have to transform their business models from a supply chain model to an agile demand network. The most disruptive technology of 4IR is additive manufacturing. This paper discusses key requirements of an agile demand network and also the role additive manufacturing plays with the transformation from a business model based on supply chain principles to a business model based on an agile demand network.

1. INTRODUCTION

The world has experienced a number of significant step-changes that changed the way people conduct business, and ultimately their lives, which we know as industrial revolutions. According to the Collins dictionary an industrial revolution can be described as: "the change in social and economic organization", while the Longman dictionary indicates that revolution indicates a change in ways of thinking and methods of working. Each one of the industrial revolutions started with the invention of a new technology (see Table I) and also demanded a change in the required ways of working and thinking that can be called a change in business models.

Table I - First three industrial revolutions – [33]

Industrial Revolution	Started	Technology
1st	Mid 1700's	Steam engine
2nd	Mid 1800's	Electricity
3rd	Mid 1900's	Computers - Mainframe, PC's, Laptops

According to Schwab [1], the 4th Industrial Revolution (4IR) will be the most disruptive of all revolutions to date due to the way in which it will change everything we know, do, and relate to others. This revolution is, as with prior revolutions, earmarked by disruptive technologies and will have a significant impact on existing business models. In 4IR, emerging technologies and broad-based innovation are diffusing much faster and more widely than in previous industrial revolutions.

The impact of 4IR on business leads to an inexorable shift from simplistic digitization, which characterized the third industrial revolution, to a much more complex form of innovation based on the combination of multiple technologies in novel ways. Intense competition, a changing world, complexity, and increased risks demand a new approach to enterprise management to optimize enterprise performance and agility. This is forcing all companies to re-examine their business models.

1.1 The research question

What will be the impact of Additive Manufacturing on the spare parts provisioning business model?

1.2 Objectives of the research

The objectives of the research are:

1.2.1 Research the business model evolution

1.2.2 Define the requirements for success in the fourth industrial revolution

1.2.3 Define an industrial component supply business model and the required attributes based on the business model evolution and the requirements for success in 4IR

1.2.4 Define the role of additive manufacturing in shaping the new business model

1.3 Final Output

The final output of this research paper will be a proposed conceptual frame work for a new business model for spare part provisioning based on additive manufacturing.

1.4 Approach used and structure of the paper.

2. BUSINESS MODEL EVOLUTION IN INDUSTRIAL COMPONENT SUPPLY SYSTEMS

2.1 Business model definition

According to Linder [2] a business model can be divided in business that is fundamentally concerned with creating value and capturing returns from that value, and a model that is simply a representation of reality. Magretta [3]. Linder [2] indicates that while a business model facilitates analysis, testing, and validation of a firm's strategic choices, it is not in itself a strategy. In some cases, organizations might consider a set of business models representing different strategic choices before drawing a conclusion about the best business model for their organization. A business model embodies a set of choices, digital or not, where executives must make decisions about changes to their business in four key categories, namely (i) value proposition, (ii) customer, (iii) capabilities and lastly (iv) finance Basilirie [5](reference). Csik

[4] indicated the following key components that should be part of a business model design. See Table 2 for the key components. This was also echoed by Linder [2], Basiliere [5].

Table II - Key business model concepts

Business model architecture	Cisk [4]	Linder [2]	Basiliere [5]
Who	Who is the customer?	Strategic choices	Customer
What	What does the customer consider to be value?	Create value	Finance
How	To build and distribute a value proposition through the firm's value chain	Value Network	Capabilities
Why	How to create revenue in business	Capture value	Value Proposition

2.2 Business model transformation

Business model transformation involves many elements of an organization, and its success relies on the support and execution of an array of functions. The emergence of new digital technology and the disruption it brings to customer preferences, market dynamics and competitive advantage, fundamentally alter how companies must approach business model change Gartner [6].

If companies become complacent and think that they are sustainable by following a traditional business model, they risk losing out to more flexible competitors. Industry is changing rapidly, and soon, an industry may cease to exist. The path to profitability is different from traditional paths and opportunities for raising capital have changed. The capabilities upon which you build your business and your customer base may not appeal to customers in the future Magretta[3].

In 4IR, companies regularly explore a far broader set of options tied to potential future states and opt to run initiatives simultaneously with broad organizational involvement. According to Schwab [1], 4IR has four main effects on businesses across industries: (i) Customer expectations are shifting; (ii) products are enhanced by data that improve asset productivity;

(iii) new partnerships are transformed into new digital models; and (iv) operating models are being transformed into new digital models.

While the third industrial revolution saw the emergence of purely digital platforms, a hallmark of 4IR is the appearance of global platforms intimately connected to the physical world. Platform strategies combined with the need to be more customer-centric and to enhance products with data, are shifting many industries from a focus on selling products to delivering services and total solutions focussing on the total cost of ownership. Product vendors will focus on their core strengths and build better products relying greatly, or even totally, on ecosystem partners to provide additional services like maintenance, repair and other support functions Schwab [1].

New business and organizational models promise innovative ways of creating and sharing value, which in turn leads to whole system changes that can actively benefit the natural world as much as our economies and societies. 4IR will enable firms to extend use cycles of assets and resources, increase asset utilization and is not only changing what assets do, but what they are. At a strategic level, organizations must ensure that the challenges that technology pose are properly understood and analysed. Only in this way can organizations be certain that 4IR will enhance, rather than harm, their health and business models.

It is evident that companies will have to reconsider their business models to align with the disruptive changes of 4IR Rojas [34]. In future, competition will take place between business models, and not between products and technologies. Managers consider business model innovation to be more important for achieving competitive advantage than product or service innovation. Csik [4]

The convergence of additive manufacturing (generally known as 3D printing) with developments like open source licensing, repositories to share 3D data and files, and platforms to access manufacturing capacity has created an environment where innovation is highly supported, but also where current regulatory schemes and business models are ill-equipped to deal with this changing landscape.

In an increasingly nonlinear world, only nonlinear ideas will create new wealth. To thrive in the age of revolution, companies must adopt a radical new innovation agenda. The future operating environment will be more hostile and far less forgiving than that which we have experienced in the past Gattorna [7]. The fundamental challenge companies face is reinventing themselves and their industries not just in times of crisis - but continually and therefore they will require agile business models that are based in true customer demand Hamel [8].

3. EVOLUTION FROM SUPPLY CHAIN TO DEMAND DRIVEN BUSINESS MODELS

Gattorna [8] states that:

> "Supply chain management never was a good term because it immediately conjured up in one's mind the "supply" side of the enterprise. The "chain" descriptor doesn't help either, as it implies we are dealing with linear chains or strings of enterprises, when in fact the real world involves three-dimensional arrays of enterprises".

Authors such as Vollman [9] and Hugos [10] suggested that a better term than supply chain management would be necessary to emphasize the shift from efficient supply to meeting the need of the customer. In Beers [11], it is indicated that since consumers should be the focus of a chain's existence, consumer demand should be at the core of a chain's business strategy. In doing so, the supply chain transforms itself into a so called demand-driven chain or simply a demand chain.

Freughtwanger [12] indicates that the change from "supply" to "demand-driven" rightly suggested that all network activities should ultimately be aligned, planned and executed in pursuit of enterprise demand imperatives. Therefore it is important that we move from a linear chain perspective to a dynamic demand *network* perspective. A demand-driven network is a system of technologies, processes, and organizations that senses and responds to signals across a value-driven network of customers, suppliers, and employees. According to Barret

[13] Soliman, & Youssef [14], to survive in today's volatile business environment with increased complexity, organizations have to transform traditional supply chains to *outside-in* demand-driven value networks that focus on creating customer value.

According to Gattorna [15], the convergence of the Internet as a communications medium, and the coincidental development of a myriad of new software applications, will require the internal and external integration of processes and demolition of silo's prohibiting real-time information sharing with all the partners in the network to create customer value.

According to Cecere [16], demand networks are adaptive structures that can quickly align organizations, market-to-market, to focus on a value-based outcome. They sense and translate market changes bi-directionally with close to real-time data visibility and integration to better

optimize and align. More mature companies are managing multi-tier networks with strong visibility and agility to support rapid change in demand or disruptions in supply Cummins [18]. Therefore the functional specialization and fragmentation of activities that are part of the supply chain will need to be revised and a new business model will have to be created to survive in 4IR.

4. REQUIREMENTS FOR SUCCESS IN 4IR.

4.1 Disruptive technology as catalyst

A disruptive event is an event that suggests the occurrence of an enterprise threat or opportunity. An agile enterprise recognizes, analyses, and responds to disruptive events that occur in the enterprise ecosystem Cummins [18]. Since the first industrial revolution, technology has played a crucial role in transforming industries and fuelling growth. These technologies disrupted and changed older ways of thinking and conducting business, thus rendering old skills and organizational approaches irrelevant.

As before, disruptive technology will transform how we connect, learn, share and innovate in the future, with broad implications on organizations, workforces, and customers. Unrealistic expectations, fears of job security, and decision uncertainty due to options are ways in which technology challenges leaders to reconsider how future value will be created and protected.

Numerous new technologies surface daily that will impact the future, but there are only a handful that will have critical impact on business models. These have the potential to significantly disrupt the *status quo* so that we have to rearrange value pools and make use of entirely new products and services.

Table III indicates the criteria to determine the disruptive potential of a technology obtained from Aghina [20].

Table III - Technology disruption criteria Aghina [20]

Criterion	**Characteristic**
The technology is *rapidly advancing* or experiencing breakthroughs	Demonstrate a rapid rate of change in capabilities andexperience… (incomplete) see page 12 Table VII the duplicate
The potential *scope of impact* is broad	Must have a broad reach, touching companies and industries affecting a wide range of machines, products, or services.
Significant *economic value* could be affected	Will have massive economic impact
Economic impact is potentially disruptive	Can change the *status quo* dramatically

Figure II shows examples of technologies that will have a disruptive impact on business going forward, as identified by Schwab [1].

Figure II - Disruptive Technologies of 4IR – Source Schwab [1]

4.2 Agility in a changing environment

A view of the world – a paradigm – will endure until it cannot explain new evidence. The paradigm must then shift to include that new information. 4IR, with all its disruptive technologies, forces a shift in business paradigms from linear, fragmented models to new agile integrated models Ganguly [20]

An agile enterprise breaks silos down into relatively autonomous service units. Enterprise agility requires access to shared knowledge about how the enterprise works as well as knowledge that provides the basis for competitive advantage. The agile enterprise must have a culture of constant change. Models are essential for understanding the current state of the enterprise as well as evaluating potential future states. Models that reflect the state of the business in the future will have to include the interaction of the eco-system and all its components Cummins [37].

An “agile” organization thus reacts quickly to change, recognizes both internal and external customer and supplier change, perceives the need for change in the future, and accepts that need as a cost of doing business Meier [36]. Agility is an essential quality of the enterprise of the future. It continuously improves to optimize cost, quality, and speed of delivery. It enables top management to quickly implement new strategies and control key business parameters to gain competitive advantage. Agility resolves some common business challenges faced by many enterprises. But the agile enterprise does not fit current business models. It requires a new business paradigm — a new way of thinking about the business and new ways of planning, organizing, operating, and controlling the business Cummins [18].

In a world characterized by persistent and intense change, institutions rich in leaders with high emotional intelligence will not only be more creative but will also be better equipped to be more agile and resilient – an essential trait for coping with disruption. A capacity for agility will be much more about employee motivation and communication as it will be about setting business priorities and managing physical assets Meier [36]. A digital mind set, capable of institutionalizing cross-functional collaboration, flattening hierarchies, and building environments that encourage a generation of new ideas is profoundly dependent on emotional intelligence. Forward-thinking strategy leaders recognize that the secret to creating a growth-focused organization is not by further improving the planning calendar and templates, but by challenging operational mind sets that keep the organization in short-term firefighting mode.

Companies are at the threshold of a radical systemic change that requires human beings to adapt continuously. As a result, we may witness an increasing degree of polarization in the world, marked by those who embrace change versus those who resist it. Agile organizations mobilize quickly, are nimble, empowered to act, and make it easy to act. They respond as a living organism in the business eco-system Bisson [19] (reference). Table IV is a summary according to Aghina [20] of the key trademarks of agile organizations.

Table IV - Trademarks of an agile organization – Aghina [20]

	Trademark	Organizational Agility practice
Strategy	North star embodied across the organization	• Shared purpose and vision • Sensing and seizing opportunities • Flexible resource allocation • Actionable strategic guidance
Structure	Network of empowered teams	• Clear, flat structure • Clear accountable roles • Hands-on governance • Robust communities of practice • Active partnerships and eco-system • Open physical and virtual environment • Fit-for-purpose accountable cells
Process	Rapid decision and learning cycles	• Rapid iteration and experimentation • Standardized ways of working • Performance orientation • Information transparency • Continuous learning • Action-orientated decision making
People	Dynamic people model that ignites passion	• Cohesive community • Shared and servant leadership • Entrepreneurial drive • Role mobility
Technology	Next-generation enabling technology	• Evolving technology architecture, systems, and tools • Next-generation technology development and delivery process

These trademarks play an important role for any organization that wants to become truly agile. Only when all the trademarks are part of a company's business model, will that company be able to embrace the opportunities of 4IR. The management philosophy of an agile network should be project- and task-based with processes, resources, tools and techniques drawn from project management principles Atkinson[35] Meier[36]. This supports agility in that organizational restructuring may take place on an "as needed" principle to align with goals and objectives that frequently change.

4IR may be driving disruption, but the challenges it presents are of our own making. It is thus in our power to address them and enact the changes and policies needed to adapt in our emerging new environment. Business organizations that are not agile will fall behind. Agility is fast becoming a key business driver for all organizations as well as a crucial factor to a firm's ability to survive and thrive in uncertain and turbulent markets Chatzopoulos[22].

4.3 Demand driven provisioning

Markets are becoming more and more demanding. Customization is required to solve a specific problem or to enhance a process. The new markets will be small with highly unpredictable demand and price elasticity. It will be based on digital demand. The traditional business culture of handling one big market with mass produced goods will struggle to handle the forthcoming niche-markets of customized products Chatzopoulos[22].

4.4 Network and eco-system integration

Fast-moving competitors provoke a disaggregation of the more traditional industry silos and value chains, and also disintermediate the existing relationship between businesses and their customers. New disruptors can scale at much lower cost than the incumbents, generating in the process a rapid growth in their returns through network effects.

Hamel [8] argues that neither value creation nor value capture occurs in a vacuum but both occur within a value network, which can include suppliers, partners, distribution channels, and coalitions that extend the company's own resources. The role a firm chooses to play within the value network is an important element of its business model.

In almost all industries, digital technologies will create new, disruptive ways of combining products and services – and, in the process, will dissolve traditional boundaries between industries. Not all industries are at the same point of disruption, but all are being pushed up a curve of transformation by the forces driving 4IR. In a world characterized by uncertainty, the ability to adapt is critical – if a company is unable to move up the curve, it may be pushed off it. The companies that survive and prosper will need to maintain and continually sharpen their innovative edge and derive value from their eco-system integration Schwab [1].

At the core of this ideal is the opportunity to shift businesses and consumers away from the linear source-make-dispose model of resource use, which relies on large quantities of easily accessible resources, and toward a new industrial model where effective flows of material, energy, labour and information interact and promote, by design, a restorative, regenerative and more productive economic system Rojas [34].

Successful organizations will move from hierarchical structures to more networked and collaborative models. Motivation will be increasingly intrinsic, driven by the collaborative desire of employees and management for mastery, independence and meaning. This suggests that businesses will become increasingly organized around distributed teams, remote workers and dynamic collectives, with a continuous exchange of data and insights about the things or tasks being worked on Atkinson [35].

Companies able to combine multiple dimensions – digital, physical and biological - often succeed in disrupting an entire industry and their related systems of production, distribution and consumption. These combination-based business models illustrate the extent of the disruption that occurs when digital assets and interesting combinations of existing digital platforms are used to reorganize relationships with physical assets. The latest advances in additive manufacturing introduce powerful disruptions to manufacturers in the areas of design, customer engagement and production location. These disruptive features require an entirely new way of engaging with the outside world Kleer[28].

In a recent survey conducted, 76% of all the business leaders participating in a survey agreed that current business models will be unrecognizable in the next 5 years and that ecosystems will be the main change agent Lyman [24].

5. A SPARE PART PROVISIONING BUSINESS MODEL FOR SUCCESS IN THE FOURTH INDUSTRIAL REVOLUTION

From the research it is clear that new dynamic business models are required to participate in 4IR. These business models require agility to understand the dynamics of the market demand from the networked eco-system. As technology played an important part in the past to start an industrial revolution, so will the disruptive technologies available in the market also play an important role in transforming 4IR. One of the most disruptive technologies of 4IR is additive manufacturing Campbell[40]. Figure III indicates the impact of technology on the provisioning business models.

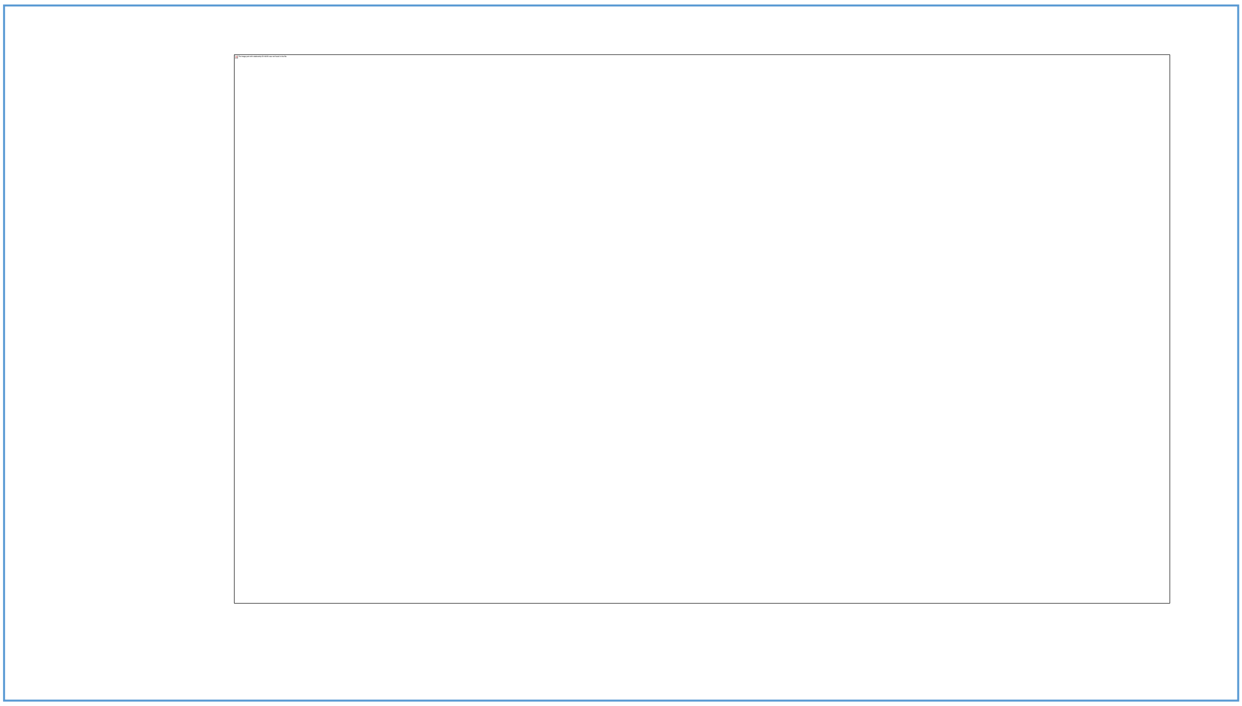

Figure III - Impact of technology on the creation of spare part provisioning business models – Source - Author

A supply chain is focused on the supply of product to the customers. It became more important to understand and service the customer according to the customer's requirements.Customer relationship management systems were implemented and paved the way for new demand driven business models. The internet linked more entities and created improved visibility throughout global networks. 4IR created disruption with new technologies as previously indicated in Figure II. This necessitated a new business model based on agility withparticipation in the network/eco system.

6. THE ROLE OF ADDITIVE MANUFACTURING IN CREATING THE AGILE DEMAND NETWORKBUSINESS MODEL

6.1 Define Additive Manufacturing and the disruptive nature on the business

Generally, additive manufacturing refers to

> "the process of joining materials to make objects from 3D model data, usuallylayer upon layer" ASTM International 2012 [25].

There is a variety of manufacturing processes behind the general term "additive manufacturing". These processes largely differ in the available choice of materials, build rates, mechanical properties of produced parts and other technological constraints. The main benefit of additive manufacturing is that it enables the flexible production of customized products without cost penalties in manufacturing. It does so by using direct digital manufacturing processes that directly transform 3D data into physical parts without the need for tools or moulds. Additionally, the layer manufacturing principle can also produce functionally integrated parts in a single production step, hence reducing the need for assembly activities. Thus, additive manufacturing technology significantly affects the cost of flexibility, individualization, capital cost, and marginal production costs Berman [26]. Additive manufacturing will also change the way in which we conduct business and will transform every day consumers into manufacturers in the future.

Additive manufacturing's impact ranges from incremental capability and finance improvements to radically new customer value propositions. Astute managers and technology planners use business models to assess the impacts and prepare their organization for the threats and opportunities brought on by additive manufacturing. Like the printing press, additive manufacturing printers have the potential to cause quite a stir from both business and legal standpoints Wilbanks[27] Bassiliere[5] Campbell[40].

Additive manufacturing will largely influence the locus of innovation and production, enabling the design of new value chains and business models Crane[28]. The impact of the eco-system will play a significant role in the development of the business models in future Kleer[29].

This is especially true with the mass-complexity business model, which allows the company to create new versions of products with fewer parts and different materials. A supplier with additive manufacturing capacity can consolidate the manufacture of many low-volume parts and therefore reduce the number of items that have to be kept. A similar logic applies to distribution, because additive manufacturing allows a company to build smaller factories close to customers Campbell[40]. Some companies even have mobile additive manufacturing factories — printers in trucks that can quickly move to a customer in need. Because AM makes factories and suppliers' more flexible, it generally works to reduce supply chain complexity D' Aveni[30].

Economic consequences of additive manufacturing can hardly be discussed at a single user level. In an interview with Jennifer Lawton (president of Makerbot) she indicated that3D printing is an ecosystem, not a device Conner[31]. Thus it is important to develop an understanding of the different elements that constitute this ecosystem that extends beyond sole manufacturing resources and industrial users. Additive manufacturing will revamp the economics of manufacturing and revive industries with creativity and ingenuity. People tend to overestimate the impact of new technologies and thereby lose sight of the long-term impact and how additive manufacturing will change the way companies operate and conduct business Bronberger[32]. Table VII is an indication why additive manufacturing will have such a disruptive nature on business models in the future.

Table VII - Disruptive nature of Additive manufacturing Manyike [39], Campbell [40]

Criterion	Characteristic	Additive Manufacturing
The technology is rapidly advancing or experiencing breakthroughs	Demonstrate a rapid rate of change in capabilities and experience breakthroughs that drive accelerated rates of change.	New materials, new printing technologies, increase in size of components, technology can be operated on desktops.
The potential scope of impact is broad	Must have a broad reach, touching companies and industries affecting a wide range of machines, products, or services.	Impacting all manufacturing, repair and maintenance activities. Change culture of organizations.
Significant economic value could be affected	Will have massive economic impact	Eliminate warehousing, capital requirements are low, print components close to point of consumption. Reduction in components due to part consolidation. Improve Overall Equipment Effectiveness and reliability of equipment. Extend life time of assets.
Economic impact is potentially disruptive	Can change the status quo dramatically	Numerous suppliers in the eco-system. Patent reverse engineering. Change of materials i.e Steel with polymer.

The key area that will be impacted by spare part provisioning is equipment availability. Two of the main causes of equipment failure continue to be (i) human intervention and also (ii) operation of equipment outside of operating conditions Snider[33]. This will require the redesign of the equipment to improve the functionality of equipment that in some cases was limited by design constraints from traditional manufacturing. With Additive Manufacturing and the new design for Additive Manufacturing principles where complexity is free, the functionality of equipment can be improved significantly. Additive Manufacturing is not just another disruptive technology but is a strategic disruptive force. Figure IV is a summary of all aspects of a business that will be disrupted by implementation of additive manufacturing.

Figure IV - Business impact of additive manufacturing – Source author

6.3 Key attributes of proposed new spare part provisioning business model

Table VI - Attributes of the evolution of the spare parts provisioning business model - Author

Table VI is a summary of key attributes that will have an influence on shaping the business model for spare part provisioning and how the proposed new spare parts business model evolved based on the research and the role that additive manufacturing will play in shaping the proposed new business model.

7. CONCLUSION

Disruptive technologies played a major role in all the industrial revolutions. Although the previous industrial revolutions were started by a key disruptive technology (refer to Table I), 4IR is characterized by a multitude of disruptive technologies. These technologies require totally new business models to ensure companies are sufficiently agile to manage the speed of change and ensure they understand how to add value to new demand networks.

New business models, based on agility and demand, will also ensure that the spare parts provisioning business model is transformed from a traditional supply chain view to an agile demand network perspective where creativity and innovation Campbell[40] are part of the business model. The agile demand network business model for spare parts provisioning will also be fueled by Additive Manufacturing. There is not a single part of the organization that will not be transformed once a company starts implementing additive manufacturing. Hence, Additive Manufacturing is not simply a disruptive technology, but a strategic force that must be embraced by an agile demand network business model.

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ANNEXURE B: CD2 THE BUSINESS IMPACT OF ADOPTING ADDITIVE MANUFACTURING IN SPARE PART PROVISIONING

THE BUSINESS IMPACT OF ADOPTING ADDITIVE MANUFACTURING IN SPARE PART PROVISIONING

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ABSTRACT

The business impact of additive manufacturing is poorly understood. Additive manufacturing is seen as a disruptive technology although it is a strategic business intervention that needs to be driven from the CEO. For business to understand and implement additive manufacturing success fully, it is important that an integrated model exist indication all the relationships of the key activities that needs to be aligned. This paper suggests such a model and then indicate through the use of case studies how 3 different additive projects were conducted.

1. INTRODUCTION:

The business impact of additive manufacturing is poorly understood [1] [3]. The challenge therefore is for firms to understand how to best leverage the technology in new business models alongside their existing models. Disruptive technology can't be imposed onto an existing business model as a replacement of, or as a complement to, existing technology in a business-as-usual approach [13]. Although for successful implementation of additive manufacturing there should be a paradigm shift [11]. This paradigm shift should result in the increasing understanding of products as individual solutions and not only a functional component and therefore industrial value creation faces considerable changes. A requirement for the implementation of additive manufacturing based business models is the availability of fully developed additive manufacturing techniques and an understanding of the impact of the interrelationship between the key elements of a business [6]. The discussion about additive manufacturing starts in companies on the production floor and this bottom-up approach creates a perception by management that additive manufacturing is limited to production. Additive manufacturing is in actual fact not just a technology confined to one area of the business but is a strategic game changer [2]. It is not just a manufacturing strategy but it is an enterprise strategy and therefore the CEO must drive the initiative of implementing additive manufacturing due to the fact that additive manufacturing will effect multiple parts of the business. Embedded economic concepts and structures that create value in current business models will be challenged [3]. Additive manufacturing changes not only how products are made and the materials that can be used but also how they are designed and distributed [28], thus its impact will be broad and extend beyond those enabled by the technical capabilities of the technology [13].

In order to understand the impact of additive manufacturing on the business, it is important that a comprehensive list of all the aspects that will be effected by adopting additive manufacturing as a strategic initiative is compiled [6]. This paper will present such a list and then elaborate on this list with case studies that will indicate what role AM has played in the transition process to create business understanding and adoption.

1.1 Research Questions

1.1.1 The first research question that needs to be answered is why is the adoption of Additive Manufacturing in the spare part provisioning system slow?

1.1.2 The second research question is what are all the components in the business that will be impacted by the adoption of Additive Manufacturing in the spare parts provision system?

1.2 Method

A literature research and case studies will be used to determine the answer to the first question. Further literature studies will be used to research the key components that will be impacted in a business through the adoption of Additive Manufacturing.

The intended output of the research will be an integrated list of all the key components that will be influenced in the business when adopting Additive Manufacturing for spare parts provisioning in the business.

Case studies will then be compiled indicating how the adoption of Additive Manufacturing impacted these key components in the model when adopted in the spare parts provisioning system.

2. LITERATURE STUDY

Since AM leads to changes in process and product structures, new requirements regarding the business activities will have to be explored and understood [1][3]. It is now possible to do cost effective prototyping and then to convert the prototype into a service part through additive manufacturing. User innovation can then be supplemented by user manufacturing that will contribute to changing the culture of the organization to an innovative and participative culture. There must be buy in from the CEO [8] and adoption and empowerment from the bottom to ensure a successful additive manufacturing implementation. In this new environment winners will be organizations that think first about their business model innovation rather than the specifics of additive manufacturing technology [12]. Successful companies repeatedly reinvent themselves by creating new business models that leverage these changes in disruptive technology with the view of increasing the value of the offering and ensuring they can capture this value commercially.

To translate strategies into action one needs new tools, new talent and a new mindset [4] [5]. In the literature there are different aspects to take into account when implementing additive manufacturing. There is a framework for the implementation of additive manufacturing based on a literature research of 116 articles. [6]. This research summarizes the current knowledge on additive manufacturing within management and business research and propose future research in relation to business models for additive manufacturing. In this article the authors indicated that:

“There is an indicated shift from positive connotations to increased questioning of the entrance and meaning of additive manufacturing in the production systems of tomorrow. What is not considered is how individual companies, given their supply chain position, change or need to change their positions but also competencies to meet those challenges and opportunities that additive manufacturing may bring about. Changes to how various activities are linked are seldom described, which could imply that additive manufacturing is viewed from the lens of traditional manufacturing” [6].

It is therefore important for the successful implementation of additive manufacturing that there is an understanding of the aspects that affect the successful implementation of additive manufacturingat business level and how these components interrelate [24]. The present literature gives a good overview of effects on production, but less often links to the entirety of the company and the internal as well as external interactions.[6].

Yet there is not a comprehensive guide line that can form the bases of new business models to ensure companies understand the hard and soft issues that needs to be addressed when implementing additive manufacturing [14]. Studies on additive manufacturing and its impact on business models are thus scarce. More empirical work is needed, moving knowledge away from scenarios and into how 3D printing in fact affects current businesses on the company level.

3. INTEGRATED ADDITIVE MANUFACTURING BUSINESS IMPACT

Table 1 indicates the key components that will be impacted when a company embarks on a journey to implement Additive Manufacturing as part of their spare parts provisioning strategy

Key Element	Literature research
Culture	[3][8][9][11][12][14][15][23]
Leadership	[2][3][8][9][12][16][29]
Eco system	[4][15][21][24][28]
Quality Assurance	[17][18]
Environmental	[4][10][15]
IT	[3][8]13][21]
Risk management	[4][6][19][21][24][28]
Component Design philosophies	[10][19][23][24][28][29]
Figure 1 indicated the relationship between the different components.	
Sales strategies	[3][4][6]
Asset strategies	[3][28]
Maintenance strategies	[7][24][26][27]
Supply Chain	[3][4][5][10][28][29]

HR/Structures	[24]
Procurement	[24][25]
Safety	[20][21][22]
Finance	[6][11][21][28][29]
IP/Legal	[10][21][23]

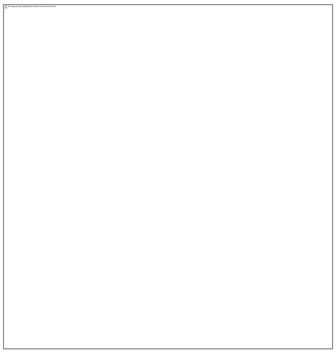

Figure 1 – Additive Manufacturing Business Impact source -

Additive manufacturing requires a culture of innovation and creativity and the core of this new culture is the leadership style in the organization [9]. As long as additive manufacturing is viewedas a disruptive technology, people will evaluate additive manufacturing along the basket of disruptive technologies and might make the wrong investment decisions based on the limited understanding of additive manufacturing [29].

Only when additive manufacturing is seen as a strategic game changer and the understanding is created of the true impact of additive manufacturing on the business as indicated in Figure 1, only then can additive manufacturing being explored and implemented to the full extend [28]. One of the key aspects that contributes to the slow adoption of Additive manufacturing is the fear of breaking the traditional boundaries and to allow for new thinking. Most of the research regarding the safety impact of Additive manufacturing, focuses on how to practice Additive manufacturing safely. Additive Manufacturing can create a safety culture in the organization and many new safety features can be introduced in the workplace that was no possible before due to the cost of traditionalmanufacturing where the focus is on lot sizes to create economy of scale and a once off requirementto solve a problem was too expensive.

The following case study will elaborate on how

In the next section case studies will be used to indicate how additive manufacturing can play a vital role to transform a business.

4. CASE STUDIES

4.1 Industrial manufacturing company

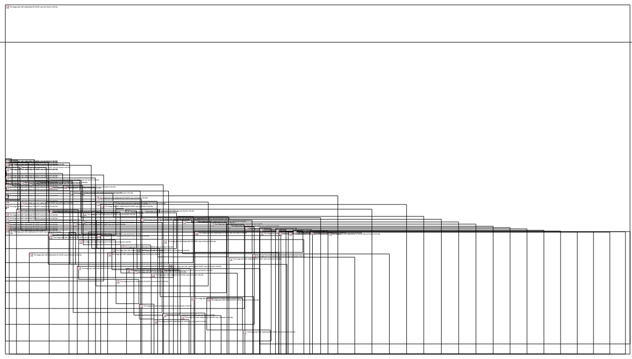

Figure 2 –Business Impact of Additive Manufacturing

ISBN 978-0-

4.1.1 Purpose

The purpose of this case study is to indicate how additive manufacturing can be the catalyst for the transformation in the company and why it is important to have a top down leadership approach when adopting additive manufacturing as a strategy.

4.1.2 Leadership

Successful implementation of Additive Manufactured spare parts rely on buy in from senior management. This will ensure that the business strategies are aligned and adjusted to include Additive Manufacturing as part of the business strategies. In this case study there was initially limited support for the adoption of additive manufacturing due to the lack of understanding of the value that Additive Manufacturing can unlock. Only after in excess of 170 spare parts were replaced in one year by Additive manufactured parts, did Senior Management start to indicate their support for this new program. The business impact of this intervention ensured that an 18% saving was achieved on the maintenance budget in the 1st year.

4.1.3 Culture

Additive Manufacturing can play an important part to change the culture of an organization. As more and more parts were replaced by additive parts, more people became aware of the value of the new technology. This created an innovation drive since new ideas could be prototyped, tested and then a commercial component could be printed.

One of the operational teams required a component that could assist them to improve the workflow and lay out of their workspace. They had an idea and requested the design of a component that works on the bases of a dog feeder. The component was designed and prototyped. After a few iterations, the final part was printed and implemented. This resulted in a 5% improvement in productivity that was wasted in the past due to set up at the start of the shift and cleaning at the end of the shift. After this implementation, many new creative ideas came forward to improve the operations.

4.1.4 Safety

Additive manufacturing can help to improve the safety culture of the organization. One of the high pressure air hoses dislodged and caused an injury. A clip was designed to prohibit the air hose to dislodge since the back pressure will grab the pipe. These clips could never be manufactured with conventional manufacturing and they were fitted every 500mm along the high pressure line.

4.1.5 Procurement

The parts that were designed and printed with Additive Manufacturing are being printed on demand and does not have to follow the normal procurement and replenishment process. These parts can be printed at any bureau that forms part of the eco-system.

4.1.6 Supply Chain

Localization is one of the key benefits of Additive Manufacturing. A number of the parts that were replaced by Additive parts were imported in the past. On some of the components part consolidation was applied and that reduced the number of spares required by close to 5%. Less warehouse space is required due to keeping the parts in the electronic warehouse.

4.1.7 Maintenance strategy

Additive manufacturing improves the reliability of equipment due to part consolidation that will reduce the number of components that can fail. One of the components was redesigned. Before the implementation of the additive enhancement, the component had to be replaced every 3 months and the time to replace the component was 4 hours. After the additive enhancement, the part was not replaced for more than 12 months and replacement will only take 5 minutes. The maintenance strategy changes from only focussing on the components to a redesign of the total system to enhance the reliability of the total system.

4.1.8 Asset Strategy

When assets near the end of its use full life, the assets had to be replaced due to the cost of servicing the equipment and also the unavailability of spares. With Additive Manufacturing, the required spares are redesigned and improved and the use full life of the equipment is extended.

4.1.9 Sales strategy

Some of the components that that were designed and implemented in the plant, could also be soldto other users. This created a new market and some of the components were exported as well.

4.1.10 Design philosophies

Subtractive manufacturing is part of production for many years and dictated the way components were manufacturing and that limited the creativity of designers.With Additive Manufacturing, complexity is free and therefore components could be redesigned toallow for part consolidation and improved functionality.

4.1.11 Risk management

One of the reasons for the slow adoption of Additive manufacturing is that the risks associated withAdditive manufacturing is not well defined. When embarking on the Additive Manufacturing route companies should use the integrated diagram as depicted in Figure 1 to compile a risk matrix and create an understanding of what is required to manage on their journey to success.

4.1.12 IT

The impact on the IT system is the creation of the e-warehouse and integration of the eco-system.In this particular implementation the e-warehouse was created on MS Excel since there was no strategy in place to create the e-warehouse.

4.1.13 Environmental

Most of the Additive components can be recycled. Additive manufactured components reduces thecarbon footprint of the supply chain significantly since parts are printed at or close to the point ofconsumption. There is limited physical movement of the components between the point of origin and the point of consumption.

4.1.14 Quality Assurance

by the technology partner. On a recent visit to the plant by the technology partner they wanted to know who granted the permission to change some of the designs.

When the reason behind the design changes were discussed, they could understand that the improved Additive designs allowed for significant process improvements and requested that these new designs had to implemented in their plants as well. The original IP was with the technology partner but due to the design freedom imbedded as part of Additive manufacturing, the designs could not be digitalized but also significantly improved.

4.1.17 Finance

Significant cost savings can be materialized by the implementation of Additive Manufacturing. The financing of the scanning, printing and post processing equipment to create the components will become part of the budgets going forward. Obsolescence of components will be eliminated since all the components are kept in the e-warehouse and only strategic spares will be kept at the plant for quick replacement.

Numerous standards for quality assurance on 3D printed components are developed by ASME and other quality assurance companies. A list needs to be compiled of all the elements that require quality assurance. Quality assurance can also be performed in the simulation software where a goodunderstanding can be created of how the component will react to applied forces.

4.1.15 Eco system

A thorough understanding is necessary of how to conduct business in the new eco-system and howto dynamically identify the different role players. The eco-system will also require a different leadership style in the organization

4.2.1 Case study 2

The question that needs to answered by this case study is if the materials available for Additive Manufacturing can replace traditional materials and improve the performance.

4.2.2 Material replacement

The component that was investigated is an agitator on a bulk liquid tank. The product starts off asa slurry and the agitators needs to mix the product while more liquid is added. Figure 3 is an indication of the original Stainless steel agitator.

Figure 3 – Stainless steel agitator

This agitator was replaced with an agitator that was designed and printed in PEEK (Polyetheretherketone). Figure 4 is an indication of the newly designed and printed agitator.

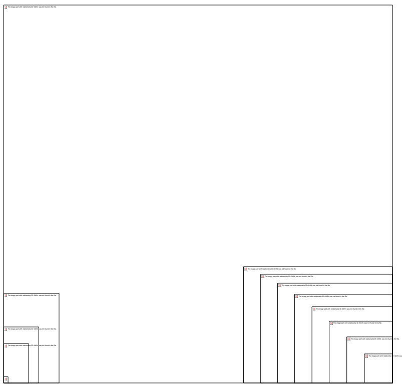

Figure 4 – Additive printed agitator with new design

The new component is significantly lighter than the original component as well as improvedbalancing that will reduce the wear and tear on the bearings. It is also expected to last longer due to the compatibility of the printed material with the product.

When this article was compiled, the components were handed to production to start the evaluation. These components were printed by 3Disrupt

4.4 Case study - Asset strategy

4.4.1 Goal of the case study

The goal of the case study is to indicate how Additive manufacturing and the available simulation software can assist in resolving a failure on a valve and therefore extend the life of the equipment.

4.4.2 Background to valve

Figure 5 Failing valve

The valve in Figure 5 was failing on a regular basis and had to be repaired at a significant cost. Therewas no indication why this valve failed and it was contributed to the abrasive nature of the product that caused wear in the valve and then caused the valve to leak. It was decided to simulate the forces on the valve in order to determine what the cause of the failure was. Figure 6 is an indicationof what happened to the valve when forces are applied to the valve.

Figure 6 – Load configuration on valve - closed position (Courtesy of Altair)

It is clear that the extreme pressure on the valve in the closed position causes a deformation of the valve around the core and that this could be the reason for the failure of the valve and that caused the valve to leak.

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5 CONCLUSION

The integrated platform presented in Figure 1 will assist organizations to plan and understand the strategic impact of additive manufacturing on their organizations and to design and build their business models. Additive manufacturing must move beyond a solution to rapid prototyping to a realstrategic, disruptive business strategy. Companies that adopt additive manufacturing in their businesses and start to embrace the new eco-system will reap the benefits in adjusting their businessmodels early on.

Although the case studies were implemented from the bottom up, the early acquainting of the technology and how it can change the business environment for the better created a platform from where other entities in the business starts to enquire about the possibilities to solve their problems as well. This will then drive the change required in the culture of the organization to an innovative and participative culture. Soon leadership will not be able to resist the tide and complete understanding will take place that will position additive manufacturing as a strategy in the companyand not just another technology.

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ANNEXURE C: CD3 INVESTIGATING HOW SYSTEMS THINKING CAN ASSIST WITH THE ADOPTION OF ADDITIVE MANUFACTURING IN SPARE PART PROVISIONING SYSTEM

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INVESTIGATING HOW SYSTEMS THINKING CAN ASSIST WITH THE ADOPTION OF ADDITIVEMANUFACTURING IN SPARE PART PROVISIONING SYSTEMS

ABSTRACT

Although the adoption of Additive Manufacturing (AM) in various industries is accelerating, theadoption of AM for industrial spare parts provisioning remains slow. AM is indicated as one ofthe most disruptive innovations of Industry 4.0 (4IR). When adopting a disruptive innovation, the reasons for the disruption needs to be understood. An innovation is defined as disruptive when it changes the way the current industry operates. This disruption challenges the status-quo and the understanding of the risks and paradigms involved when adopting this innovation. Uncertainty can cause the innovation to be perceived as complex and can prolong the adoptionof this technology in an organization for spare part provisioning. A paradigm shift from linearmodels to integrated, networked non-linear models will be required for adoption of AM produced spare parts and provisioning system evolution.

This paper will attempt to identify how the concept of Systems Thinking can assist organizations that would like to adopt AM for spare part provisioning to resolve the above mentioned reasons and increase the adoption of AM for spare part provisioning.

Key words: Additive Manufacturing, provisioning system, risk, complexity, DfM, DfAM, SystemsThinking.

1 INTRODUCTION:

Additive Manufacturing (AM) or 3D printing refers to the process of joining materials to make objects from 3D model data, usually adding layer upon layer, as opposed to subtractive manufacturing methodologies, such as normal milling, grinding and CNC machining. ASTM[1],Walker [2], Delberoglu [3]. AM is gaining more popularity as an emerging manufacturing method in various areas of the economy for the production of customized components from jewellery, footwear, toys, architecture, automotive, aerospace, dental and the medical industry Delberoglu [3]. AM is also used for rapid prototyping where a component can be created in the Computer Aided Design (CAD) software, modelled and then printed to test formand function before the production of the component for industrial use.

The use of AM technology is growing at an exponential growth rate year on year Wohlers [4] as indicated by Figure I.

Figure I : Annual AM growth rate – Wohlers [4]

As the technology matures and moves away from rapid prototyping towards production of spare parts Kianian [5], so does the requirement to understand and manage the uncertainty initiated by this disruptive technology Ituarte [6]. Den Boer [7] contemplates that AM will notonly disrupt the manufacturing and Supply Chain processes but will also fundamentally transform these activities. AM presents significant potential to enable organizations to apply new creative, non-linear thinking to create components that can improve the reliability and process efficiency of the operations Liu [8].

According to Olesen [9], successful organizations distinguish themselves by their willingness and ability to acquire technology and to take technology risks. AM is described as one of the most disruptive innovations of the Fourth Industrial Revolution (4IR) Marak [10], Beltaguia [11].A technology is described as disruptive when it replaces current operating practices and industry norms with radical new ways Atteram [12]. This will require a paradigm shift from traditional design for manufacturing (DfM) and Supply Chain principles to new design for AM (DfAM) and network integrated provisioning systems Roos [13].

With DfM, and with the current spare parts manufacturing processes, complexity is expensive.One of the requirements for operating in the new business eco-system is the ability to managecomplexity. When spare parts are produced with DfM, material is removed from a block of material, layer by layer until the final component is created. This process leads to significantwaste and there is little room for complexity. AM shifts the paradigm from a reductionist approach to a systemic approach. AM is a system where complexity can be accommodated, and components are built layer by layer from the bottom Booth [14]. Figure II indicates the design principles for traditional manufacturing (DfM) and AM (DfAM).

Figure II : Difference between Traditional Manufacturing and Additive Manufacturing - Author

In order to adopt AM in spare part provisioning, a paradigm shift will be required from DfM toDfAM. This will require a disruptive change in how business risks are managed, from the traditional linear paradigm to a dynamic, systemic network paradigm and understanding howto manage the perceived complexity of AM. Christensen [15] states that disruptive innovationsare seen to be complex because their value and applications are uncertain. However, Roos [13] indicate that the strategic implications of AM across industries are significant, yet poorlyunderstood and this attributes to the slow adoption of AM in spare part provisioning.

AM can also require a change in business model Oberg [16] Savolainen [17]. The process of adopting a new business model must be an agile and dynamic process. Successful companies repeatedly reinvent themselves by creating new business models that leverage these changesin disruptive technology. To translate strategies into action companies will need new tools, new talent and a new mindset Roos [13].

When adopting a technology that will disrupt the status quo, there will all ways be resistanceto change Muita [18]. This resistance to change can lead to the slow adoption of the technology. The purpose of this paper is to investigate what are the main reasons that are responsible for the slow adoption of AM in spare part provisioning. Once these reasons have been established, the concept of Systems Thinking will be applied as a possible solution to enable the accelerated adoption of AM in spare part provisioning.

2 PURPOSE AND METHODOLOGY

The research questions that will be investigated in this paper are:

Q1: What are the reasons for the slow adoption of AM in the spare part provisioning systems?

Q2: How can Systems Thinking be utilized to enhance the adoption of AM in spare part provisioning.

In order to answer question 1, a literature review was be conducted that will elucidate the main reasons for the slow adoption of AM in spare part provision (Section 3). Question 2 will be answered by investigating how System Thinking can be utilized to assist in improving the adoption rate of AM in spare part provisioning (Section 4).

The paper ends with a discussion on the findings summarizing the research outcomes and suggestions for future research will be provided.

3. LITERATURE REVIEW

3.1 Reasons for slow adoption of AM in spare part provisioning

Thomas-Seal [19], Mellor [20] indicated that the barriers to the progression of AM for the wider adoption of AM for industrial spare parts requires attention. The focus of researchers to datewas either based on broad level adoption or been highly focused on material and energy consumption. According to Douglas [21], AM is to an extend following the S-curve model of diffusion, although for wider adoption, AM will need to deviate from the current rate of adoption.

According to a literature review based on the adoption of AM in spare part provision, three aspects were identified that according to the authors contributed to the slow adoption of AMin spare part provisioning. The three reasons are depicted in Figure III and will be discussed individually in the sections to follow.

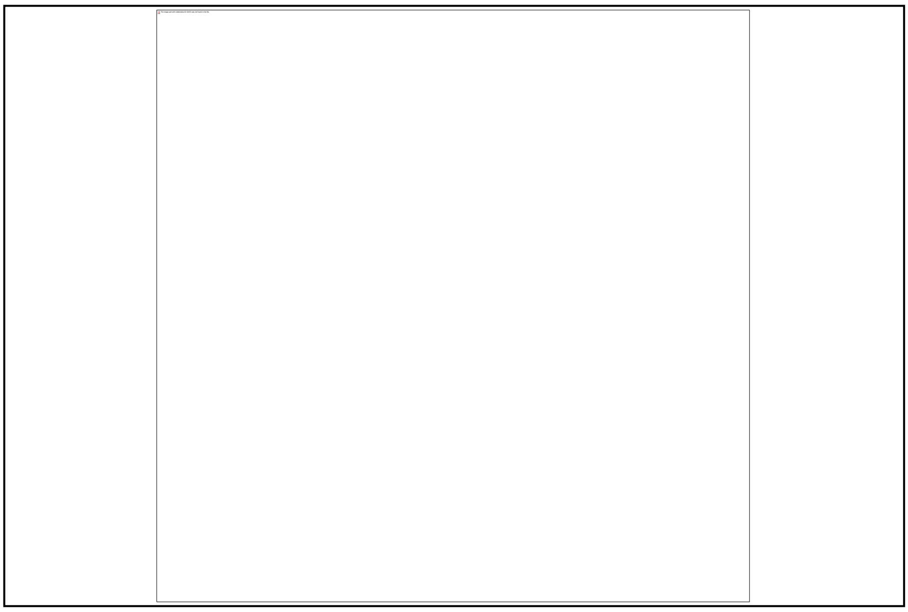

Figure III :Reasons for slow adoption of AM - Author

3.2 Provisioning system evolution

Apart from the exponential growth of AM, the adoption and provisioning systems for the use of AM for spare parts is not developing at the same rate Vinodh [22]. With the advent of the 4^{th} Industrial Revolution (4IR), provisioning systems have to evolve from a linear perspective where the sum of the parts makes op the whole, to a holistic systemic view where the interrelationship in the system needs to be managed and understood Kim [23],Feldman [24].

One of the risks that remains inherent in the current Supply Chain, is that it re-enforces traditional linear thinking. Gattorna [25] states that the term Supply Chain Management was never a good term because it emphasizes the supply side of the enterprise. The chain descriptor implies, participants are dealing with linear chains or strings of enterprises, when in fact the provisioning systems are involved in multi-dimensional, integrated networks or eco-systems. 4IR necessitates that organizations move away from static, linear provisioning systems to dynamic eco-networked non-linear systems Verboeket [26].

Disruptive technologies change the attributes required to manage the business and the natureof the provisioning systems which is sometimes ignored by companies Christensen [15], Muita[18]. The business is not operating in a linear supply chain any more but will become part of the global network or eco-systems Parker [27]. Harmse(a) [28] in their study on the evolution of business models from supply chain to demand networks contemplates that the focus in theprovisioning system has to transcend from a supply culture to a demand culture understandingthe dynamic requirements of the integrated networks.

Moore [29] defines the eco system as:

> "an economic community created from interaction between individuals or groups, withthe emphasis on the networks between the actors within the ecosystem and the dynamic interaction between these networks."

Choi [30] indicate that eco-systems are complex adaptive systems that can function in a dynamic business environment.

Figure IV is a summary from Mellor [20] of the model that they propose for adoption of AM. This model indicates the integrated nature of the different activities when embarking on theadoption of AM for spare part provisioning. Although Supply Chain is part of the model, it stillpresents a linear view with the emphasis on the supply side of the business.

Figure IV : Model for AM adoption – Mellor [20]

MacCarthy [31] contemplated that a new Supply Chain evolution is needed to adapt to the requirements of 4IR. There should be a transition from Supply Chain to Supply Networks to incorporate the multitude of different actors in the operating environment. Harmse (a) [28] indicated that due to the disruptive nature of AM, it will also require a disruptive view of Supply Chain that will focus on the integration into the eco-system.

Harmse (a) [28] compiled a model for the Supply Chain evolution from Supply Chain to Agile Demand Networks. This model can be seen in Figure V.

Figure V : Provisioning system evolution model – Harmse [28]

The evolution from Supply Chain to Demand Chain has been initiated by the implementationof Customer Relationship Management (CRM) software and a focus on the demand side of thebusiness. The next evolution was initiated by the advent of the global internet. The internet allowed many different networks to be connected and created more real time visibility. 4IR, introduced new disruptive technologies and the requirement for agility became sturdier. Withthe proliferation of these technologies, where AM is the most disruptive, an improved systemicunderstanding of the provisioning system and how to function in turbulent, agile and complexbusiness networks will be required to fulfill the dynamic demand Harmse [28].

3.1.4 Complexity

Organizations are facing unprecedented levels of change and the ability to adapt to and manage the change should be well understood Burnes [32]. As the world becomes more interconnected as part of the participation in the eco-system, so does the need to understandand manage complexity Colchester [33].

Gartner[34] indicates that AM is still perceived to be a single technology whereas AM consistsof a whole manufacturing paradigm and a wide range of different processes and techniques that integrate across boundaries and networks adding to the complexity of the global eco- system.

Rogers [35] published the Innovation diffusion theory (IDT), an influential work which helps toexplain the adoption of innovation. The IDT indicates that an innovation's adoption rate is influenced by five specific innovation attributes. Table I is a summary of these attributes.

Table I : Innovation adoption Attributes – Rogers [35]

Innovation Attributes	**Definition**
Relative advantage	Perceived superiority of an innovation to existing practices
Compatibility	Perceived consistency of an innovation with existing values, past experiences and needs of potential adaptors
Complexity	Perceived difficulty to understand and use the innovation
Trialability	Perceived degree to which the innovation can be experimented with
Observability	Perceived degree to which results of an innovation are visible to others

The IDT indicates that a high degree of relative advantage, compatibility, trialability and observability of an innovation is positively associated with its adoption, whereas complexity is negatively related to an innovation's rate of adoption. Rogers [35] further indicated that theidea about a disruptive innovation can cause some uncertainty by possible adopters and that some degree of risk is involved in the adoption that exacerbates the uncertainty and fear of complexity.

Gartner [34] indicated in their study on the construction of a theoretical framework to explain the disruptive potential of Additive Manufacturing that the complexity of AM technologies has been underestimated. According to Oettmeier [36] this can be attributed to the insecurity about the how, where and why to deploy additive technologies.

Burnes [32] contemplates that organizations are like complex systems in nature, they are dynamic, non-linear systems and that their actions can be unpredictable as part of the integrated network environment.

Table II indicates the difference between complicated (traditional linear) systems and complex (eco-based systemic, non-linear) systems. This summary is derived from Sammut- Bonnici [37] and author own inputs.

Table II : Difference between complicated and complex systems - Sammut-Bonnici [37] &Author

Complicated (Traditional systems)	Complex/Complexity (AM Eco system)
Complexity is a burden	Complexity is a challenge
Attention to detail	Investigate behaviour of whole system
Rich in detail	Rich in structure
Getting task done	Action in one-part effect other
Problems are broken down into small parts	Activities shift and adapt according to situation on hand
Experts solve parts	Agile, multi-disciplinary teams create solution
Management hierarchy	Evolves and adapt with internal systems and externalenvironment
Rules established – linear processes	Operations framework
Organizations viewed as complicated and static	Organizations viewed as complex set of self-organizing components
Mass production and division of labour	Economic and organizational phenomena are like those observed in science and nature
Attributes: Diminishing returns, rules based regulated environment, stagnation, linear dynamics	Attributes: Increasing returns, self-organizing system, continuous adaptation, sensitivity to initial conditions, non-linear dynamics
Component design Methodology: Design for manufacturing (DfM)	Component design methodology: Design for AdditiveManufacturing (DfAM)

Table II indicates that organization must move from complicated, linear systems to complex,non-liners systems. It is therefore important that there needs to be a clear understanding of how to manage the complexity introduced by adopting AM as part of the spare part provisioningsystems.

3.1.5 Business risk

Roos [13] and Christensen [15] contemplates that disruptive, innovative technologies that replaces current industry platforms, can have a significant impact on the structure of the industry. It is therefore important to understand the systemic nature of the structural changesand the risks associated with such a disruptive, innovative change. Disruptive technologies also require new structures and capabilities of the organizations where they are implementedChristensen [15]. The philosophy of management towards new technologies will also influencetheir decision to adopt disruptive technologies Ariss [38], Matinaro [39]. It is important that managers understand the systemic impact that these new technologies introduce in the business and the risks associated with them.

Matinaro [39] contemplates that the diffusion of a new technology is linked to the propensityof the organization to adopt innovation and change. According to their study, the key to the adoption of new innovation in an organization, is much more linked to the attributes of the organization and their propensity for risk and not so much to the new innovation. Table III is a summary of the list Matinaro [39] prepared of the business attributes required for adoptionof an innovation

Table III : The innovation process characteristics and explanations - Martinaro

Innovation Process characteristics	**Explanation**
Braking industry traditions	Willingness to change traditional approaches
Communication	Increased communication between organizations and its employees including clients and subcontractors
Co-operations	Increased co-operation between organizations from company level to projectsand from projects to other projects. Increased cooperation in top and middle management and with stakeholders
Leadership skills	As general, identifying innovators, and strengthen innovators, positive messengers, skills and competencies, with clients, with design etc. Leading the people.
Knowledge management	Sharing the knowledge throughout organization and project boundaries, thespread of know-how.
Organizational learning	Support of all functions of learning. In project-based industry learning musthappen in a project itself and across inter-organizational boundaries.
Organizational culture	Positive and supporting. Positive towards innovations and changes
Management acceptance	Open mindset, resource allocation, investment in technology, supporting innovations, leadership
Top down – bottom up approaches	Emphasises organizational learning and breaking the barriers that project basedindustry have.
Vertically integrated organizations	Increased ability to spread needed information to organizations, learning aspect,decrease internal barriers.

Human resource management	Need of changes compared to traditional approaches, emphasis leadership kind of features on management, work circulation, creating an open atmosphere, social skills of management and project management, willingness to change, changing career paths.
Stakeholder integration	All stakeholders should take part in developing industry, better cooperation, common ways of doing designs
Standardization	Common and accurate standardization to integrate stakeholders and making models more usable, accurate designs.

Thomas-Seal [19], Oberg [16] focus on risks relating to the implementation of disruptive newtechnologies like AM. The authors focused on risks that are related to the production of the components i.e. the operational risks. Harmse (b) [40] contemplates that one of the most important business risks is the adaptation of AM by the leadership of the organization. AM is not only a disruptive innovation but is also a disruptive strategic intervention impacting a multitude of processes and structures inside and outside the organization. Leadership is also identified in table III as an important component for the adoption of an innovation.

Schniederjans [41] indicate in their study on the adoption of AM that there is limited focus onthe impact of the required change in leadership of the organization as a risk for the adoptionof AM in spare part provisioning and successful functioning in the eco-system. In Christensen

[15] the author reasons why great companies fail. The conclusion is that they don't fail because there are changes in the market that they don't understand, but because the leadership in the companies did not understand the specific requirements of disruptive technologies. This denial of the business impact of disruptive technologies where AM is impliedas the most disruptive, is one of the most significant risks of any company.

Some of the other business risks that will be impacted when adopting AM is a required changein the culture and the structure of the organization when adopting AM for spare part provisioning Matinaro [39] Harmse (b) [40].Due to the disruptive nature of AM, it will require significantly different skills than what has been prevalent in most traditional organizations Christensen [15].

Oettmeier [36] indicates in their study on AM technology adoption that it is important to focusnot only on the intra- but also on the inter-organizational factors. Gartner [34], Oettmeier

[36] and Matinaro [39] emphasises that there are external factors outside of the organizationthat plays an important role in the successful adoption of an innovative new technology in thiscase AM that requires careful attention. These external factors and the systemic interaction of these factors as risks to the organization must be well defined and understood.

Oberg [16] contemplates that companies don't have a clear understanding of how to managethe risks involved in venturing into AM. One of the key risks that traditional organizations is faced with, is the risk of changing from linear processes to non-linear, network based processes with constantly changing competitors Matinaro [39].

In a study by Oettmeier [36], they concluded that the adoption of a new technology, in this case AM, will be emphasized by three groups of variables or risks depicted in table IV.

Table IV : Variables for adoption of innovative new technology – Oettmeier [36]

	Adoption Variable
1	Technology related factors – relative advantage and ease of use – complexity
2	Firm related factors – how adaptable is the company to embrace change
3	Market structure related factors (Eco system) – external pressure and perceived outside support

To reduce the risk of slow adoption of AM in spare part provisioning, the variables in Table 4 needs to be well understood and managed.

Organizations are still trapped in a mindset where risks can be avoided by removing the complicated activities from the processes and therefore create a stable, manageable and linear environment where they can control the behaviour Colchester [33]. The first innovationcharacteristic in Table III and the second variable in Table IV is a requirement to depart with old habits. Figure VI is a summary of the traditional risk management process. White [42]

Figure VI : The process of risk management – White [42]

White [42] summarized in a study on risk management models that most of the current modelsare based on a reductionist approach. This way of managing risks is to identify the risks, breaking it down into its smallest components and then use experts to identify the criticalityof the components. The risk factors are then multiplied, and a hierarchy of risks is establishedthat is seen as the total risk exposure. This linear approach fails to recognise the interrelationship of the components of the whole system and that the identified risks can be affected by components surrounding the identified risk De Langhe [43], Jackson [44] as part of the global eco-system.

Table V is a summary of the key differences between the linear approach and the holistic approach of risk management derived from White [42].

Table V : Difference between Reductionist and Systemic approach to risk management –

White [42]

	Reductionist Thinking - Linear	**Holistic Thinking – Systemic**
Method	Systemic	Systemic
Issue tackled by	Reducing problem into smaller and smaller parts	Investigating the problem's environment
Approach characterized by	A downward movement	An upward movement
Simplifies by	Breaking down problems into simplest parts	Taking multiple partial views

When adopting AM, the organization will have to transition from the traditional reductionist thinking and business management to a holistic and systemic culture. In the next section an understanding of Systems Thinking will be investigated as a possible solution to assist with theadoption of AM and the required change in thinking from reductionist, linear thinking to holistic, systemic thinking.

4 THE ROLE OF SYSTEMS THINKING TO IMPROVE AM ADOPTION

In section 3, three reasons that can contribute to the slow adoption of AM in spare part provision have been identified. In section 4 the role of Systems Thinking will be discussed asa possible solution of how to manage these risks and to create a culture that will allow organizations to improve the adoption of AM for spare part provisioning as indicated in FigureVII.

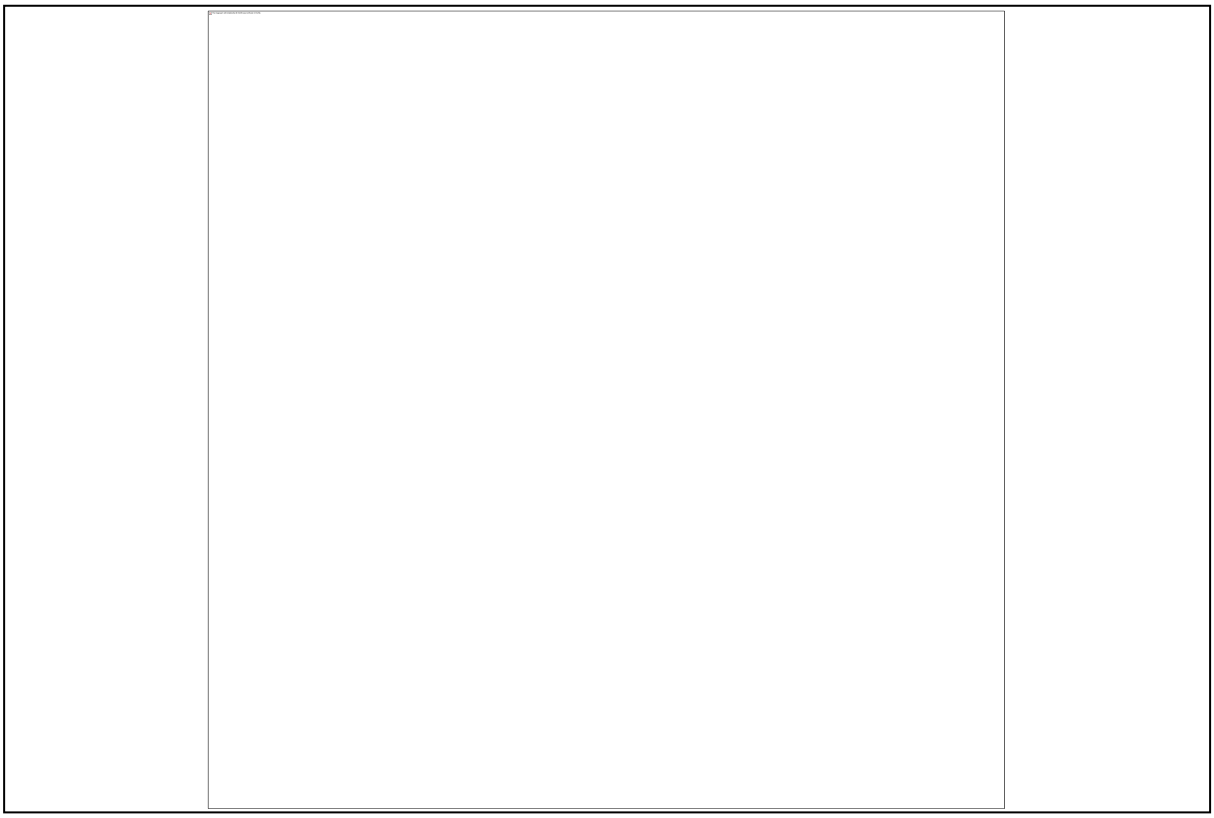

Figure VII : The role of Systems Thinking in adoption of AM - Author

Behl [45] defines Systems Thinking as the ability to think holistic about a system, rather thanonly considering the parts individually. Senge [46] defines Systems Thinking as a discipline for seeing wholes and as a framework for seeing interrelationships rather than things, for seeing patterns of change rather for seeing snapshots. Systems thinking can be defined according to Arnold [47] as:

> *"a set of synergistic analytical skills used to improve the capability of identifying and understanding systems, predicting their behaviours, and devising modifications to them in order to produce desired effects. These skills work together as a system".*

A sub section of Systems Theory is Complexity Theory. Sammut-Bonnici [37] indicates that Complexity Theory provides an understanding of how systems, grow, adapt and evolve. Complexity Theory explains how the relationship between the members give rise to collective behaviour and how to understand and utilize complexity for adopting disruptive innovation Colchester [33].

The principles of Systems Thinking and Complexity Theory enables the user to create an understanding of the systemic nature of the system and how to manage the perceived complexities. Behl [45] specify that companies are faced with increased complexity due to the nature of the integrated networked business environment and dependencies.

Critical to systems theory is firstly the recognition that because of dependencies, the properties of components cannot behave independently but must obey certain rules and secondly, it is their relationship that provides for emergence and can create complexity. In order to successfully managing this transition and understanding how to embrace complexity, it is imperative that there is a comprehensive understanding of Systems Thinking and Complexity Theory and the inter-relationship of all the components in the eco-system Colchester [33].

Figure VII designates the 3 main reasons from section 3 that influences the adoption rate of AM in spare part provisioning. Systems Thinking integrates the 3 components through the creation of a holistic paradigm and understanding of how these elements interact.

Provisioning systems requires an evolution from Supply Chain to an Agile Demand Network as can be seen in Figure V. This evolution will allow practitioners to focus on the dynamic interaction and the agility required for success in the global networks or eco-system. This evolution will transcend the Supply Chain from a linear system to a non-linear system where it is important to understand the interrelationship and cross functional effect of the differentcomponents of the network. Systems Thinking will assist with this to create an understandingof the total system in a non-linear complex network.

Complexity can be daunting especially if a myriad of activities requires different understanding away from the stable status quo. AM is a system that moves spare part provisioning from a complicated, linear environment to a complex, non-linear environment. Understanding complexity, allows companies that adopt AM not only to resolve the immediaterequirement but to use complexity to improve the efficiency of the total system. Anunderstanding of Systems Thinking and Complexity Theory will assist in understanding and managing the complexity in the global network or eco-system. Complexity creates new risks and alter activities that were not seen as risks to become risks due to the new requirements in the global eco-system.

Risks are identified and broken down into small manageable components. This is a reductionistapproach the same as traditional manufacturing where material is removed untill the final component is created. AM is a process where components are manufactured layer by layer from the bottom up and an integrated view of the risks is required for an optimized solution.An understanding of the principles of Systems Thinking will contribute to understand the risksand to define the interrelationship between the different risks. Figure VII indicates how Systems Thinking influence each of the three elements identified as possible contributors in the adoption process of AM in spare part provisioning.

5 CONCLUSIONS AND FUTURE RESEARCH

The adoption of AM as part of the spare part provisioning system, will not only disrupt the business or the eco-system but also requires fundamental new ways of operating and managingbusiness risks and complexity Harmse (b) [40]. Gharajedaghi [48] indicates that when we understand something, we don't see it any more as chaotic or complex. The role of Systems Thinking is to assist organizations to create the understanding of the true value that AM can deliver by eliminating the fear for complexity and to see risk as an opportunity.

To complete this process, a maturity model can be developed where organizations can plot their current position on the provisioning system evolution against the key business risks. This maturity model can then assist organizations to understand the systemic relationship betweenthe key business risks and what is required to manage these risk for the adoption of AM as partof spare part provisioning.

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ANNEXURE D: COMPLETE QUESTIONNAIRE

Business Risk Provisioning Maturity Model (BRPM²)

Thank you for your willingness to participate in this survey

The survey forms part of the research dissertation: Developing of a Maturity Model to enhance the adoption of Additive Manufacturing in spare part provisioning in South Africa. (Ethics reference number: NWU-).

The purpose of the questionnaire is to determine the validity of the above mentioned research as well as the BRPM² model.

Reason for the research and development of the BRPM² model:

Additive Manufacturing (AM) or 3D printing is indicated as one of the most disruptive technologies of Industry 4.0. A technology is disruptive when it does not only replace a technology, in this case a new method of manufacturing, but also change the way in which a business operate and relate to the external environment. Therefore, AM can be seen as not only a disruptive technology but a disruptive strategic intervention.

During the initial investigation regarding the adoption of AM in South Africa as part ofthe spare part provisioning, it became clear that there is a slow adoption for AM in spare part provisioning. The main reasons for this slow adoption are:

* Linear provisioning processes vs new dynamic and systemic provisioning processes required for participation in Industry 4.0.
* Lack of a systemic understanding of the change involved in the key business risks when adopting AM.

It was therefore decided to develop a maturity model with the following outputs:Output

from BRPM² model:

* Determine the current organizational maturity on the provisioning evolution
* Determine the key business risk framework, and
* To create a road map for the effective adoption of AM related to the key business risks

Please note the following:

You may ask the researcher any questions about any part of the study that you do not fully understand. It is very important that you are satisfied that you clearly understand what this research is about and your involvement in the research. Your participation is entirely voluntary.

By continuing with this survey, you agree to take part in the research study titled: Developing of a Maturity Model to enhance the adoption of Additive Manufacturing in

spare part provisioning in South Africa. You declare that:

* You have read the information above
* You clearly understand the research
* You have asked questions to the researcher and all your questions have been answered
* You understand that taking part in this study is voluntary
* You may choose to leave the study at any time

Biographical Information

Please provide the following details, which is for record-keeping purposes only. Please note that your biographical data will be kept confidential and will not be shared

1. Name and Surname

____

2. Email address

____

3. How many years of experience do you have in the field of Additive Manufacturing? (Please select one) Mark only one square.

Check all that apply.

- [ ] 0-1 year
- [ ] 1-2 years
- [ ] 2-3 years
- [ ] 3-4 years

☐ 4-5 years

☐ 3 years or more

This section relates to theResearch Problem addressed by the study

The research problem is stated as:

The Adoption of Additive Manufacturing (AM) as part of the spare part provisioning system remains slow in South Africa

4. The research problem:

Mark only one circle per row:

Mark only one oval per row.

	Strongly Disagree	*Disagree*	*I don't know*	*Agree*	*Strongly Disagree*
The adoption of AM as part of the spare part provisioning system in South Africa remains low	◯	◯	◯	◯	◯
The adoption of AM in spare part provisioning is low due to a lack of understandingof the systemic impact on the key business risks when adopting AM	◯	◯	◯	◯	◯
The linear provisioning paradigms slows down the adoptionof AM in spare part provisioning	◯	◯	◯	◯	◯

5. Comments (Optional)

Design requirements of $BRPM^2$ model

Design philosophy	Design for manufacturing /DfM/ Avoid complexity	Design for manufacturability. Complexity is expensive	Design fo r mai ntainab ili ty. Introduce some complexity. Standardization of components across network.	Design for functionality & personifi cati on / DfAM (Design for Additive Manufacturing). Desi gn to optim ize TCOE/ Complexity can be
Quality assurance	Adhere to set standa rds/1nspect quality in	Adhere to set standards/ Inspectquality in	Adhere to set standards /Build qualityin	Ad here to set standards/ Imbedquality in process/Create new

6. Please answer the following questions regarding the design requirements of the model:

Mark only one oval per row.

	Strongly Disagree	Disagree	I don't know	Agree	Strongly Disagree
The model is basic in design	⬭	⬭	⬭	⬭	⬭
There is coherence amongst all the elements in the model	⬭	⬭	⬭	⬭	⬭
The maturity levels relates toprovisioning systems	⬭	⬭	⬭	⬭	⬭
The maturity levels follows an evolutionary path	⬭	⬭	⬭	⬭	⬭
The dimensions off the model indicates the key business risks	⬭	⬭	⬭	⬭	⬭
The elements in the risk/provisioning matrix is clear and easy to understand	⬭	⬭	⬭	⬭	⬭

7. Comments

Usability of the model

This section relates to the usability of the model

BRPM² Strategic Map

7. Please answer the following questions regarding the usability of the model:

Mark only one circle per row

Mark only one oval per row.

	Strongly Disagree	*Disagree*	*I don't know*	*Agree*	*Strongly Disagree*
The model can be used by anyone who wants to adopt AM as part of spare part provisioning.					
The model assist in creating an as is status relating to the key business risks..					
The model assist in creating a basic road map towards provisioningmaturity.					

9. Comments

Effectiveness of the model

This section evaluates the effectiveness of the model

8. Please answer the following questions regarding the effectiveness of the model:

Mark only one circle per row

Mark only one oval per row.

	Strongly Disagree	Disagree	I don't know	Agree	Strongly Disagree
The model will assist in the effective adoption off AM as part of spare part provisioning.	⬭	⬭	⬭	⬭	⬭

9. Comments

10. Please answer the following questions regarding the validity of the business risks identified in the model:

Mark only one circle per row

Mark only one oval per row.

	Strongly Disagree	*Disagree*	*I don't know*	*Agree*	*Strongly Disagree*
Validation: Evolutionary role of Business risks when adopting AM for spare part provisioning.	⬭	⬭	⬭	⬭	⬭

This section evaluate the validity of the business risks identified in the model. Please indicate if an understanding of the evolutionary role of the key business risks identified in themodel will assist in an improved adoption of AM.

11. Comments

14. Please answer the following questions regarding the validity of the provisioning system evolution identified in the model:

Mark only one circle per row

Mark only one oval per row.

	Strongly Disagree	*Disagree*	*I don't know*	*Agree*	*Strongly Disagree*
Validation: Provisioning System Evolution.	⬭	⬭	⬭	⬭	⬭

This section will evaluate the evolution of the provisioning system

15. Comments

Validation: Originality of the BRPM² model

16. Evolution of the provisioning system is required to ensure alignmentwith the business requirements for successful participation in the new eco/network based economy.

Mark only one circle per row

Mark only one oval per row.

	Strongly Disagree	Disagree	I don't know	Agree	Strongly Disagree
There is a clear revolution from supply to demand.	⬭	⬭	⬭	⬭	⬭
There is a clear evolution from linear chain to a dynamic systemic network.	⬭	⬭	⬭	⬭	⬭
Agility is a key requirement for success in the dynamic economy.	⬭	⬭	⬭	⬭	⬭

Validation: Systemic relationship between the dimensions (key businessrisks)

17. Systemic relationship:

Mark only one circle per row

Mark only one oval per row.

	Strongly Disagree	Disagree	I don't know	Agree	Strongly Disagree
An improved understandingof the systemic relationship between the model dimensions (risks) can improve the adoption of Additive Manufacturing in spare part provisioning	⬭	⬭	⬭	⬭	⬭

18. Originality of the model

Mark only one circle per row

Mark only one oval per row.

	Strongly Disagree	*Disagree*	*I don't know*	*Agree*	*Strongly Disagree*
To the best of your knowledge, would you consider the construction of the BRPM² model as an original design (as opposed to just a duplication of other previous work?)) If you disagree, please elaborate in the comments bellow	◯	◯	◯	◯	◯
The BRPM² model could assist in increasing the adoptionoff AM in spare part provisioning in South Africa?	◯	◯	◯	◯	◯

19. Closure

Once again, thank you for taking time to complete this questionnaire, your inputis greatly valued.

20. Would you be available for follow up questions relating to this questionnaire?

Check all that apply.

- [ ] No
- [ ] Yes via e-mail
- [ ] Yes via telephone (please provide your contact number in the comment section below)

21. Would you like to receive a copy of the final dissertation (via email)?

Mark only one oval.

( ) Yes

( ) No

22 Any final comments relating to the $BRPM^2$ model

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ANNEXURE E: PARTICIPANTS FEEDBACK - QUALITATIVE

Section 1–5 is only biographical data that is captured in chapter 10 This

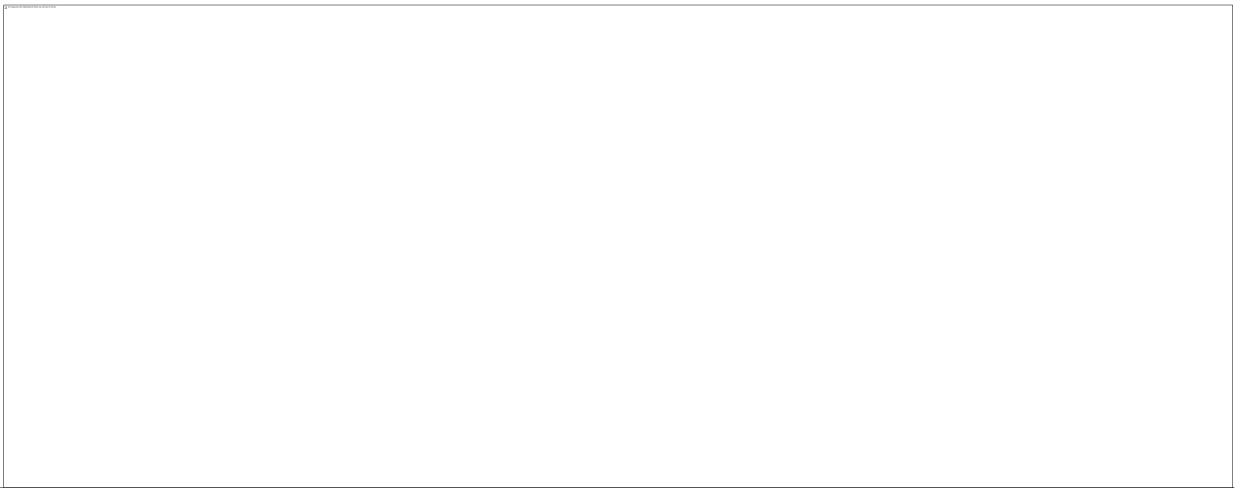
section relates to the research problem addressed by the study

01-01-02	Most South African manufacturers are under severe financial strain currently and arefocused on staying afloat in the short term.
01-01-07	The technology is sometimes overwhelming and new and the market does not trust thetechnology yet. Sometimes the cost of AM is also a draw back.
04-03	In South Africa at the current moment there are bureaucratic supplier qualification processes that excludes many suppliers. Even when the supplier qualifies, he still gets disqualified due to preferential treatment of other suppliers. A business needs long term supply agreements to survive and thrive. At the current moment it is too risky for new AM suppliers to enter the market as there is no long term vision and support. The capital requirements for AM is high and investment can only be done on solid supply agreements. Linear provisioning paradigms is the excuse that gets used when there is no real commitment to supplier development

01-01-01-01	Slow adoption is also attributed to the following: 1. Awareness (This is more geared toward the capabilities of utilising the AM technology to produce functional parts. Currently, the technology and the parts created using it is still considered "Prototyping or Rapid Prototyping" mainly due to its initial introduction to the industry and a tool specific to prototyping. This is slowing changing, but only those that are involved know about it) 2. Design for Additive Manufacturing (DfAM) rules and techniques (This falls under skills and knowledge). Traditional design for manufacturing and assembly methods (CNC, Injection moulding, Cutting, Grinding, and so forth) can not be applied directly to AM parts. All parts that are produced using AM must be designed specific to that printing technology and not designed to be a replica of the part it intends to replace. Understanding the design process and matching it to the AM process to produce functional 3D printed parts adds to the skills and knowledge challenge, which results in slow adoption. 3. Spare part requirements (If mass production is required, AM may not be a beneficial option; however, this would largely depend on the part itself and the available AM process). Spare parts, in most instances would be a part that was initially produced using traditional manufacturing. When using AM (and to use it to its full benefit) the part would need to follow new design changes to allow it to be printed and be functional (fit for purpose).

01-01-01-02	The slow adoption of AM in the industry is also due to the cost associated with the fabrication of parts. It becomes important to categorise which spare parts will benefit from AM e.g low stock, long lead time components
01-01-05-02	AM currently cannot compete with productivity effectiveness and costs of mass production
01-01-06-02	AM is widely adopted in SOUTH AFRICA. One big issue is the OEM monopoly overspares

This section is about the design requirements of the BRPM² model



01-01-07	The model shows a natural flow is possible with many added benefits.
03-01	I would just like to qualify my answers to the above: The model does indeed seem basic in its design when taken at face value. However, I have no previous experience with such maturity models and hence very little context from which to make this type of judgement.
04-02	Understandable model with key element changes as the adoption of AM progresses
04-03	Too complex. Yes a big organisation needs to look at all these aspects, but I believe you need to define the one single factor that is stopping the adoption of AM. AM has been proven. Technically there are no obstacles. So what is stopping its adoption?
04-06	The model is well portraying the picture of current status of AM not only in SOUTHAFRICA

01-01-01-01	My comment on the model, looking at the dimensions and elements separately (from left to right): 1. Yes, for each category, it shows a gradual development and change from a closed-loop system to an open one.
01-01-01-02	The model is a bit complicated and the structure of the entire model is not coherent.The first part addresses procurement and the second part the different elements that
	have an impact in AM. The procurement and market section is not descriptive and doesn’t fully describe the drive toward AM.

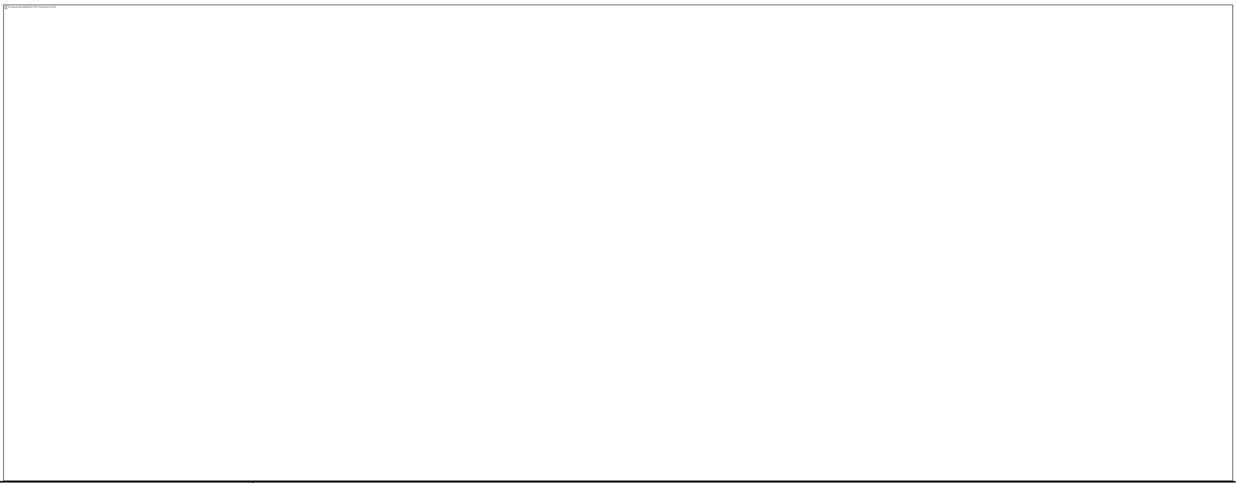
04-02	With the potential of AM clusters being setup, a group of companies may jump fromvery immature to a mature adopter of AM in a short time span.
04-03	Maturity levels stagnates a business. Its ability to adopt to change, specifically in identifying and empowering good new suppliers get hampered by bureaucracy and process. Current suppliers will do ANYTHING to maintain their supplier status and exclude new suppliers
01-01-01-01	Some factors may need to be looked into and how they may interact with your dimensions: 1. Material handling corresponding to the AM process. (From raw material to AM ready material - This is important in achieving reliable, functional spare parts) 2. Technology type for AM. 3. Part production and delivery processes (logics - either in-house manufacturing or external service providers).

	4. Identification process of parts (spare parts) that could actually be manufactured using 3D printing. Not all parts in all industries could benefit from AM, which is why the identification process is important. Just replicating parts that were made from traditional manufacturing processes to AM without utilising the benefits of the technology has no benefit. 5. Identification process of printed spare parts (Once mass production or production scale-up is achieved)
01-01-05-02	The AM technology especially in South Africa is still very much in the pre-development phases and focused on niche materials and applications

01-01-02	The adoption of AM and benefits thereof by direct competitors can be viewed as a potential risk if an organisation is slow to adapt.
02-01	How does the model support a business to address changes in market perception / industry requirements, or industry driven technology requirements. I miss detail with respect to how the business will respond to changes in the market, as a business risk to be managed.
04-03	This model looks at the business from a very traditional paradigm. 4IR and Disruptive technologies work in a new paradigm. This model is sufficient for a baseline analysis, but a new model is required that takes into account disruptive change.

01-01-01-01	Some points on the dimensions: 1. IT - Be mindful that IT is a relatively broad category. When you mention Ecosystem, I am assuming this would include all levels of technology and software that would fall under spare part provisioning using AM for areas such as: a. Production (actually producing them 3D printed parts), b. Monitoring (for 3D printed parts, AM machines, People/customer interaction management, material handling, waste disposal), Safety A dimension of repeatability. Not sure if your model is going to be the benchmark to ensure that this process will ensure consistent repeatability. Some factors that affect the repeatability of 3D printed functional spare parts include: c. Certification and tracking of raw materials and the final AM material. d. Specifications and standards (these are for all levels from manufacturing, to quality, to end-of-life). e. AM technology and printer capabilities. f. Customer and manufacturer interactions. g. Quality control.
01-01-06-02	Risk areas rather than risks

04-03	You need to create a new model that will take the business into the future
01-01-01-02	The elements are clear and easy to understand. However, the maturity levels isdifficult to understand
01-01-05-01	Well defined and simplistic to apply



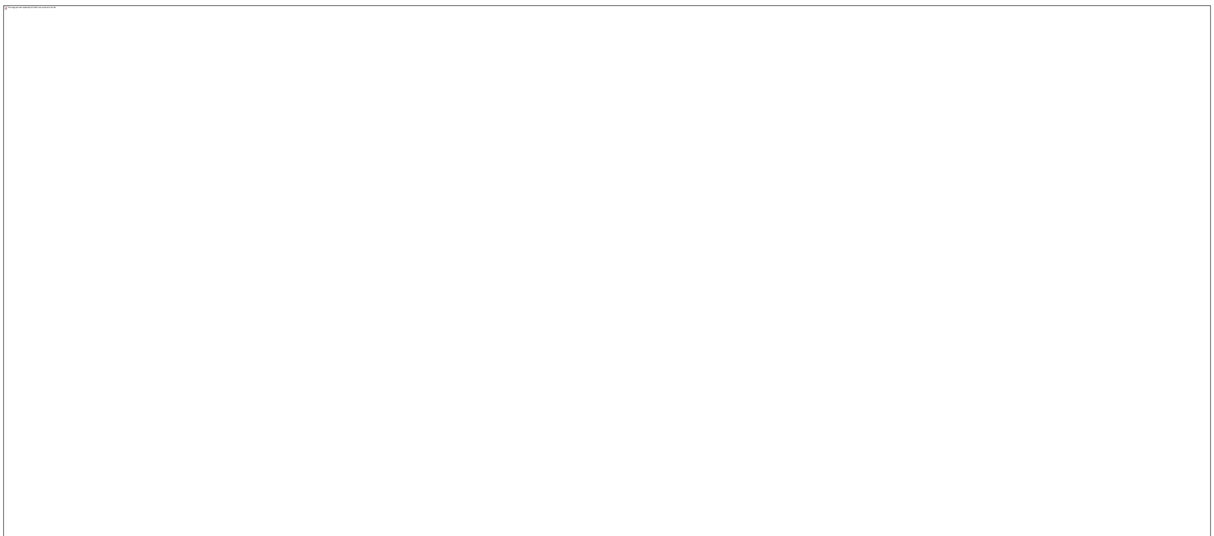
01-01-07	It certainly shows a clear "pathway" to maturity.
03-01	The second question in 16 above is not so clear.
04-03	Disruption aims to upset traditional models. The model shows the end goal (Demand network agility) and will show the steps that need to be achieved at each level. It needs another dimension of the how. Change management is a management science on its own, but it will define the pathway. This is also a bottom up approach. It needs to be top down if AM is to succeed. Especially when an organisation has a top heavy executive level.
01-01-01-01	MyOpinion:

	If your dimensions for Leadership, Structure, Safety, and Storage remains within the demand chain, full adoption may not be completely an open-system if this remains. safety - There are multiple levels of complexities which speaks to safety at various levels within the AM process. This should be at the Demand Network Agility or is your reason for having it progress only to the Demand Chain (structured linear process) because of the rules and regulations. Structure - This needs to be at the very least, at the Demand Network level due to being team-based. Again, unless this specifically focuses on having linear-processes. Cross-functional silos still result in functional silos and when people and organisations operate in silos, advancements don't always happen. This may result in not fully adopting AM since it is a very transformative manufacturing technology. Your seniors will make decisions based on what they feel is right and not what is best for the business of spare part provisioning using AM methods. This would then revert back to the beginning of your maturity level. Leadership - I honestly am not sure about this as this seems subjective. If you are focusing on leadership such as the founder, CEO, South African Managers then it would be fine. But you make the point in your elements that decisions are based on internal and external input at the Demand Network which is a bit confusing since your map for the leadership does not go to that level. At the end of the day, if your leadership are not communicating openly with internal and external networks, full understanding and adoption may become harder to achieve. Confidence is built with leaders that have the knowledge, the experience and understands the challenges affecting the business from an internal and external perspective through all criticism, not just some. This may also open up a gap in the silo mentality. Storage - One of the main benefits of the AM process is the ability to reduce warehouse and storage facilities. This should include both conventional methods and e-warehousing elements. It should not be at the Demand Network level. If it remains, then it is no different to traditional supply and demand warehouses.
01-10-01-02	The model is complex and will only be understood by subject matter expertsespecially the maturity level section
01-01-06-02	

The image part with relationship ID [illegible] was not found in the file.

01-01-07	The model is a definite "head start" towards AM and how it could improve processes.
04-03	Question still remains. Why would an organisation embrace a technology that is still seen as novel? Traditional supply chain still works. Why take the risk? In the near future environmental pressure will bring this organisation to its knees. AM isnt the solution for that. What are the agenda items that the executives are dealing with? Share price, environmental risk, business sustainability. If you can define AM's roll within that context, you may affect change. Otherwise it will always be a low priority. You can use our case study here. We have proven and qualified that the technology works, but it has taken a back seat to everything else as the business struggled with share price collapse
01-01-01-02	It should be noted that in terms of quality, standards are still being established. So this is also a risk in the adoption of AM. Not all risks have been outlined
01-01-06-02	Spares is a part of AM - Spares manufacturing will get you to adopt AM - its the other way round

Validation: maturity levels



04-03	Agility comes with risk. You need to explore and quantify the risk(s) and try to create mitigatingprocesses.

Validation: systemic relationship between the dimensions (key business risks)

04-03	Yes. This is the correct approach. Requires in depth analysis. (Delphi model)

Validation: originality of the BRPM^2 model

01-01-07	Most definitely an original design that I have never come across before.
03-01	I am not aware of a similar model, but must also just acknowledge that I have not explicitlysearched for a similar model before.
04-03	AM needs to operate outside the normal processes (for now). You cannot apply the same paradigm. It needs its own place in the organisation- It needs its own budget and independence and it needs license to disrupt. You CAN NOT change the institutional bureaucracy that is based around suppliers. AM will disrupt the supply chain and the supply chain will resist. Your model is correct in showing what is required but if you want to do something ground breaking you will have to address the elephant in the room. Suppliers dominance, supplier agreements, supplier influence.
01-01-05-02	The model do not need to be original ... it needs to be adapted to industry standards and market pull
01-01-05-03	First time I have seen it in a combined format. Not sure the content is original. But veryclear depiction thereof

Validation: solution of the BRPM^2 model

01-01-07	As AM is becoming more known in the local markets people will need more guidance towards adopting the principles. This model could become a great tool to assist with the processtowards adoption.
04-03	The model is accurate and correct, but cannot be implemented without a proper understand of the financial implications. Which suppliers will benefit and which will fall on the waysideand what will be the implications of that
01-01-01-02	AM is not applicable to all spare parts manufacturing. The model does not assist in understanding which parts will benefit from AM.
01-01-05-05	The model gives a clear path but in itself does not address lack of industry and trusting of thetechnology involved in AM
01-01-06-02	Could do Not convinced

Final comments:

01-01-07	This is indeed a fine piece of work Henk. Indeed ground breaking work from my point of view. Definitely a step in the right direction to promote AM.
04-03	Goeie werk. Ek het maar my ervaring as verwysingsraamwerk. Jy het miskien beter insigte. Sterkte met die volgende stappe!
04-06	Excellent understanding of current status to lay the foundations for a new paradigm
01-01-01-01	All the best
01-01-01-02	The model is a step in adoption of AM in the manufacturing industry. However the author needs to establish a coherency in the representation of ideas. E.g. the linkage between procurement and product development. Better elaboration of IP rights regarding AM needs to be established. This model also needs to be multidisciplinary in that it should be understood by everyone in an organisation. The supply and demand section is a bit complicated and only subject matter experts in this field will understand
01-01-05-01	Mad about the model. Well done.
01-01-05-02	The model needs to be practical and implementable. The focus should be on niche spare parts and not spare parts in general (Mass production). Targeted spare parts is the catalyst for success for implementation and can be part of the model

01-01-05-03	Thank you for the work and including me. Good luck with completion! May it bring much growth and improvement!
01-01-06-02	Need to link Additive Manufacturing, AM and spares together. AM is the driver of the above, cost management is the driver of Additive Man & spares supply chain reviews.

ANNEXURE F: PARTICIPANTS FEEDBACK - QUANTITATIVE

Industry: Defence, Aerospace, Engineering, Machine Vendor, Manufacturing Bureau

	Questions			P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11		
Research	6. Research Problem	a	The adoption of AM as part of spare part provisioning system remains slow in SouthAfrica	5	5	5	4	4	5	4	4	5	4	4	4.4	4.1
		b	The adoption of Am as part of spare part provisioning is low due to a lack of understanding of the systemic impact on the key business risks when adopting AM	4	4	2	4	4	5	2	5	5	5	4	4.0	
		c	The linear provisioning paradigms slows down the adoption of AM in spare part provisioning	4	4	4	3	4	5	3	5	4	4	5	3.8	
Design	8. The Model	a	The model is basic in design	3	2	2	3	4	5	3	3	2	4	2	3.2	3.6
		b	There is coherence (systematic or logical connection) amongst all the elements in themodel	4	4	5	4	4	4	4	5	5	4	4	4.0	
	10. Maturity levels	a	The maturity levels relates to provisioning systems	4	4	4	3	4	4	4	4	4	4	4	3.9	3.9
		b	The maturity levels follows an evolutionary path	4	4	4	4	4	4	4	4	1	4	5	4.0	
	12. Dimensions	a	The dimensions of the model indicates the key business risks	4	4	5	4	4	5	4	4	4	5	4	4.1	4.1
	14. Elements	a	The elements in the risk/provisioning matrix is clear and easy to understand	5	4	4	4	4	5	4	5	4	5	4	4.1	4.1
	16. Usability	a	The model can be used by people on any level in the organisation who wants to adopt AM as part of spare part provisioning	4	2	2	4	4	4	2	4	5	3	3	3.2	

Model		b	The model assist in creating an as-is status relating to the key business risks	4	4	2	4	4	4	4	4	4	4	3	3.8	3.7
		c	The model assist in creating a basic road map towards provisioning maturity	4	4	4	4	4	5	4	4	4	5	4	4.0	
	18. Key business risks	a	An understanding of the evolutionary role of the key business risks identified in the model will assist in an improved adoption ofAM	3	4	4	4	4	5	2	5	4	4	5	3.8	3.8
	20. Evolution of provisioning system	a	There is a clear evolution from supply to demand	4	4	4	4	4	5	4	4	5	4	5	4.1	4.2
		b	There is a clear evolution from the linear (chain) philosophy to a systematic network philosophy	5	4	4	4	4	5	4	5	5	4	4	4.0	
		c	Agility is a key requirement for success in the dynamic eco-network	5	4	5	4	4	5	4	5	5	5	5	4.5	
	22. Systemic integration of business elements	a	An improved understanding of the systemic relationship between the model dimensions (risks) can improve the adoption of Additive Manufacturing in spare part provisioning	4	4	5	4	5	5	2	4	4	4	4	4.2	4.2
Model	24. Originalty	a	To the best of your knowledge, would you consider the construction of the BRPM² model as an original design (as opposed to just a duplication of other previous work?)	5	4	3	4	4	5	4	4	5	5	5	3.9	3.9
	26. Solution of model	a	The BRPM2 model could assist in increasing the adoption of AM in spare partprovisioning in South Africa	4	4	4	4	4	5	4	4	5	4	5	4.1	4.1
				4.2	3.8	3.8	3.8	4.1	4.7	3.5	4.3	4.2	4.3	4.2	4.0	4.0
				4.2	3.9	4.0		3.7	4.1		4.3	3.9				

ANNEXURE G: ETHICAL APPROVAL

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

11/13/2020

Based on approval by the North-West University Engineering Research Ethics Committee (NWU-ENG-REC) on 11/13/2020, 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 a maturity model to enhance the adoption of Additive Manufacturing inspare part provisioning in South Africa

Principal Investigator/Study Supervisor/Researcher: Ronette Coetzee Student: Willem Hendrik Harmse (28397207)

Ethics number: **NWU-00106-20-A1**

Institution Study Number Year StatusStatus: S

Application Type: Single Approval date: 9/30/2020 **L**

Approval of the study is provided for a year, after which continuation of the study is dependent onreceipt and review of annual monitoring report and the concomitant issuing of a letter of

General conditions:

While this ethics approval is subject to all declarations, undertakings and agreements incorporated andsigned 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:*
  - *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 nothesitate to contact the NWU-ENG-REC for any further enquiries or requests for assistance.

Yours sincerely,

Dr. Rojanette Coetzee Chair

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