Evaluating Sectoral Innovation System Functional Performance in the additive manufacturing sector: Cemented tungsten carbides case studies

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Declaration

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Abstract

It is well known that innovation and manufacturing have traditionally played a vital role in the economic growth of developing countries. A ceramic widely used in manufacturing is cemented tungsten carbide, also known as hardmetal. Hardmetals are known for their significant ability to withstand extreme conditions and are used to manufacture abrasives, bearings and cutting tools as it is more heat-resistant than diamonds. Although traditional hardmetal manufacturing techniques are successful globally, several additive manufacturing (AM) technologies are being investigated as complementary manufacturing processes due to the design benefits the technologies offer.

For society and the South African hardmetal industry to benefit from AM technology, the research studies on these technologies must be translated into valuable and innovative products, processes and services that are diffused and integrated into industry and the economy. Although the South African government has developed several national strategies relevant to the South African hardmetal industry, the effectiveness of the governmental support of the industry has not yet been explored through the innovation system framework.

This study proposes an analysis framework to study the evolution of innovation systems. The framework, based on the literature on the innovation system framework, the method of event history analysis and the realist evaluation perspective's logic structure, are developed through the design science research (DSR) methodology. Its objective is to guide the obtainment and documentation of the influential events in a system's development and to structure the analysis of the event data according to context, intervention, mechanism, and outcome logic. The framework may therefore aid innovation scholars and system analysts to successfully analyse and compare the evolution of innovation systems and gain practical insights into possible support mechanisms. Moreover, the framework is shown to address and successfully overcome shortcomings of existing frameworks in the literature.

As part of the DSR methodology, this study presents four instantiations of the framework to four novel case studies. These instantiations demonstrate the frameworks' comprehensiveness in gaining case-specific insights. The framework's ability to generalise across case levels is also validated as the insights from four cases could be compared. Additionally, this study presents the derivation of a survey instrument from the framework's functional elements. Finally, this study presents the analysed survey response data from 70% of the South African AM enterprises, along with policy support suggestions, derived from the case insights, to support the enterprises' development.

Conclusions derive from the case studies and survey include that the South African AM enterprises are still relatively young and typically employ less than 50 people. Value-added enterprises also dominate the industry, although several international service bureaus exist. Furthermore, the enterprises struggle to identify laws and regulations that support AM technology, and startup enterprises struggle to build sufficient knowledge networks. Finally, this study suggests six important process mechanisms for translating manufacturing inventions into valuable and innovative products and processes that are diffused and integrated into industry.

Opsomming

Dit is welbekend dat innovasie en vervaardiging tradisioneel 'n belangrike rol speel in die ekonomiese groei van ontwikkelende lande. 'n Keramiek wat dikwels in vervaardigingsprosesse gebruik word, is die harde metaal genaamd gesementeerde wolframkarbied. Harde metale beskik oor die vermoë om uiterste toestande te weerstaan en word gebruik om skuurmiddels, laers en snygereedskap te vervaardig aangesien dit meer hittebestand as diamante is. Alhoewel tradisionele hardemetaalvervaardigingstegnieke wêreldwyd suksesvol aangewend word, word verskeie additiewe vervaardigingstegnologieë (AV) as komplementêre vervaardigingsprosesse ondersoek vanweë die ontwerpsvoordele wat dié tegnologieë bied.

Om te verseker dat die samelewing en die Suid-Afrikaanse hardemetaalbedryf voordeel trek uit AV-tegnologie, moet die navorsingstudies oor hierdie tegnologieë lei tot die skep van waardevolle en innoverende produkte, prosesse en dienste wat geïntegreer word in die industrie en die ekonomie. Alhoewel die Suid-Afrikaanse regering verskeie nasionale strategieë ontwikkel het wat relevant is tot die Suid-Afrikaanse hardemetaalbedryf, is die doeltreffendheid van die regeringsondersteuning van die bedryf nog nie deur die innovasiestelselraamwerk ondersoek nie.

Hierdie studie stel 'n ontledingsraamwerk voor om die evolusie van innovasiestelsels te bestudeer. Die raamwerk, gebaseer op die literatuur oor die innovasiestelselraamwerk, Historiese Gebeurtenis Analise-metode en die realistiese evalueringsperspektief se logikastruktuur, is deur die wetenskaplike ontwerpsnavorsingsmetodologie (WON-metodologie) ontwikkel. Die doel daarvan is om die verkryging en dokumentering van die invloedryke gebeure in 'n stelsel se ontwikkeling te lei en die ontleding van die gebeurtenisdata volgens konteks, intervensie, meganisme en uitkomslogika te struktureer. Die raamwerk kan dus innovasiewetenskaplikes en stelselontleders help om die evolusie van innovasiestelsels suksesvol te ontleed en te vergelyk, en praktiese insigte te verkry oor moontlike ondersteuningsmeganismes. Verder word daar aangetoon dat hierdie raamwerk tekortkominge van bestaande raamwerke in die literatuur aanspreek en suksesvol oorkom.

As deel van die WON-metodologie, bied hierdie studie vier instansiërings van die raamwerk aan vier nuwe gevallestudies. Hierdie instansiërings demonstreer die raamwerk se omvattendheid om geval-spesifieke insigte te verkry. Die raamwerk se vermoë om op grond van gevallestudies te veralgemeen word ook bekragtig aangesien die insigte van vier gevallestudies vergelyk kon word. Daarbenewens bied hierdie studie die afleiding van 'n opname-instrument uit die raamwerk se funksionele elemente aan. Laastens hou hierdie studie die geanaliseerde opname-responsdata van 70% van die Suid-Afrikaanse AV-ondernemings voor, tesame met beleidsondersteuningsvoorstelle, afgelei van die geval-spesifieke insigte, om die ondernemings se ontwikkeling te ondersteun.

Gevolgtrekkings wat uit die gevallestudies en opnames spruit, sluit onder andere in dat die Suid-Afrikaanse AV-ondernemings nog relatief jonk is en tipies minder as 50 werknemers het. Waardetoegevoegde ondernemings oorheers ook die bedryf, hoewel verskeie internasionale diensburo's bestaan. Verder sukkel die ondernemings om wette en regulasies te identifiseer wat AV-tegnologie ondersteun, en jong ondernemings sukkel om voldoende kennisnetwerke te bou. Laastens stel hierdie studie ses belangrike prosesmeganismes voor wat nodig is om te verseker dat vervaardigingsuitvindings aanleiding gee tot waardevolle en innoverende produkte en prosesse wat in die industrie geïntegreer word..

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Psalm 27:14 (TPT) – *Here is what I have learned through it all: Do not give up; do not be impatient; be entwined as one with the Lord. Be brave and courageous, and never lose hope. Yes, keep on waiting - for He will never disappoint you!*

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Glossary

Acronyms and Abbreviations

AM	Additive manufacturing
AMTS	Advanced manufacturing technology strategy
CAD	Computer-aided design
CIMO	Context Intervention Mechanism Outcome
CSIR	Council for Scientific and Industrial Research
CUT	Central University of Technology
DMLS	Direct metal laser sintering
EDM	Electrical discharge machine
EHA	Event history analysis
GVC	Global value chain
IS	Innovation system
SU	Stellenbosch University
TIS	Technology innovation system
VoD	Valley of death

Chapter 1

Introduction

This chapter describes the project's motivation through a research background, a problem statement, and the objectives that must be accomplished to complete the project successfully. The scope, the main research contributions and the proposed research methodology are also discussed.

Chapter 1 objectives:

- Provide background and motivation for the study (§1.1).
- Define the research problem, questions, and objectives (§1.2, 1.3 and 1.4).
- Present the main research contributions (§1.5).
- Define the scope and limitations of the research (§0).
- Present the ethical implications of the study (§1.7).
- Provide an overview of the research design and the document structure (§1.8).

1.1. Background

It is well known that manufacturing has traditionally played a vital role in the economic growth of developing countries. The global manufacturing industry is a significant employer, accounting for around 14.2% of the world's workforce [1]. According to the United Nations' Sustainable Development Goals (SDG) 2021 Report, the global manufacturing industry plummeted in 2020 due to the COVID-19 pandemic, causing significant job losses and declining worker incomes [2]. However, the SDG 2022 Report indicates that global manufacturing has rebounded from the pandemic, particularly higher-technology industries, as they were more resilient in the crises [3]. Furthermore, the report reports that for Goal 9 - Industry, innovation, and infrastructure (Figure 1.1) – to be achieved, industrialisation, improvements in infrastructure, and the promotion of technological innovation by increasing investment in research and development are essential. Policy commitments towards financing for R&D, especially in developing economies and regions such as Sub-Saharan Africa, need to continue and be strengthened [3].

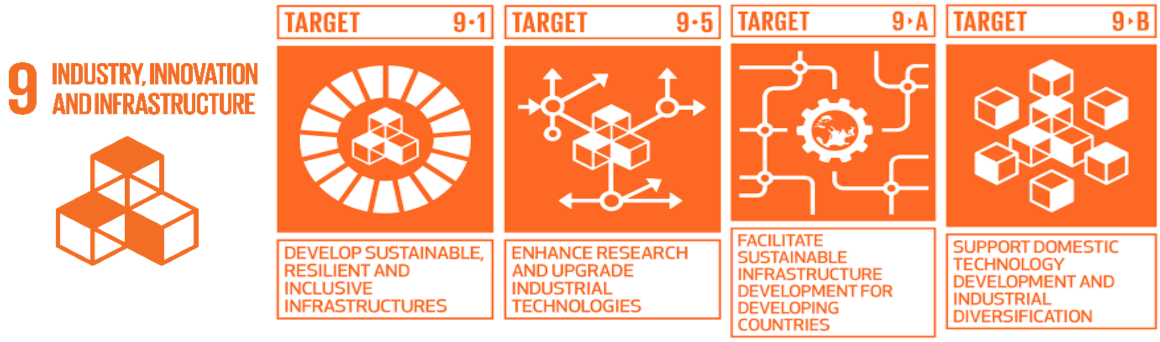


Figure 1.1: Sustainable Development Goal 9

To support the development of innovations and growth of the South African manufacturing industry, the South African Government developed at least three strategies, namely the National Research and Development Strategy [4], the Integrated Manufacturing Strategy [5] and the South African Advanced Manufacturing Technology Strategy [6]. These strategies focus on developing capabilities to master various advanced manufacturing domains, develop human resources for the sector, and facilitate innovation [6]. These strategies all acknowledge the central role of innovation in improving South Africa's competitiveness.

Additionally, the Department of Science and Innovation (DSI) and the National Research Foundation (NRF) also established several manufacturing-focused Centres of Excellence to stimulate collaborative and interdisciplinary research and development in targeted fields that are locally relevant and internationally competitive [7].

The DSI-NRF Centre of Excellence in Strong Materials (CoE-SM) [8] is one of the manufacturing-focused centres. Strong materials retain their distinctive properties under extreme conditions and have established or potential commercial applications [7]. A particular focus of the CoE-SM is cemented tungsten carbides or hardmetals as they are used to manufacture metals and are utilised in various applications. These include the tooling (for metal cutting), mining (for rock drilling), defence, electronics, jewellery, agricultural and automotive industries [9], [10]. Hardmetals are known for their significant durability, wear resistance and ability to withstand extreme conditions [9]–[11]. In addition, components made from hardmetals typically have a 3-20 times longer service life than steels and other alloys [12]. Therefore, in harsh environments where wear resistance is crucial for productivity, hardmetal is the material of choice [13]. To stimulate further use of hardmetal and facilitate technology development in line with SDG 9, the CoE-SM encouraged several research projects – this study included - to study and investigate additive manufacturing (AM) technologies as complementary manufacturing processes to manufacture hardmetal products [14]–[17].

In line with Goal 9, for global manufacturing and the South African manufacturing industry to benefit from materials such as hardmetals and technological innovation such as additive manufacturing, the research studies on these technologies must be translated into valuable and innovative products, processes and services that are diffused and integrated into industry and the economy [18], [19]. However, this transition between research and product commercialisation is known for its roadblocks [18]–[20].

Therefore, this study aims to utilise the innovation system (IS) framework to explore the dynamics involved in the growth of the South African hardmetal industry and the mechanisms that enable the adoption of novel technology, such as additive manufacturing, into the industry. The IS framework is often used to analyse the dynamics of industry development and operationalise industry support measures [21]–[24]. In addition, the IS framework is typically used to identify and map linkages and engagements between actors and institutions and the manner through which knowledge is shared between them to develop, produce and diffuse innovations [25]. It is also a framework through which the complex interactions between elements are acknowledged, and the feedback loops and non-linear behaviour that exist due to various actors' activities in these systems are acknowledged [26], [27]. Therefore, the framework is often used to facilitate policy development processes to stimulate and support innovation [27]–[30].

As the IS is a system, it has components that work together to achieve a common goal [31]–[33]. The activities these structural components perform are also essential as they are required to accomplish the IS's objective of conceptualising, developing and diffusing innovations [33]. Seven IS activities, known as functions, are prevalent in IS literature. They include entrepreneurial activities, knowledge development, knowledge diffusion, the guidance of search, market formation, resource mobilisation and creation of legitimacy [23], [27], [33], [34]. In IS literature, IS functions are said to influence each other over time [23], [24], [33], [35]. The fulfilment of a specific function influences the fulfilment of another's [33], [36]. Innovation system authors have acknowledged that functions could influence each other both positively and adversely, leading to either positive or negative feedback loops [24], [33], [34]. Over time, these feedback loops are said to lead to cumulative causation, also known as motors of innovation [23], [24], [34], [37]. Hekkert et al. [33] considered the interactions and influences the functions have on each other necessary for constructive structural change and systematic innovation. Therefore, studying the IS structures, functions and motors of innovation allows for the identification of blocking mechanisms that hinder the development and diffusion of innovations [23], [32], [38].

1.2. Problem Statement

The IS framework has been utilised for the analysis of several innovations, particularly in the field of sustainable energies [23], [24], [27], [33], [34], [36], [39], [40]. However, although the South African government has developed several strategies relevant to additive manufacturing and the hardmetal sector, the functional performance of the South African hardmetal sector using AM has not yet been explored or analysed through the IS perspective [41]–[43]. Therefore, little is known regarding the level and appropriateness of industry and government support of the various AM policies and strategies that the government has formulated to support the hardmetals industry in South Africa. It is also unclear how the IS of hardmetals using AM effectively develops capacities for local ISs and employment creation. Also, since hardmetal application industries are vast and cross-cutting in many sectors, it is difficult to assess how and through which mechanisms technological and innovation capacities may be improved and developed. Therefore, an evaluation framework and tool can be developed to support the application of the IS framework to the analysis of industries, such as the South African hardmetal industry.

The problem statement of the proposed study thus aims to:

Develop an evaluation framework and tool that support innovation system analysis.

Although this study focuses on the South African hardmetal industry and additive manufacturing, the pursued tool will not be designed exclusively for the industry but to guide and support any innovation system analysis.

1.3. Research Questions

Based on the above-mentioned problem statement, the main research question of the study may be formulated as:

Which elements should be included in a framework and tool, relevant but not limited to the South African hardmetal and additive manufacturing industries, to support innovation system analysis?

The research question incorporates two domains, namely innovation systems, and evaluation and analysis tools methods. Therefore, to address the main research question, three sub-questions were developed. The sub-questions are as follows:

1. How can research paradigms and their related analysis approaches be leveraged to guide the analysis of innovation systems?
2. How can functional performance metrics best be defined to evaluate systems' innovative performance?
3. How can innovation evaluation methods best be leveraged to analyse change and development that occurs in innovation systems?

To support these sub-questions, three questions were developed for each case studied.

1. What were the underlying structural drivers and barriers that explained the emergence of the various motors of innovation?
2. What were the motors of innovation that led to development within the case?
3. How did the various motors of innovation, in turn, influence the technology innovation system of each case?

1.4. Research Objectives

The proposed study aims to *develop an evaluation framework and tool that support innovation system analysis.* Although this study focuses on the South African hardmetal industry and additive manufacturing, the pursued tool will not be designed exclusively for the industry, but to guide and support any innovation system analysis.

To achieve this aim, the following objectives are pursued in this dissertation:

I. To *conduct* a comprehensive review of the literature related to this study. In particular
   a. To review the field of hardmetals, its industrial applications, the traditional manufacturing technologies used to manufacture hardmetals, and explore the South African hardmetals landscape,
   b. To review the field of additive manufacturing and its characteristics as a transformative technology and explore the South African additive manufacturing landscape,
   c. To describe the most prevalent methods for studying industry and technology development dynamics and phases,
   d. To explore the roadblocks within the 'Valley of Death',
   e. To review the field of innovation systems and their structural and functional components,
   f. To explore the innovation mechanisms documented in innovation system literature, particularly the motors of innovation mechanisms,
   g. To report on the prevalent research designs and methods to study innovation systems and motors of innovation and explore the method of Event History Analysis in more detail,
   h. To document standard guidelines for applying the Event History Analysis method and the design of a framework from the motors of innovation and ensure the verification and validity of the quality of this method.

II. To *design*, based on the literature review of Objective I, an event history analysis framework which may be used to analyse the growth and development of technology innovation systems. This framework should facilitate:
   a. The obtainment of relevant TIS event data over a period of at least a year,
   b. An analysis of the context in which the TIS developed,
   c. The transformation of qualitative TIS data into quantitative data and graphs,
   d. An analysis of the TIS structures, functions and relevant actors performing the functions,
   e. The development and analysis of motors of innovation that develop in TISs over time, and
   f. The analysis of the TIS deliverables.

III. To *verify* and *validate* the framework of Objective II through semi-structured interviews with industry experts.

IV. To *implement* instantiations of the validated framework of Objective II in four hardmetal and additive manufacturing applicable case studies to demonstrate its practical applications.

   a. Study an *industry-level* case on the introduction and development of new technology, additive manufacturing, in South Africa. Analyse the case through to the innovation system framework,
   b. Study a *project-level* case of an academic research and development 'additive manufacturing for hardmetals' project and analyse the dynamics of the case through to the innovation system framework,

c. Study a *company-level (SME)* case of research and development 'additive manufacturing for hardmetals' project and analyse the dynamics of the cases through to the innovation system framework, and
d. Study a *company-level (Large enterprise)* case of research and development 'additive manufacturing for hardmetals' project and analyse the dynamics of the cases through to the innovation system framework.

V. To *conduct* further semi-structured interviews with the related government-, industry- and research-level actors to verify and validate the case studies, the analysis, and the motors of innovation.

VI. To *synthesise* the case study findings of Objective IV into a high-quality decision support framework that guides manufacturing TIS's to bridge the Valley of Death.

VII. To *survey* the South African additive manufacturing enterprises to discover the South African innovation dynamics, policies, and roadblocks present within the Valley of Death.

1.5. Novel scientific contribution

The main contributions of this study are seven-fold. This section contains a summary of each of these contributions.

Contribution I. *The proposal of a novel generic innovation system framework paradigm*

This study proposes an innovation system framework paradigm from which innovation system analysis may be developed. This study identifies the innovation system framework paradigm from the generic analysis steps typically followed in the innovation system literature. The study contributes to innovation system literature as it may provide a good starting point for developing future frameworks to facilitate the analysis of innovation systems. Furthermore, it may provide a structure for comparing similar analysis frameworks.

Contribution II. *The novel relation of the generic innovation system framework paradigm to the components of the CIMO-logic structure*

The relation of the generic innovation system framework paradigm to the components of the Context-Intervention-Mechanism-Outcome logic (CIMO-logic) structure presents innovation scholars with a novel framework to structure innovation system analysis and document system dynamics. Through utilising the CIMO structure, the innovation system analysts are guided to derive functional insight into the mechanisms that develop in particular contexts and how these contexts influence the outcomes delivered. Consequently, the proposed combination presents a process methodology through which policymakers may be informed on context-specific, targeted interventions to foster innovation and technology development.

Contribution III. *The development of a novel CIMO-based EHA framework to analyse the evolution of innovation systems.*

The CIMO-based EHA framework proposed addresses the shortcomings of existing frameworks identified in the literature. Based on the realist evaluation perspective, the framework comprises a context-specific, actor-specific, and cumulative causation analysis, structures pattern analysis, presents guidelines for analysts to design and implement interventions and is modular in nature. Furthermore, through the proposed combination of the CIMO-logic structure, event history analysis and the TIS framework, the framework enables comparison between the innovation systems, answering *"what works for which innovation systems, in which contexts, in what respects and how".*

Contribution IV. *The application of the proposed CIMO-based EHA framework to four novel real-world case studies*

The design of the proposed framework was not limited to a conceptual level. Practical implementations of the framework were demonstrated through four novel real-world case studies. These cases demonstrated the comprehensiveness of the framework as case-specific insights could be derived, as well as the generality of the framework as the insights and dynamics of four cases could be compared.

Contribution V. *The proposal of six process mechanisms for crossing the Valley of Death*

This study extends the existing literature on technological developments bridging the valley of death (VoD) by arguing that a technological invention should complete six process mechanisms to bridge the VoD. The process approach of the six process mechanisms acknowledges the complexity of the VoD dynamics and supports technology developers in managing these challenges. Furthermore, the novel application of the TIS framework enabled identifying and analysing the TIS innovative activities performed during the VoD. As the TIS functions induce cumulative causation over time, the study contributes a process approach grounded on cumulative causation to the VoD literature.

Contribution VI. *The development of a novel method to develop a survey instrument and a policy suggestion priority tool.*

The framework instrument has elucidated a novel method to derive survey instruments. Furthermore, the derivation of the survey instrument from the innovation system framework's functional indicators presents a novel contribution to how survey instruments may be derived. Additionally, the functional indicators ensure that TIS analysis comprises the analysis of all relevant innovation activity types and related activities. Additionally, incorporating the importance, difficulty, and extent performed Likert scale data enables the development of a priority tool that allows innovation scholars and managers to visualise response data and identify opportunities for improvement and policy support suggestions.

Contribution VII. *Results from applying the survey instrument and resultant prioritisation tool to the South African AM enterprises.*

This study contributes a novel application of the TIS framework to the South African AM industry through a functional analysis of the dynamics of the South African AM enterprises. Consequently, insight could be obtained into the industry's challenges and opportunities. The application of the survey instrument to the South African AM enterprises presents innovation scholars and managers with practical results. Additionally, the prioritisation tool derived also elucidated policy support opportunities innovation managers and policymakers may address. Additionally, as the framework may be related to any TIS, the functional indicators may be utilised in future surveys to analyse other developing countries' AM industries to compare their dynamics to those of the South African industry.

1.6. Scope

This research study considered the hardmetal technology innovation system's (TIS) functional performance, focusing on additive manufacturing as a manufacturing technology. Although this study's evaluation framework was developed for the South African context, projects and companies from other countries were studied to gain insight from world-class examples. The scope of the research study is summarised in Figure 1.2.

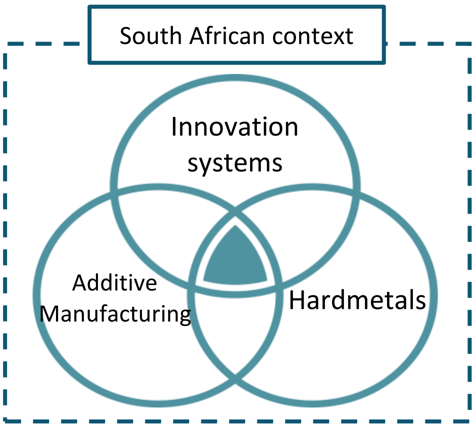


Figure 1.2: Graphical representation of the research scope

The research scope was narrowed to the South African hardmetal industry as numerous manufacturing research studies have been conducted for the industry. Additive manufacturing (AM) was selected as the focus technology as it is a novel, Industry 4.0 technology opposite of the traditional, subtractive technology that has been implemented in industry for many years. The innovation systems framework is applied to the hardmetal industry as it has often been used to study industry development, but not yet to the development of a hardmetal industry and not the South African hardmetal industry.

Although numerous AM studies have been done, most of them have been feasibility or proof of concept studies leading to a gap in knowledge regarding business and economic aspects thereof. The current use of AM for hardmetals is mainly in the research and development phase to determine feasibility. Furthermore, there is a global 'unspoken' race to see who can manufacture hardmetal products without cobalt binder using AM technology. Therefore, few companies and researchers are willing to share their stories and progress. Thus, very little literature is available regarding the business and economic aspects of AM. Due to this limited literature, the cases available for study are also restricted.

1.7. Ethical implications of the study

The data gathering phase of the case studies' construction and the validation of the case studies in this study required ethical clearance from the Research and Ethics Committee (REC) of the University of Stellenbosch. The nature of the data acquisition and validation comprised interviews with field experts involving human opinions and data from external parties. During the interviews, the researcher created an atmosphere that encouraged learning, and the participants were not threatened by any physical or psychological risks. Therefore, the REC granted the ethical clearance for this study under project number ING-2020-18663, and the researcher took note of the following:

1. Participation in this study was entirely voluntary, and the participants were free to withdraw at any time.
2. The researcher obtained consent from the participants before data collection commenced.
3. The participants were not forced to answer any questions they did not feel comfortable with.
4. All information disclosed during the study remained confidential and stored in a secure location.
5. No personal information of any participant was disclosed.

1.8. Dissertation organisation

Apart from this introductory chapter, this dissertation comprises a further thirteen chapters (organised in five parts), a bibliography and three appendices. This document comprises fourteen chapters. The introduction part comprises Chapter 1 and Chapter 2. This chapter presents the research background and formulates the research problem, objectives, and motivation. Chapter 2 presents the methodology used to meet the project objectives as well as the validation methodologies utilised.

Part I was devoted to a review of the pertinent literature. Chapter 3 describes hardmetal products, their industry applications, their manufacturing technologies, and their presence in the South African context. Additionally, additive manufacturing as a transformative technology is discussed along with its different technologies and presence within the South African context.

Chapter 4 presented an overview of innovation and industry and technology development. It introduces the concept of innovation and fundamental theories explaining innovation and change processes. Additionally, the chapter explores industry and technology development dynamics and phases, and the concept of the valley of death. Barriers and enablers of advanced manufacturing technology adoption are also explored. Finally, the chapter concludes with an overview of the literature pertaining to analysis approaches developed to study industry development.

Chapter 5, the final chapter of Part I, presented a detailed overview of the innovation system framework. The review considers the different types of innovation systems, their structural and functional components, and previous approaches and frameworks developed to analyse them. Thereafter, the chapter explores the innovation system deliverables and the method of event history analysis.

Part II was dedicated to the presentation of the newly proposed analysis framework. First, the chapter presented the shortcomings of similar existing frameworks. Thereafter the development of the proposed framework was presented. The chapter elaborated on the framework parts, presented the validation process performed by expert reviewers and the final refined framework.

Part III presented the application of the framework to four case studies conducted. First, in Chapter 7, the application of the proposed framework to real-world case studies was detailed. The chapter comprised a detailed description of the case study selection process, the application of the framework steps, as well as the data collection and validation methods utilised.

Chapter 8 studied the first case study in a series of four case studies. The chapter applied a macro perspective by exploring the evolution of the South African additive manufacturing sector over thirty years. The events that occurred during the development were described in the form of a narrative. The narrative was analysed, and the drivers, barriers and impacts of the evolution events were identified.

Chapter 9 studied the second case study. A project perspective was applied to an ongoing research collaboration project. The project involved the development of an AM technology to manufacture hardmetal products. The project actors involved include actors from academia, industry, and the German government. Studying the project through the innovation system framework and the event history analysis method, insights were gained regarding the drivers and barriers of research collaboration projects.

A company-level research and development project was studied for the third case in Chapter 10. The case explores the innovation activities of a Canadian start-up company that developed tungsten carbide 3D printer nozzles and expanded their company. The case sheds light on the effectiveness and influence of governmental initiatives to support innovative companies and novel technologies.

The fourth and final case study, Chapter 11, presented a novel writeup of an R&D project conducted by an established multinational engineering enterprise. Through the application of the proposed framework, the case sheds light on the company-level dynamics involved in the collaborative development of novel technologies and products.

Part IV is dedicated to an industry survey. Chapter 13 presented the development and validation of a survey instrument and priority tool developed. Additionally, it presented the application of the survey instrument to the South African AM enterprises and the derivation of policy support suggestions to support AM enterprises to grow and perform innovative activities.

Finally, Part V: Chapter 14 concludes the study, communicating the study's contributions. It also presents suggestions for future research opportunities.

Chapter 2

Research design and method

The previous chapter stated the purpose of the study, namely, to develop an analytical framework to analyse the evolution of (manufacturing) innovation systems. This chapter elaborates on the research methodology utilised to achieve this stated purpose. This chapter describes how the Design Science Research approach was adopted in this study to develop the framework. Thereafter, the tools exploited to develop the framework is detailed. The data collection methods and analysis techniques are also discussed, along with the research approach's validity and reliability considerations.

Chapter 2 objectives:

- Present an overview of research paradigms and indicate the one used in this study (§2.1).
- Introduce the Design Science Research and its cycles (§2.2).
- Present the Design Science Research Methodology and its application in this study (§2.3).
- Discuss data validation methods used in this study (§2.4).
- Discuss the ethical implications of the study (§2.5).

2.1. Research paradigm

When conducting research, a researcher must make a series of decisions [44]. These decisions are influenced by underlining theoretical perspectives, and together these decisions and theories characterise the research paradigm. The research paradigm is an important aspect of the study as it refers to the researcher's *theoretical lens,* which consequently influences the thought processes, methodological aspects, and interpretation of the research data. James [44] and the Institute for Development [45] explained essential elements of a research paradigm by adopting an iceberg metaphor, as seen in Figure 2.1. The metaphor of an iceberg comprises the idea that concepts have some visible aspects (part of an iceberg that is visible above the surface) and several aspects that are not visible (the rest of the iceberg below the surface). Therefore, James [44] and the Institute for Development [45] emphasise the interconnected nature of methods, methodologies, ontology, and epistemology by noting that although methods are visible, they are built on the methodologies, ontology, and epistemology hidden beneath the surface [44], [45]. The top and visible part of the iceberg refers to research methods typically well described in research. The methods include techniques that are typically used for data gathering. These include, amongst others, interviews, questionaries or surveys, observations, experiments and analytical techniques such as coding, statistics and

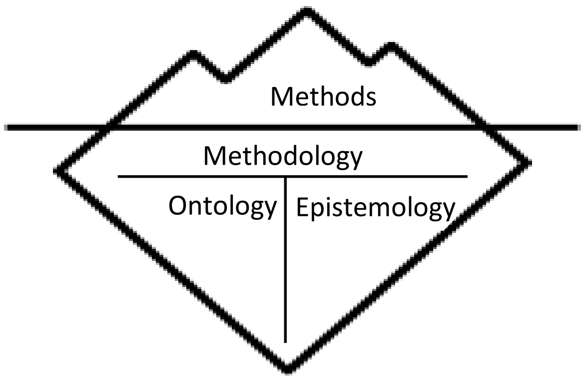


Figure 2.1: Research paradigm iceberg metaphor

discourse analysis [44]. The section right below the surface refers to the methodology of the study [44], [45]. The methodology relates to the research approach of a study. Research approaches include qualitative, quantitative, and mixed methods and can refer to a case study, ethnography or an experiment [44]. The depths of the iceberg refer to epistemology and ontology. Epistemology describes what is or should be regarded as adequate knowledge [44], [46]. Ontology refers to the nature of a phenomenon and what is seen as reality [44]–[46]. A researcher's ontological and epistemological orientation forms the researcher's holistic view of knowledge [46]. The holistic view leads to the researcher's decisions regarding its research approach. Patel [46] summarises the different research terms and the relationships between them in Figure 2.2.

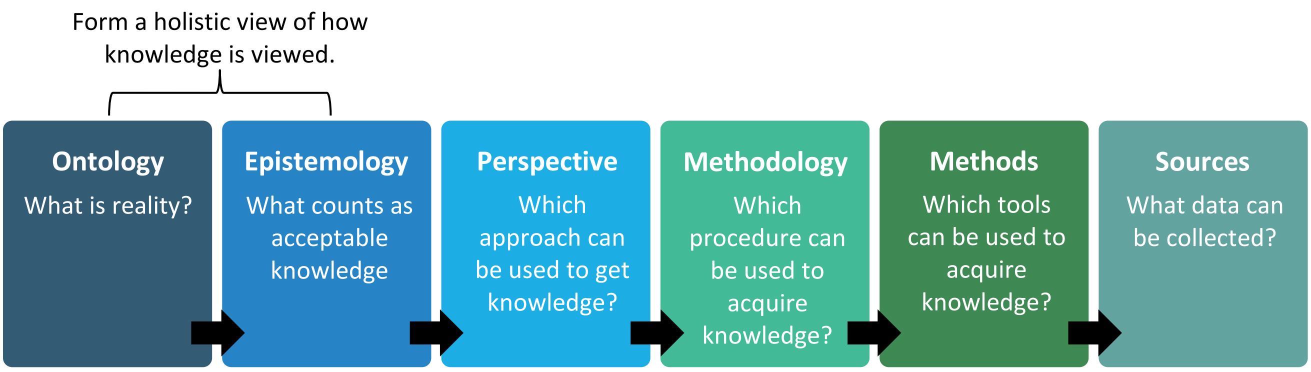


Figure 2.2: Research terms and their relationships

Positivism and interpretivism are the two most common research paradigms [46]–[48]. Positivism studies the social sciences and is focused on measurements and evidence to identify a single reality [44], [47]. In contrast, interpretivism assumes that multiple realities may exist that are not always measurable or observable as a deeper understanding of the phenomena's context need to be developed [44], [45]. A third paradigm, known as pragmatism, evolved as a mid-way between positivism and interpretivism [46]. Pragmatism adopts the notion of intersubjectivity using objective and subjective perspectives to represent reality. It states that reality should continuously be debated, renegotiated, or interpreted [46]. Therefore, it is problem-oriented and focuses on what is needed to solve an identified problem. The pragmatic paradigm also acknowledges the harmony between knowledge and actions [49]. Table 2.1 presents the specific elements associated with the three research paradigms.

Positivism utilises a deductive objective approach and quantitative methods to determine the single reality. However, positivism is often criticised for its low relevance and contribution to discarded solutions. In contrast, interpretivism follows an inductive approach with qualitative methods to discover theory or extend understanding of reality and therefore has high relevance. However, subjective interpretations are not generalisable and often lack rigour as interpretations are subjective.

Pragmatism suggests using mixed methods for complex problem solving to obtain value from qualitative exploratory and quantitative confirmatory sides [50]. Pragmatism, therefore, provides a balance between rigour and relevance [44], [46], [50]. Furthermore, pragmatism does not focus on problems' quantitative or qualitative nature but on solutions that address the identified problems. It thus follows the adoption of a research design best suited for solving problems and discovering new knowledge [51]. Furthermore, it adopts the notion that knowledge and purpose should direct actions to achieve the desired change. Finally, pragmatism aims to move beyond the status quo and instead focus on what might be [52]. Realism shares similarities with pragmatism as both paradigms believe in the contingency of events and the importance of socially-influenced individual agency in their approaches to social theory [53]. Realism is a research paradigm that asserts that both the material and the social worlds are real, can have real effects and that it is possible

Table 2.1: Research paradigms and the paradigm selected for this study [46]–[48]

Elements	Positivist	Interpretivist	Pragmatism	Realists
Ontology	• Naïve realism • A single reality • Knowable • Probabilistic	• Relativist • Multiple realities, socially constructed	• Non-singular reality • Reality is continuously renegotiated or interpreted	• Reality is partially independent of the human mind • Material and social reality • We interact with reality
Epistemology	• Objective • Dispassionate • Observer of the truth • Reality can be measured	• Subjective, need to be interpreted • The meaning of events is discovered in context	• Relational • The best method solves problems • Change is the objective	• No final truth or knowledge • Improvement in knowledge is possible
Perspective	• Positivism • Post-positivism	• Interpretivism • Critical inquiry • Feminism	• Deweyan pragmatism • Research through design	• Realism
Methodology	• Experimental - search for cause-and-effect relationships • Survey research	• Ethnography • Grounded theory • Action Research • Discourse analysis • Heuristic inquiry	• Mixed methods • Design-based • research • Action research • Experimental	• Mixed methods • Case study • Survey research
Method	• Scientific • Quantitative - sampling, focus groups, interview, statistical analysis, questionnaire, measurement, and scaling	• Qualitative - • interview, case study, participant observation, life history, narrative	• Combination of methods, quantitative, • qualitative, data • mining, usability • testing, prototype	• Combination of quantitative and • qualitative methods • Hypotheses • Case study, observations, and questionnaires
Criteria for Validation	• Internal and external validity • Reliability and objectivity	• Credibility, dependability, confirmability, transferability	• Mixed criteria, best suited to the research purpose	• Mixed criteria, best suited to the research purpose

to work towards a closer understanding of what causes change [54], [55]. It is a form of applied research that pursues to inform the thinking of policymakers and practitioners [54], [55]. Realist evaluation changes evaluation questions as it does not draw from what does or does not work. Instead, it asks "*what works for whom, in which contexts, in what respects and how*" [10, p. 1]. A task of realist evaluation is to make the theories within artefacts explicit by developing clear hypotheses about how and for whom artefacts might be useful [55]. Artefacts are then implemented and evaluated to test the hypothesis. Consequently, information is collected on the artefact's impact, implementation process and, most importantly, the context that may impact the artefact and the specific mechanisms that may cause change [54], [55].

Following the purpose and characteristics of the study, pragmatism was implemented as the research paradigm to develop new knowledge and develop a framework to analyse the evolution of innovation systems. However, as the framework focuses on the evolution of innovation systems, the study also draws from the realism paradigm, particularly *realist evaluation*. In addition to pragmatism's aim to move beyond the status quo and instead focus on what might be [51], realist evaluation will inform the contexts and mechanisms that lead to future states. The following sections present the research approach, methodology, and methods utilised in this study based on pragmatic principles.

2.2. Design Science Research

Design Science Research has its roots and primary application in engineering and is also vastly used in healthcare, computer science, and education [51]. Hevner and Chatterjee [56] define design science research as "*... is a research paradigm in which a designer answers questions relevant to human problems via the creation of innovative artefacts, thereby contributing new knowledge to the body of scientific evidence. The designed artefacts are useful and fundamental in understanding that problem*" [10, p. 3].

Vom Brocke et al. [57] describe DSR by stating that the approach seeks to enrich technology and scientific knowledge by creating innovative artefacts that solve problems and improve the environment in which they are instantiated. Helms et al. [58] simplify the fundaments of DSR by stating that DSR is a problem-solving process used to develop an artefact similar to design in the engineering sciences. The outcomes of the DSR process are thus novel artefacts and knowledge that provide a fuller understanding of why the artefacts enrich or disrupt their application contexts. DSR is thus different from routine design practice, as routine design practice is merely the application of best (existing) practices. In DSR, however, new knowledge is created through the combination of existing components to create a new artefact [56]. Table 2.2 summarises the primary aspects of DSR as follows.

Table 2.2: Primary aspects of Design Science Research (DSR)

Primary aspect	Explanation
Purpose	To invent and improve existing artefacts to enhance individual, group and organisational productivity and effectiveness [48].
Rational	To establish rigorous ground rules for growing knowledge contributions around building and evaluating artefacts [59]
Focus	Utility, usefulness, and contributing to practice [52]
Theoretical or practical	DSR incorporates both a theoretical knowledge base and a practical area of application. It emphasises both rigour and relevance [52]
Approach	Artefacts are developed through *iterations* of development and evaluation stages and interconnected cycles [60]
Outputs	New, innovative artefacts to solve or improve a problem identified in a specific application environment [51]. The possible artefacts delivered through DSI include [51], [61] • Constructs - The conceptual vocabulary of a domain • Models - Sets of propositions expressing relationships between constructs • ***Frameworks - Real or conceptual guides to serve as support or guidelines*** • Design Principles - Core principles and concepts to guide design • Methods - Sets of steps used to perform tasks • ***Instantiations - Situated implementations in specific environments that do or do not operationalise constructs, models, methods, and other abstract artefacts***

Due to the size and complexity of the problems and solutions spaces studied through DSR in engineering and computer science, the DSR approach is not focused on finding optimal solutions [60]. Instead, the approach focuses on discovering satisfactory solutions to identified problems without explicitly identifying all possible solutions [62]. Furthermore, the DSR approach involves creating, utilising, and evaluating heuristic search strategies and emphasises that particular solutions suit particular contexts. Therefore, the DSR implements an iterative process to enable the simplification of complex problems to subproblems that are satisfied and expanded with each iteration [60], [61]. Table 2.2 lists the possible artefacts or outputs DSR may deliver. According to Hevner *et al.* [63], the different artefacts delivered by DSR incorporate varying degrees of abstraction and contribute different types of knowledge. Consequently, Gregor and Hevner [60] distinguished three knowledge contribution levels and grouped possible outputs accordingly. Furthermore, they developed a framework to categorise types and levels according to their solution and application domain maturity [60]. As a result, four possible types can be identified depending on the starting point of the solution and problem maturity [60], [61]. Table 2.3 presents the knowledge contribution types and maturity level framework Gregor and Hevner [60] developed, along with examples they used to explain them.

Table 2.3 Knowledge contribution types developed by Gregor and Hevner [60]

Knowledge contribution types			
	Contribution Types	**Example Artefacts**	**This thesis**
More abstract, complete, and mature knowledge	Level 3. Well-developed design theory about embedded phenomena	Design theories (mid-range and grand theories)	
↕	Level 2. Nascent design theory - knowledge as operational principles or architecture	Constructs, methods, models, design principles, technological rules	Framework to analyse the evolution of innovation systems
More specific, limited, and less mature knowledge	Level 1. Situated implementation of an artefact	Instantiations - software products, implemented processes	Industry survey and four case studies

This thesis developed a framework artefact to guide the analysis of innovation systems. Furthermore, knowledge and novel insights were gained from the industry survey and the cases studied for the innovation system and manufacturing literature fields. According to Gregor and Hevner's [60] contribution types, levels one and two knowledge were thus created in this project. This project may be positioned as an Improvement contribution (Figure 2.3). First, a novel innovation system's (IS) approach is developed to study the evolution of ISs. Secondly, the IS is newly applied to the Valley of Death literature and the innovation activities of the South African additive manufacturing enterprises.

According to Gregor and Hevner [15] and Vom Brocke *et al.* [57], research positioned in the improvement quadrant should draw from a deep understanding of the problem environment to build an innovative solution artefact to improve the identified problems. The primary challenge of the *improvement quadrant* is to demonstrate the advancements of the improved artefacts in relation to the previous knowledge base [15]. Consequently, DSR authors have developed a DSR methodology process to direct researchers to ensure the development of useful, innovative improvement solutions [52], [57], [59], [60].

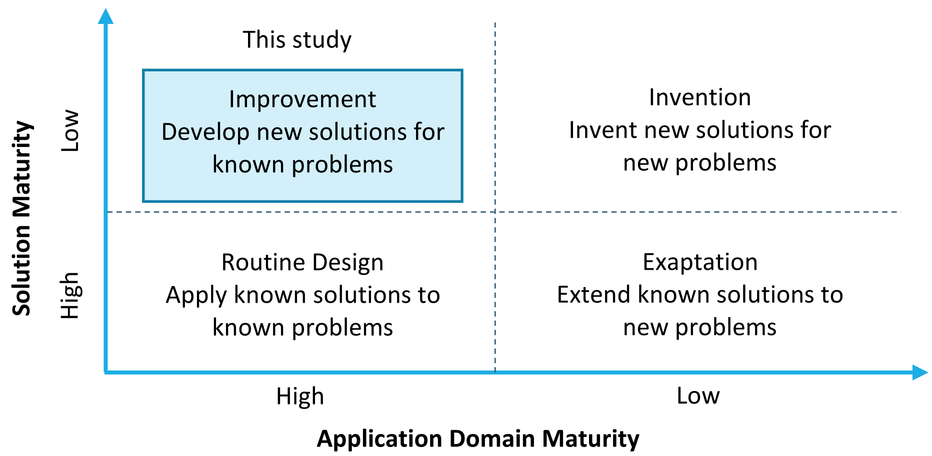


Figure 2.3: Positioning of this study within the knowledge contribution framework

2.2.1. DSR guidelines to support the research process

To support the research process, Hevner *et al.* [63] have developed seven DSR guidelines grounded in the fundamental principles of DSR. Hevner *et al.* [16] highlight that the guidelines should not be used in a mandatory or routine manner, but that researchers "*must use their creative skills and judgment to determine when, where, and how to apply each of the guidelines in a specific research project*" [16, p.82]. To this end, Table 2.4 summarises the application of the guidelines in this study.

Table 2.4: DSR guidelines developed to support the research process [63]

Guidelines	Description	Application in this thesis
1. Design as an artefact	DSR must produce a viable artefact as a construct, model, method, or instantiation.	This study developed a conceptual framework artefact. It is presented in Part II: Chapter 6.
2. Problem relevance	The objective of DSR is to develop technical-based solutions to important and relevant business problems.	The study aims to address real problems in the South African AM industry (Chapter 1). It repeatedly draws from the application environment through instantiations of the framework to ensure that relevant problems are addressed.
3. Design evaluation	A design artefact's utility, quality, and efficacy must be rigorously demonstrated via a well-executed evaluation method.	The framework is iteratively evaluated to ensure relevance and rigour. Four case studies (Chapters 8 - 11), multiple semi-structured interviews (Chapters 6, 8 - 11) and a survey are incorporated for the evaluation (Chapters 13). The application process of these methods is discussed in this chapter.
4. Research contributions	Effective DSR must provide clear and verifiable contributions to design artefacts, foundations, and methodologies.	Level 2 contribution: Proposed framework to analyse the evolution of innovation systems (Part II: Chapter 6) and the results of an industry survey. These contributions are assessed with Level 1 contributions: Application of the four case studies and an industry survey, a method to derive survey instruments, and a policy support tool (Parts III and IV).
5. Research rigour	DSR relies upon rigorous methods in constructing and evaluating the design artefact.	The methods applied in the construction and evaluation of the framework are discussed in this chapter.
6. Design as a search process	The search for an effective artefact requires utilising available means to reach desired ends while satisfying laws in the problem environment.	The four-cycle view and DSR process for iterative development and evaluation are implemented to achieve the study's aim.
7. Communication of research	DSR must be presented effectively both to technology-oriented as well as management-oriented audiences.	The research process details the framework sufficiently for innovation system scholars. Careful attention is also placed o the framework's discussions and application to the case studies (Chapters 8 - 11) and survey (Chapter 13) to ensure its relevance to management-orientated audiences.

2.2.2. Design Science Research cycles

Hevner [59] defined four cycles to assist the understanding and execution of DSR (Figure 2.4). These cycles must be present and identifiable for a research study to be classified as a DSR study. The cycles include 1) the change and impact cycle, 2) the relevance cycle, 3) the design cycle, and 4) the rigour cycle. The change and impact cycle highlights that the research does not stand alone but should integrate and contribute to its specific environment and the existing knowledge base. In contrast, the relevance, rigour and design cycles comprehensively conceptualise the critical aspects of a DSR project [62].

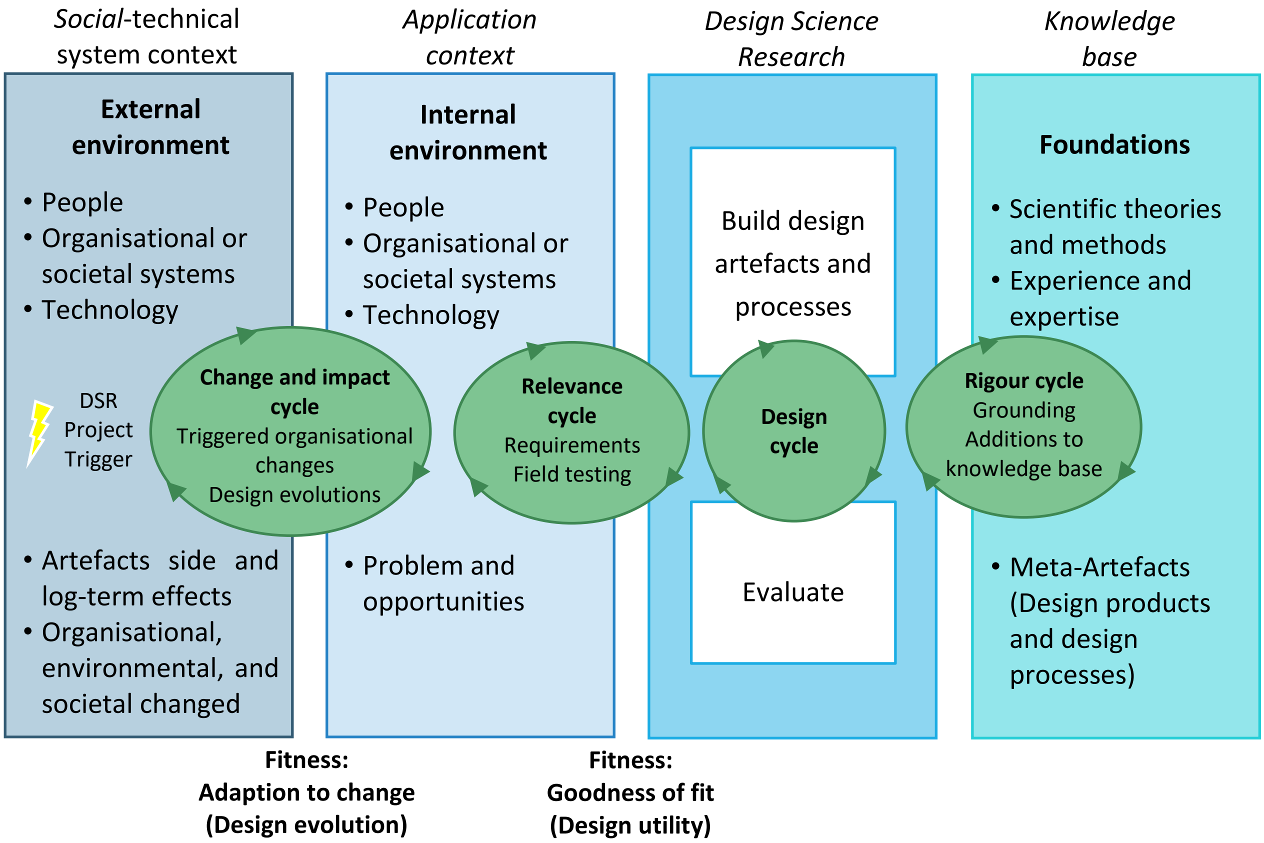


Figure 2.4: The four cycle view of Design Science Research [62]

2.2.2.1 Change and impact cycle

The change and impact cycle is initiated within a social-technical system context, highlighting that research does not occur in isolation but is integrated into a specific environment and should contribute to an existing knowledge base. The change and impact cycle aims to capture the dynamic nature of the artefact to be designed to suit the dynamic nature of the real-world contexts within which it exists [62]. The change and impact cycle covers the entire socio-technical system by differentiating the immediate application context from the encompassing societal and organisational environments to incorporate the second-order impacts of the artefact [62]. It is acknowledged that the delineation between the two contexts depends on a researcher's interests and initial DSR project goals [62]. Therefore, Drechsler and Hevner [62] have presented the DSR project trigger outside the immediate application context in Figure 2.4. Therefore, project objectives are said to be driven by factors from the external environment, with the DSR goals accounting for the second-order or broader impacts the stakeholders may have [62]. Finally, it is also recognised that not DSR project scopes may account for the external environments. Therefore, iterations of the change and impact cycle are not compulsory.

2.2.2.2 Relevance Cycle

The relevance cycle forms the bridge between the contextual environment of the research project and the design science activities [64], [65]. It presents the research opportunities and problems in the application environment, which consists of organisational and technical systems and the people operating them to satisfy a specific goal [64], [65]. Additionally, it presents the requirements of the artefact and the acceptance criteria for the artefact's utility in the field [6]. Furthermore, it ensures that the developed artefact contributes to its environment. Consequently, all potential solutions should be tested and evaluated in a suitable environment [57]. As the cycle indicates, this process is iterative and will recommence with feedback from the environment as better aligned research requirements are discovered from actual experience [64].

2.2.2.3 Design Cycle

According to Hevner [59], the design cycle is central to the DSR project. It iterates between the development, evaluation, and refinement of the designed artefact until a satisfactory design is obtained. The central design cycle supports the artefact's design and redesign and the corresponding artefact evaluation and refinement until a satisfactory design is obtained [62]. The relevance cycle provides the input requirements used for the evaluation, while the rigour cycle provides the necessary evaluation methods and theories [59]. The evaluation process demonstrates how the three cycles are interlinked and mutually dependent and highlights the independence of the development phase when all the obtained knowledge is combined. The artefact evaluation may presume within artificial settings (for example, through thought or laboratory experiments) or in real-world contexts (field tests that become part of the relevance cycle) [62].

2.2.2.4 Rigour Cycle

The rigour cycle demonstrates the integrity and competency of the research process. The rigour cycle connects the design science activities and the knowledge base that informs the research project [64]. It builds upon and contributes to existing knowledge that includes, but is not limited to, scientific theories, experience, and expertise [57]. The rigour cycle enables the researcher to identify and reference the relevant current and past knowledge, thereby guaranteeing valuable innovative contributions. Additionally, it enables artefact evaluation, the documentation of feasible solutions, and how the evaluation findings fit with and extend the knowledge base [59].

Overall, the DSR four-cycle process iteratively refines an artefact's design through several interconnected design, relevance, and rigour cycles. The refinement is essential as it increases the artefact's ability to address the real-world problem and its knowledge contributions over several iterations [62].

2.2.3. DSR progression checklist

Hevner and Chatterjee [64] provide a widely used checklist of questions to assess researchers' progress through the DSRM. They related the checklist to the various DSR cycles from Figure 2.4 to demonstrate their relationship. By successfully answering these questions, researchers can ensure that their project addresses

Table 2.5: DSR progression checklist [64]

Question	Relevant cycle
1. What is the research question (design requirements)?	Change and Impact Relevance
2. What is the artefact? How is the artefact represented?	Design
3. What design processes will be used to build the artefact?	Design
4. How are the artefact and the design processes grounded by the knowledge base? What, if any, theories support the artefact design and the design process?	Rigour
5. What evaluations are performed during the internal design cycles? What design improvements are identified during each design cycle?	Design
6. How is the artefact introduced into the application environment, and how is it field tested? What metrics are used to demonstrate artefact utility and improvement over previous artefacts?	Relevance
7. What new knowledge is added to the knowledge base, and in what form? (For example, peer-reviewed literature, meta-artefacts, new theory, new method)	Rigour
8. Has the research question been satisfactorily addressed?	Change and Impact Relevance

the key aspects of DSR. They advise researchers to continually refer to the checklist throughout the design process to ensure that the activities are correctly followed. Table 2.5 presents the checklist questions and the research cycle they relate to.

2.3. Design Science Research Methodology and its application in this study

The DSR methodology (DSRM), developed by Peffers et al. [66], is a commonly accepted framework and methodology utilised to conduct DSR studies [64], [66]. The DSRM guides researchers through the design process to recognise and validate the research objectives, processes, and outputs. Figure 2.5 presents the DSRM proposed by Peffers et al. [66]. The six steps of the DSRM and their application in this study are described in this section.

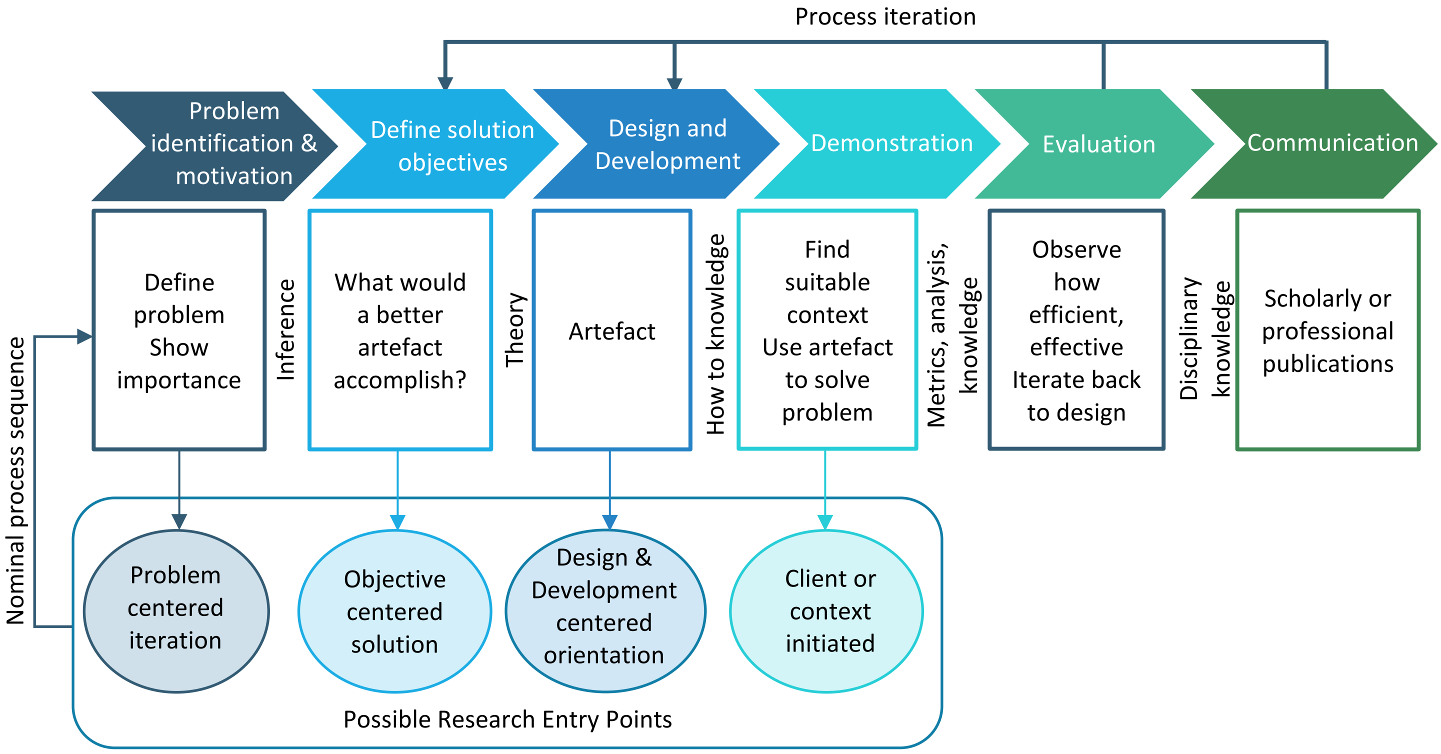


Figure 2.5: DSR method process model [66]

2.3.1. Activity 1: Problem identification and motivation

Activity one comprises the definition of a research problem and the justification of a solution's value [64], [66]. A well-defined research problem forms the foundation on which an artefact is developed [64]. To define the research problem, Peffers *et al.* [66] suggest that the problem be atomised conceptually to capture its complexity. Justifying the value of a solution motivates the research study and the pursuit of the solution [64], [66]. It also supports the audience in understanding the researcher's reasoning and understanding of the problem [64], [66]. Therefore, to complete activity one, researchers require knowledge of the problem's state and the solution's importance [64], [66].

Activity 1 is documented in Chapter 1 and Chapter 2. In Chapter 1, background information was presented on innovation systems (IS), additive manufacturing (AM) and how the South African AM industry may be studied through the IS framework to support its growth. This background information was used to define the study's research problem and justify the need for a framework to study the evolution of ISs. Subsequently, research questions, objectives, and contributions were derived to solve the research problem. The Change and Impact and Relevance cycles are active during Activity 1 and pertain to ISs, AM and the South African AM industry literature.

2.3.2. Activity 2: Define the objectives for a solution

The objectives for a solution artefact should be derived from the problem definition and specification and knowledge of what is possible and practical [64], [66]. These objectives may be quantitative or qualitative [64], [66]. Furthermore, knowledge of the state of the problem, existing solutions, and their efficacy is once again necessary to complete activity two [64], [66].

Activity 2 is documented in Chapter 3 and Chapter 4, where the Rigour cycle was active. To enable the accurate definition of solution objectives, a competent knowledge base of the state of the problem, existing solutions, and their efficacy was obtained. This was achieved through the two conceptual literature reviews on additive manufacturing, industry development, innovation systems and CIMO logic. Knowledge was gained on additive manufacturing (AM) technologies, the phases, drivers, and barriers of industry development, as well as the theory of CIMO-logic (context-intervention-mechanism-outcome logic). In depths knowledge was also gained on the IS framework, the existing IS framework and tools. Finally, IS methods and theories that may be used to develop an IS CIMO-based framework to analyse the evolution of ISs were identified.

2.3.3. Activity 3: Design and development

The primary objective of the design and development activity is to create the artefact, particularly an artefact in which a research contribution is embedded in the design [64], [66]. Therefore, as long as a contribution is embedded in the artefact, the artefact may take on any output form described in Table 2.2 (for example, model, construct, instantiation or method) [64], [66], [67]. However, before the artefact may be developed, the artefact's desired functionality and architecture must be determined [64], [66]. Consequently, collective and culminative knowledge of research theory is required to design and develop an artefact [64], [66].

The design cycle present during the design and development of the CIMO-based framework is documented in Part III: Chapter 5. As the framework's objective is to analyse the evolution of (manufacturing) innovation systems, similar existing frameworks are briefly studied. After that, the proposed CIMO-based analysis framework is presented, its four steps (Context, Intervention, Mechanism and Outcome) are unpacked and related IS, and EHA methods are presented. The chapter concludes the development process by verifying that all the design requirements were adhered to.

2.3.4. Activity 4: Demonstration

Activity four comprises testing the artefact's efficacy by demonstrating its ability to solve one or more examples of the problem [64], [66]. Demonstrations may include simulations, case studies, interviews, experimentation, or other appropriate activity [64], [66]. Consequently, effective and sufficient knowledge of the use of the artefact to solve the problem is required [64], [66].

The relevance cycle was present during the demonstration phase of the study documented in Part II: Framework and Part III: Case studies. The demonstration phase involved applying the framework to four 'AM for hardmetal' cases and presenting the framework to expert reviewers. In Part III: Case studies, the framework was applied to an industry-level case, a research-level case and two enterprise-level cases. Semi-structured interviews were held with IS and manufacturing field experts to validate the framework's application in the case studies. Furthermore, the expert reviewers validated the framework steps and methods, evaluated the framework's efficacy, and provided insight into concepts that could improve the framework.

2.3.5. Activity 5: Evaluation

Following the artefact demonstration, the artefact's ability to solve the problem should be observed and measured [64], [66]. The artefact's results observed during the demonstration are thus compared against the solution's objectives set in activity 2 [64], [66]. The evaluation of design artefacts and theories is an essential activity as it provides feedback for further development and, if performed correctly, assures the rigour and relevance of the research [56], [59], [68]. Therefore, artefacts need to be analysed according to their performance, use, validity, utility, quality, and efficacy in formulating explanations or improvements [56], [59], [60], [69]. The evaluation process required depends on the problem venue's nature and artefact. For example, it may include empirical evidence, logical proof, quantitative performance measures, such as budgets, client feedback, or simulations or quantifiable performance measures, such as availability and response time [64], [66]. At the end of the evaluation, researchers may iterate back to Activity 3 to improve the artefact's effectiveness or continue to Activity 6 [64], [66].

The framework evaluation was documented in Parts II and III (alongside the demonstration) and Part IV, while the relevance, design and change and impact cycles were present. Case studies and semi-structured interviews were primarily used to evaluate the framework. In contrast, the industry survey was used to gain practical insight into the industry and to refine the framework suggestions. Together, the case studies, interviews and industry survey triangulate the framework's evaluation, as discussed later in Section 2.4.

The evaluation of design artefacts and theories is an essential activity. It provides feedback for further development and, if performed correctly, assures the rigour and relevance of the research [56], [59], [68]. According to Venable *et al.* [68], the DSR evaluation process should be effective in rigour and efficiency. Therefore Prat *et al.* [70], through a systematic review, identified the evaluation criteria deemed important by DSR authors and constructed a hierarchy of criteria for artefact evaluation. The hierarchy includes five system dimensions, namely goal, environment, structure, activity, and evolution, each with evaluation sub-criteria. The application of the system dimensions and evaluation sub-criteria in this thesis is summarised in Table 2.6.

2.3.6. Activity 6: Communication

Activity six comprises the communication of the problem and its importance, the artefact's novelty and utility, and its design's rigour and effectiveness to the appropriate audience [64], [66]. It may include scholarly or professional publications and therefore requires knowledge of the disciplinary culture [64], [66].

The final activity commenced through the presentation of the final framework, case synthesis, survey priority tool developed and the South African additive manufacturing enterprises' industry survey results. Parts of Chapters 6 for part of a paper published in the 28th IEEE ICE/ITMC & 31st IAMOT Conference proceedings [71]. Additionally, Chapters 12 and 13 form part of articles from the Technovation and IEEE Transactions on Engineering Management journals. Finally, the research problem, its importance, the study's contributions, and suggestions for future research are presented in Chapter 14 with the rigour cycle present.

Figure 2.6 presents and summarises the Research Design steps, the relevant chapter, the activities performed, and the theories utilised during each DSRM activity.

Table 2.6: Criteria for DSR artefact evaluation [70]

System dimensions	Evaluation criteria	Description	Application in this thesis
Goal	Efficacy	The degree to which artefact produces its desired effects	Interviews Case studies
	Validity	The degree to which the artefact correctly achieves its goal	Interviews Case studies
	Generality	The range of the artefact's applicabilities.	Interviews
Environment	Consistency with people	Harmony of artefact features to one another or a whole, utility, ease of use, and understandability.	Interviews Case studies Industry survey
	Consistency with organisation	Harmony of artefact features to one another or a whole, artefact's alignment with its organisational environment.	
	Consistency with technology	Improvement of the artefact to existing artefacts, the side effects of the artefact on its environment	
Structure	Completeness	Level of detail, the inclusion of all appropriate or necessary concepts	Interviews Case studies
	Simplicity	Easy of understanding	Case study Interviews
	Clarity	Clear understanding	Interviews Case studies
	Style	Static aspects of artefact	Interviews
	Homomorphism	Correspondence of a model artefact with another artefact or the fidelity of a model to modelled phenomena	Artefact design
	Level of detail	The adequacy of the level of detail provided	Interviews Industry survey
	Consistency	Uniformity of (internal) structure	Interviews Case studies
Activity	Completeness	Functionality	Case studies
	Consistency	Dynamic aspects of artefact	Interviews
	Accuracy	Demonstrated agreement with the results of existing experiments	Industry survey
	Efficiency	The ratio between outputs and inputs of activity	Case studies Industry survey
Evolution	Robustness	Ability to respond to fluctuating environments	Expert reviews Case studies
	Learning capability	The capability of a system to learn from its experience and reactions to its environment	Case studies Industry survey

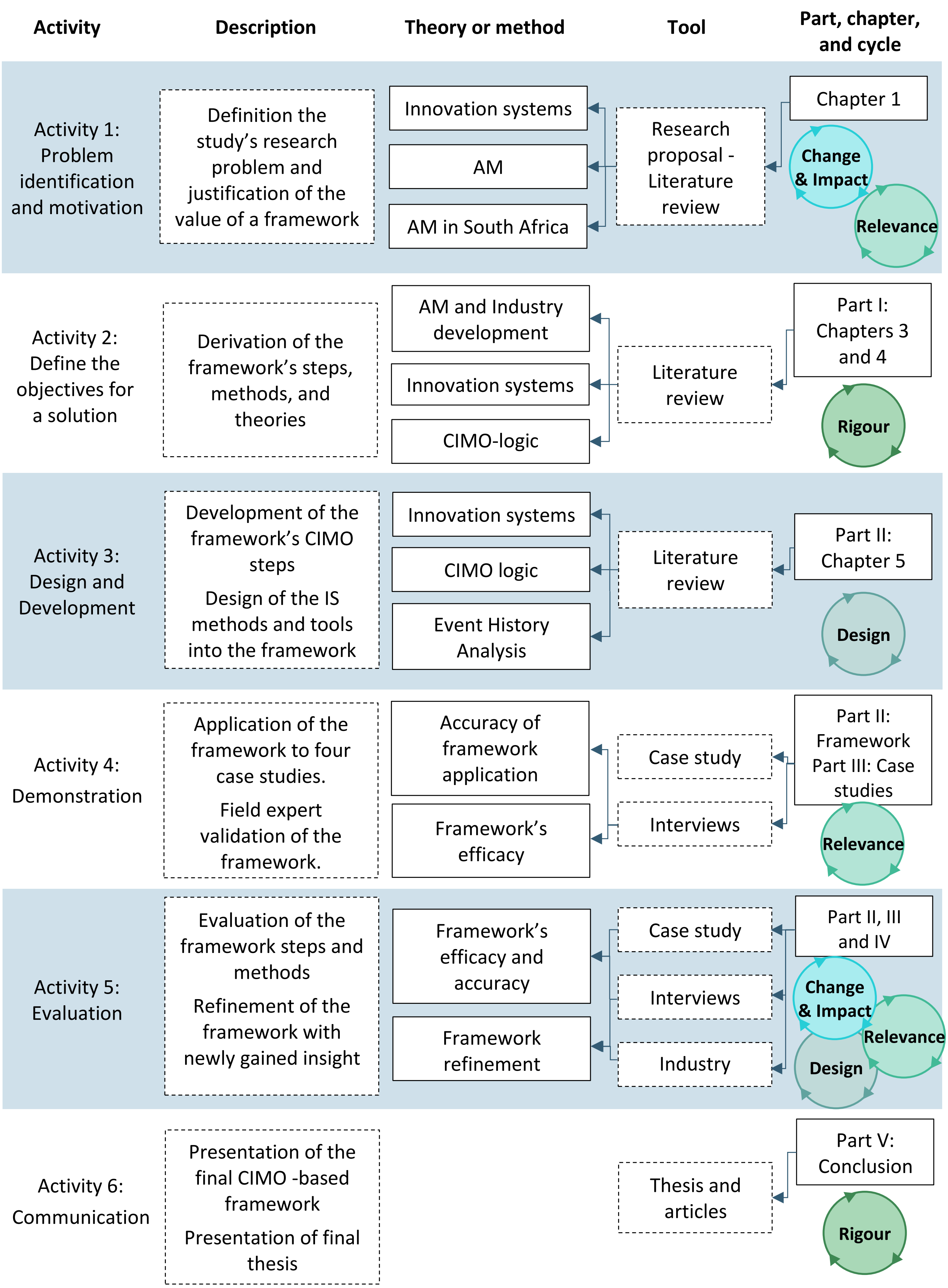


Figure 2.6: Application of the DSRM and design cycles in this thesis' research design

2.4. Validation

Validity and reliability are two important considerations in qualitative research [50], [72]. Qualitative validity is the degree of accuracy with which research findings reflect the truth [50]. Qualitative reliability refers to the consistency of research across different researchers [50], [72]. Golfashani [73] extensively researched validity and reliability as criteria associated with qualitative research. He concluded that qualitative research could conceptualise quality, rigour and trustworthiness [73]. His research suggested triangulation as a method that ensures validity and reliability as it eliminates bias and increases the truthfulness of a proposition [73]. Authors such as Cresswell [50], Gibbs [74] and Bashir and Tanveer [72] also suggest triangulation as a method to improve the validity and reliability of qualitative research as it uses different methods to verify results.

Triangulation is a qualitative evaluation and cross-checking method that ensures that research findings are valid and reliable [72], [73]. It is based on the triangulation metaphor used in navigation. Triangulation compares the results of multiple data collection methods to increase confidence in the quality and rigour of the research [50], [72], [73], [75]. Comparing the results from, for example, surveys, interviews, focus groups, participants and direct observation, bias can be minimised, and the truthfulness of propositions strengthened [50], [72], [73], [75].

This study sought to ensure and protect the validity and reliability of the research findings. Therefore, the triangulation approach was adopted and implemented. A combination of case studies, semi-structured interviews, and an industry survey, as seen in Figure 2.7, was used as a triangulation strategy to minimise bias and threats to validity.

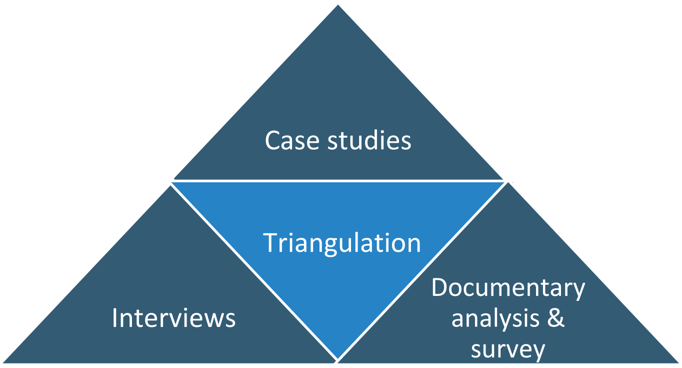


Figure 2.7: Triangulation approach to ensure valid and reliable research

2.4.1. Case study

Case studies are generally used as a qualitative research design [44], [45]. However, case studies were used in this study to evaluate the proposed framework. Case study research investigates a complex phenomenon within its natural context using various data sources [76]. Various data sources enable a researcher to take on different lenses to understand a phenomenon better [192]. According to Yin [77], case studies are useful to researchers investigating a social phenomenon's 'how' and 'what'. Additionally, every case study yield insights particular to the case of study. Yin [78], therefore, suggests that the insight gained from multiple case studies, typically three to five, is necessary to yield more general insights into a study field [78]. However, a limitation of using case studies is that it is time-consuming [23]. This limitation implies that the case studies cannot be generalised using statistical techniques. Suurs [23] and Abell [79] suggest that generalisation should be made by comparing and arguing from the content of the cases and relating these results to theory.

In this project, four case studies were conducted and analysed through the proposed framework. Three of the cases focused on research and development projects that involved additive manufacturing as a manufacturing technology for hardmetals. These projects were conducted by different actors: academia, an SME, and a large enterprise. The other case focused on introducing additive manufacturing technology into a country. Figure 2.8 presents these levels of the studied cases. Therefore, each case represents an instantiation of the DST methodology and the proposed framework. Part III: Chapter 7 details the methodologies for selecting and conducting the cases.

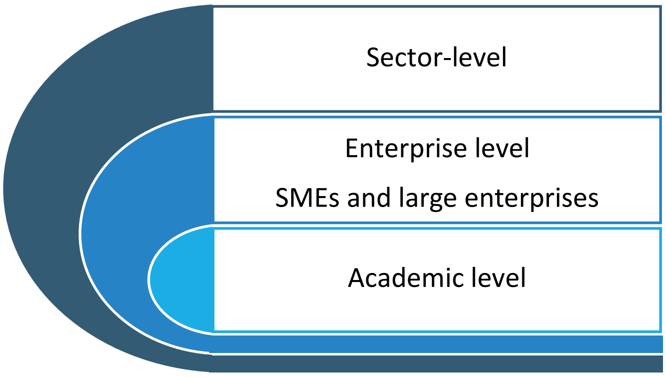


Figure 2.8: Levels of the cases studied

2.4.2. Semi-structured interviews

Interviews are a standard and powerful method to obtain information and build an understanding [50]. It is a conversation that involves an interviewer, who coordinates the conversation by asking questions, and an interviewee, who responds to the questions and provides information [80]. They can take on different designs based on the information that is required. These designs can be grouped into three categories, namely structured, semi-structured and unstructured interviews [80].

This study used semi-structured interviews to evaluate the proposed framework and survey instrument and collect and validate case study data. Several expert reviewers were interviewed during the evaluation of the framework and survey and the collection and validation of the case study data to mitigate the possibility of inadequately prompting interviewees to collect relevant data and to ensure that a wide range of perspectives was included.

The semi-structured nature of the interviews allowed a balance for in-depth information to be collected systematically and for new themes, topics, or perspectives to be explored and included. It allowed for questions and supplementary questions to be prepared ahead of time and provided the interviewer with the opportunity to clarify questions. The interview process followed in this study is detailed in Part III: Chapter 7. The profiles of the expert reviewers are presented in the evaluation sections. They may be found in Chapters 6, 8 to 11 and 13.

2.4.3. Industry survey

Fuller, Warren and Argyle [81] define a survey as a list of questions aimed to extract specific data from a particular group of people. The design of surveys depends on a researcher’s objective [82]. For example, it may include collecting exploratory information such as qualitative information to understand an artefact better or the generation of hypotheses on a subject. It may also involve collecting quantitative information to test specific hypotheses generated previously [82], [83].

The benefits of survey studies include that they are relatively easy to administer, may be administered online, and advanced statistical techniques can be utilised to analyse the qualitative and quantitative aspects of the survey responses. However, survey instruments also have several drawbacks. They include, amongst others, a low response rate, too time-consuming to complete, biased questions that may influence responses, and if the survey questions are too closed-ended, additional insights may not be gained from the framework.

Part IV presents the survey study conducted as part of this thesis. The survey aimed to gain insight into the dynamics of the South African AM enterprises, investigate whether the programmes and support documented in Case I were still operational and effective, and compare the South African industry with the insights gained from the case studies. The survey did, therefore, not test the comprehensiveness and usefulness of the proposed framework. Instead, it utilised components of the framework to derive the survey instrument and insights gained from the cases analysed through the framework to compare with the survey response data. Consequently, the survey responses presented the formative data that informed the data analysis methods.

Forty South African AM enterprises (approximately 80% of the industry) were surveyed, and 35 complete responses were collected. The findings show that the AM enterprises are still relatively young and typically employ less than 50 people. Value-added enterprises also dominate the industry, although several international service bureaus exist.

2.5. Ethical clearance

This study, project number ING-2020-18663, adhered to the scholarly and scientific ethical guidelines set by Stellenbosch University. As interviews were held and information in the public domain was used, the study was categorised as a minimal/low-risk project. No confidential personal information was obtained, nor was information gathered from vulnerable individuals. All interview participants were informed of their right not to participate in the study and consent to be interviewed.

2.6. Chapter 4 summary

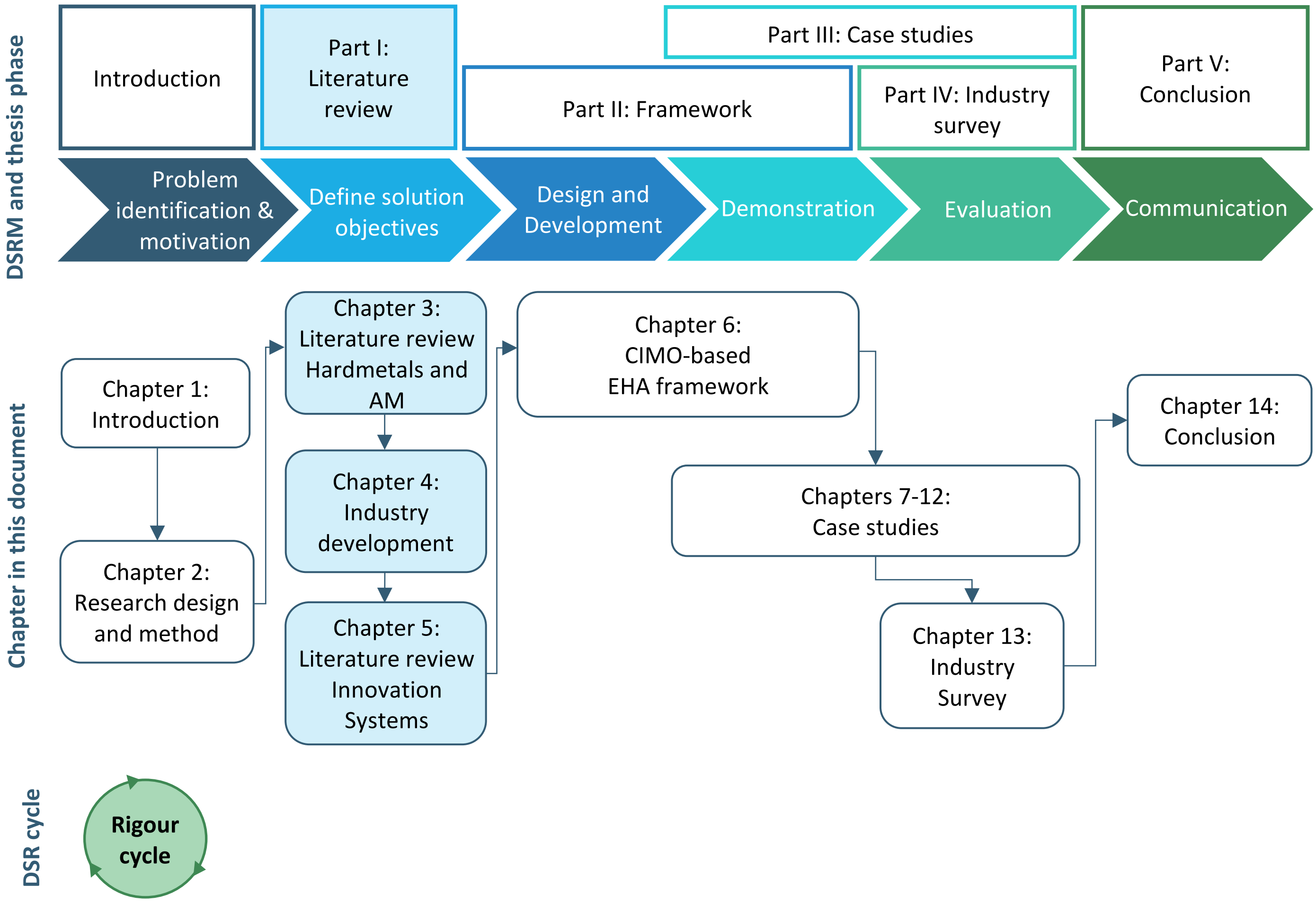
This chapter focused on the research design of this project. It reflected on research approaches and detailed the Design Science Research approach and its application in this study. The primary data collection, analysis and validation techniques followed within the Research Design are described and summarised in Table 2.7. The document now transitions to Part I of the study, namely the literature reviews.

Table 2.7: Research design techniques and their methods or processes followed

Research design technique	Chapter and parts presenting the methods	Method or process followed
Design Science Research	Chapter 2	Peffers *et al.* [66]
Case study	Part III	Tellis [77]
Semi-structured interviews	Parts II, III and IV	Rabionet [84]
Industry survey	Part IV	Cassim [81]
Data analysis process	Parts I and III	Cresswell [50]
Coding	Parts I and III	Miles, Huberman and Saldana [85]
Quantitative content analysis	Parts I, III and IV	Bryman *et al.* [47]

Part I

Literature review



Chapter 3

Literature review: Hardmetal and Additive Manufacturing

The previous chapter gave a detailed overview of the project design. The purpose of this chapter is to present the reader with a contextual understanding of hardmetal and additive manufacturing as this study studies cases on additive manufacturing for hardmetals. It introduces the different additive manufacturing technologies and the relevant hardmetal manufacturing techniques. Furthermore, it provides an overview of the state of the South African additive manufacturing industry as well as the hardmetal industry. This chapter contributes to objective 1, as mentioned in §1.4.

Chapter 3 objectives:

- Present the case for hardmetals (§3.1.1, 3.1.2).
- Reflect on hardmetal applications (§3.1.3).
- Provide an overview of traditional hardmetal manufacturing technologies and the relevant additive manufacturing technologies (§3.1.4).
- Present an overview of hardmetal industry in South Africa (§3.1.5).
- Introduce Industry 4.0 technologies and additive manufacturing (§3.2).
- Present an overview of the additive manufacturing technologies (§3.3.1).
- Provide an overview of the South African additive manufacturing industry (§3.3.3).

3.1. Hardmetals

This section presents the case for hardmetals. It reflects on the material properties that deliver hardmetals' significant poperies and the industries in which the material is typically utilised. This section also reflects on the technologies hardmetal components are traditionally manufactured with and presents an overview of the South African hardmetal sector.

3.1.1. Case for hardmetals

As mentioned in Chapter 1, manufacturing is a significant employer globally, accounting for around 14.2% of the world's workforce [1]. In 2018, the global job multiplication effect of industrial development was estimated to have a positive impact on society, as 1.1 jobs in manufacturing created 2.2 jobs in other sectors [2].

In 2019, the manufacturing industry contributed 13.53% of South Africa's GDP (R386 billion) [84]. Although South Africa's tungsten deposits are seen as insignificant, hardmetal (cemented tungsten carbide) is of great importance to the South African manufacturing industry [85]. Its exceptional properties (§3.1.2) enable it to be used to, amongst others, cut, drill or mould other metals and excavate minerals and oil [9]–[11], [13]. For example, in South Africa, hardmetal is utilised in the powder compacting moulds for automobile engine parts, the moulds of aluminium cans and to manufacture the tools used to break up bedrock during shield tunnelling and to cut the surface of asphalt on roads [9], [10]. Furthermore, in 2020, hardmetals were utilised to manufacture approximately R11.8 billion worth of various steel products [86]. Therefore, due to its usefulness and utilisation in nearly all South African manufacturing applications, this study selected hardmetals as its application material.

3.1.2. Hardmetal material properties

Tungsten is a chemical element with extraordinary thermal and mechanical properties, such as having the highest melting point and lowest vapour pressure of all metals. When tungsten is combined with carbon, a non-metal, a ceramic called tungsten carbide, characterised by very high hardness, is produced [87]. When tungsten carbide, which exists in powder form, is further metallurgically combined with a metallic binder such as cobalt to form a product classified as a cermet, cemented tungsten carbide or hardmetal [88]. Hardmetal also has excellent properties, such as its ability to resist high pressures, impacts, heavy loads, deformation, corrosion and high temperatures [9]–[11] and is known to be twice as stiff and dense as steel [89]. Additionally, components made from hardmetals typically have a 3-20 times longer service life than steels and other alloys [12].

Hardmetal is mainly known for its fracture toughness, transverse rupture strength and high hardness or wear resistance [11], [90]. Its hardness makes it useful for manufacturing abrasives, bearings and cutting tools as it is less expensive and more heat-resistant than diamonds. The hardness and strength are obtained from the tungsten carbide component, while the cobalt binder ensures the fracture toughness [11], [91]. Thus, a hardmetal product's mechanical properties can vary over a wide range depending on the size of the tungsten carbide grains and the amount of cobalt content in the product. For example, for a product such as a water jet nozzle which requires extreme hardness to withstand high water pressure and abrasives but does not have to withstand bending loads or impacts, small tungsten carbide (WC) grains with minimal cobalt content will be used [92]. Figure 3.1 demonstrates this by indicating the balance which must be obtained between the hardmetal components to achieve the respective properties of hardmetal products [92]. Figure 3.2 demonstrates the usefulness of these combinations of tungsten carbide grain sizes and cobalt content by indicating the wide range of application products that can be obtained [93].

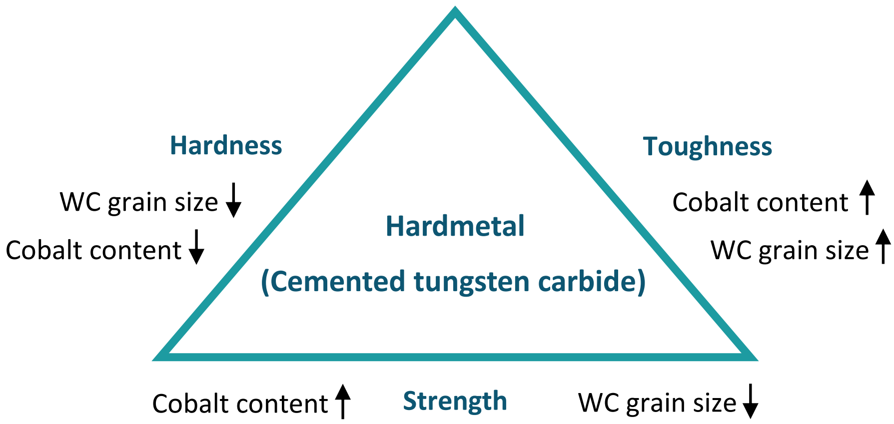


Figure 3.1: Hardness, strength and toughness of cemented tungsten carbide based on the balance between WC grain size and cobalt content [9]

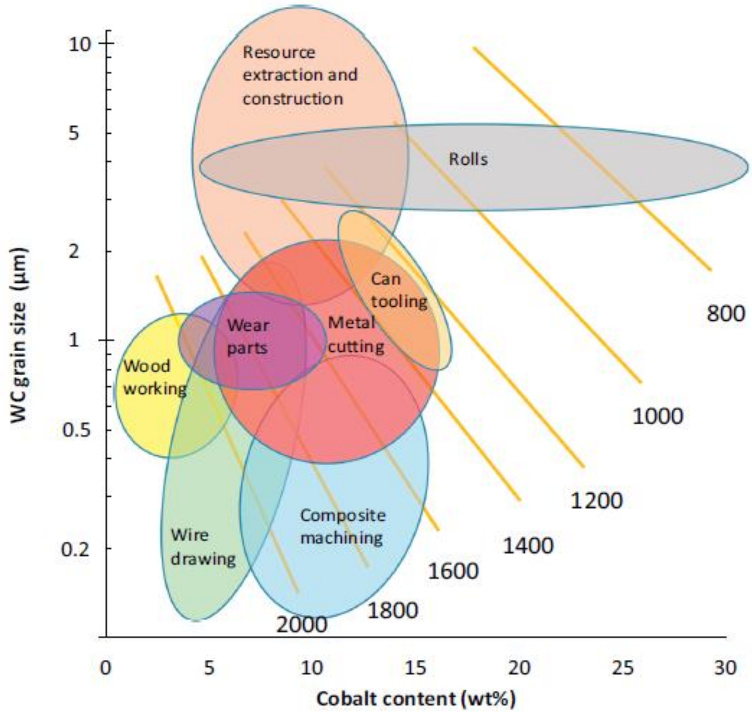


Figure 3.2: Cemented tungsten carbide applications based on the combinations of tungsten carbide grain size and cobalt content [93]

3.1.3. Application industries

The fracture toughness, transverse rupture strength and extreme hardness of hardmetal, in combination with its other excellent properties, make it unique, versatile, and extremely useful to various application fields. For example, cutting tools are one of the top products manufactured from hardmetals, accounting for nearly 65% of hardmetal usage [93]. Cemented carbides also make up 50% of the global hard material market, dominating high-speed steels, ceramics and polycrystalline diamond together with cubic boron nitride, which accounts for 45%, 4%, and 1% of the global market, respectively [93], [94].

In Figure 3.3, the global hardmetal market is segmented based on application industries [95]. Figure 3.3 indicates that the transportation industry is the leading industry in the global hardmetal market, followed by the oil and gas, aerospace and defence, and mining and construction industries. The term `other' in the figure refers to the jewellery, medical and sports industries [95], [96].

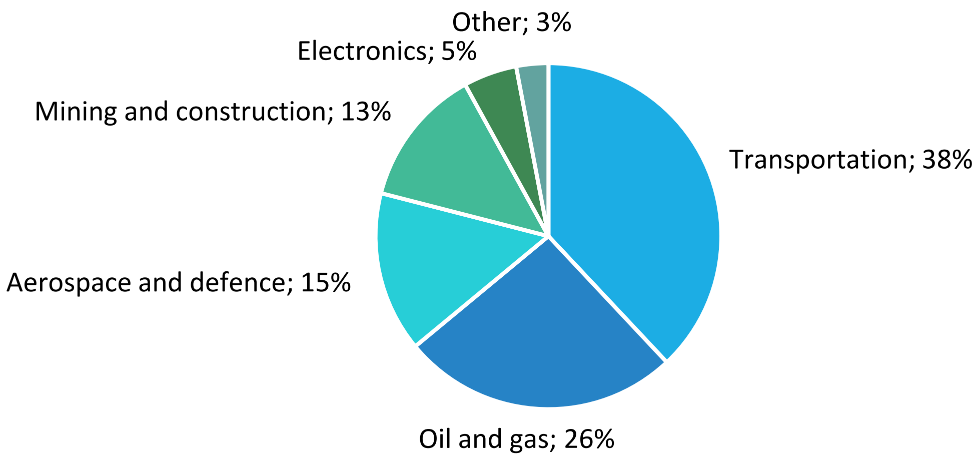


Figure 3.3: Global hardmetal market based on application industry [95]

In the transportation industry, hardmetals are used mainly in the automotive and railway sectors. Hardmetal is used to manufacture certain automotive parts where high temperatures, high stress and excessive wear are expected, such as brakes, crankshafts and ball joints [97]. Some motor vehicles, light-duty trucks and large construction vehicles use tire studs made from hardmetal to manage extreme weather conditions as hardened steel studs, which were used in the past, wore, cracked and broke too quickly [97]. The automotive sectors also use hardmetal cutting tools to turn, mill and drill metal components [93], [96]. The railway sector uses hardmetal equipment such as skids, tamping tools and ploughs to maintain railroads.

The oil and gas industry is the second-largest and fastest-growing hardmetal application industry [96], [98]. Hardmetal products are extensively used as drilling products and internal components of fluid handling and flow control devices as these components are subjected to abrasion, corrosion, erosion and other extreme conditions [99]. These products include choke valves, nozzle for drill heads, flow cages, valve seats, wear sleeves, inserts and mechanical seal rings.

Figure 3.3's aerospace and defence industry refers to the use of hardmetal in aircraft and the manufacturing of military armaments [95], [100]. In aircraft, hardmetals are used in surface enhancement coatings of aircraft parts to increase life expectancy. As hardmetals have a high density, it is generally used as counterweights by aerospace designers to reduce vibration and balance components, such as rudders, ailerons and rotor blades [101]. In the defence industry, hardmetals are mainly used in dies and cutting tools to machine high-speed steels. Hardmetals are also used in, among others, armour-piercing ammunition, shrapnel heads and bullet-proof vehicle [100].

Mining and construction is the fourth largest application industry in the global hardmetal market [95]. Large mines use rotary drills to drill holes with diameters ranging between 15 to 45 cm. The drill bits are typically made of three cones containing hardmetal cutting edges [93]. Hardmetals are also extensively used to manufacture mining and machinery components such as drilling tools, cutting tools, inserts, nozzles, rods, buttons and sheets [96], [100].

3.1.4. Hardmetal manufacturing technologies

Traditionally hardmetal products are manufactured by powder metallurgy processes [102]. The process involves different complex stages such as raw powder processing, mixing and milling of powders, spray drying to prepare the powders for pressing, pressing, moulding to the required shape, dewaxing, pre- sintering, sintering, post-sintering treatment and finishing operations such as grinding and blasting (Figure 3.4) [93], [103]. During each stage of the manufacturing process, the process parameters are carefully controlled as a change in a stage would influence the subsequent stages and the quality of the final product [93]. The sintering stage is particularly critical as it is influenced by several variables, such as temperature, time, pressure, and the rate of heating and cooling, which may alter the mechanical properties and microstructure of the final product [102], [103]. As a result, it was previously assumed that it was either impossible to manufacture hardmetal parts with the AM technology or that the components could not meet the rigorous quality and functional requirements [103]. The powder metallurgy processes are also time- and cost-intensive, challenging for prototyping and small-batch size requirements and subjected to significant design restrictions [93]. However, due to recent advancements, researchers have found complementary processes, namely AM techniques, to manufacture hardmetal parts with properties close to their conventional counterparts. The technique also provides exceptional benefits in manufacturing complex, lightweight parts with reduced manufacturing lead times [93], [102], [103].

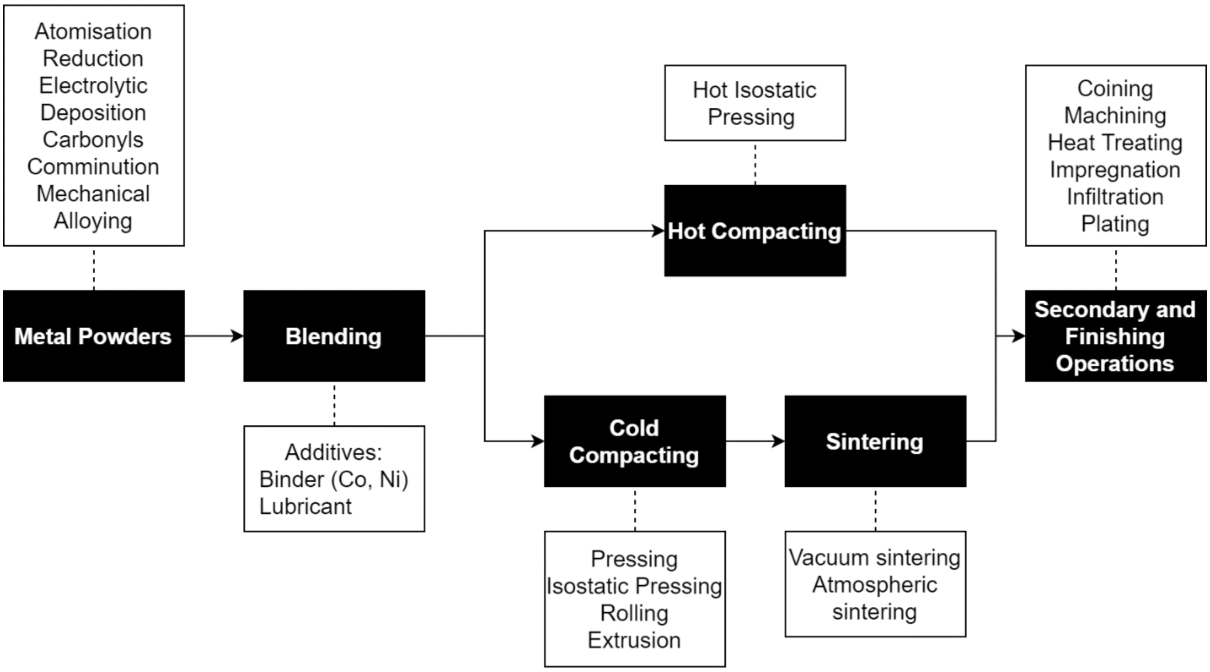


Figure 3.4: Traditional manufacturing process of cemented carbides [106], [422]

As mentioned in §1.2, additive Manufacturing (AM) can also be used to manufacture products from metal powders such as tungsten carbide. The three AM techniques that are most prevalent in AM literature for the manufacturing of hardmetal parts are Selective Laser Melting (SLM), Selective Laser Sintering (SLS), and Binder Jet 3D printing (BJ3DP) [104], [105]. The SLM and SLS techniques are classified as part of the Powder Bed Fusion technique, and when it comes to the AM of hardmetal parts, SLM and SLS are fundamentally very similar [104]. All three manufacturing processes are initialised with the digital design of the three-dimensional part mathematically divided into thin layers [106].

The SLM and SLS processes have two pistons, the build platform piston and the powder delivery piston, encapsulated in a chamber of inert gas [106]. To manufacture the first layer of the part, the powder delivery platform is raised to a predefined distance, and its recoating roller deposits the powder mixture onto the build platform, as seen in Figure 3.5. By tracing the 3D CAD model, the SLM process uses a higher intensity laser to melt and solidify the newly deposited powder [105]. Once the first layer is built, the build platform moves down to a predefined distance for the next layer of powder to be deposited. The process continues until all layers of the part have been solidified together, and the final part is built [103]. The SLS process

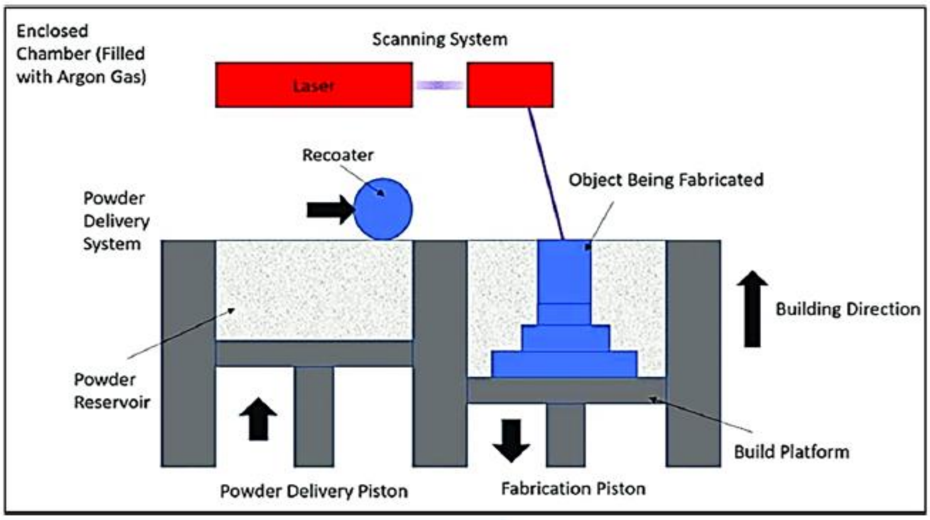


Figure 3.5: Schematic diagram of the SLM process [103]

differs from SLM as the SLS process uses a comparatively lower laser intensity to fuse the powder particles together on a molecular level [103].

The BJ3DP technique also involves a build platform piston, a powder delivery piston that moves to predefined distances, and a recoating roller to deposit the powder. It, however, differs from the SLM and SLS processes as a liquid binding agent is used to join the powder particles instead of a heat source such as a laser [104], [106], [107].

3.1.5. Cemented tungsten carbide in South Africa

Approximately 88% of the world's tungsten supply is found in only eight countries [11], [85]. South Africa does not fall within the top eight countries, so its tungsten deposits are seen as insignificant [85]. In the late 1980s, the mining industry's demand for hardmetals products drove the initiative to import the powders required to produce hardmetal products locally [3]. During this period, Boart International Springs Centre was established to produce hardmetals and grew to be the largest hardmetal producer in the southern hemisphere in the 1990s [11], [85]. Today, South Africa has several companies manufacturing hardmetal products, such as EngNet, Umico SA, Pilot Tools and Navarro SA. At least one local manufacturing company also recycles hardmetal scrap and produces powders to manufacture new parts [85], [108].

In 2002 and 2003, the South African government developed the National Research and Development Strategy [4] and the Integrated Manufacturing Strategy [5] in conjunction with the Department of Science and Technology and the Department of Trade and Industry, respectively [6]. These strategies focused on developing capabilities to master various advanced manufacturing domains, develop human resources for the sector, and facilitate innovation [6]. These strategies led to the development of the DSI-NRF Centre of Excellence in Strong Materials in 2004 and the Advanced Materials Initiative in 2005 [8]. The DSI-NRF Centre of Excellence in Strong Materials, CoE-SM, hosted by the University of the Witwatersrand, was explicitly developed to support strong material research and the collaboration between researchers across disciplines and institutions [8] and to "*diffuse the knowledge to where it is needed*" [7], [109], [110]. The CoE-SM has six research focus areas. The Carbides and Cermets (CACE) focus area conducts extensive hardmetals research focussing "on the design and development of new tools and coatings, improving production processes, recycling of scrap metal, and exploring new manufacturing technologies. Tribology and corrosion are critically investigated" [111]. The CACE research is undertaken by academics and students at Stellenbosch University and the University of the Witwatersrand, often collaborating with local and international institutes on specific themes.

A large body of knowledge exists on the traditional manufacturing techniques of hardmetals, and a body of knowledge is quickly being established on the additive manufacturing of hardmetals. However, most publications have focused on the manufacturing technologies and material properties, not on the dynamics and mechanisms involved in developing the hardmetals industry, nor how these dynamics are influenced by novel technologies [42], [43]. A research opportunity thus exists in the current hardmetals body of knowledge to explore research in this area.

3.2. Industry 4.0 technologies and additive manufacturing

Additive manufacturing is a fundamental building block of Industry 4.0 technologies (Figure 3.6) [112], [113]. The fourth industrial revolution, Industry 4.0, comprises the automation and digitisation of industry and all business-related processes [113]. As with every industrial revolution, Industry 4.0 has revolutionised how products are manufactured, improved and distributed [1], [112]. Moreover, it has made utilising modern manufacturing skills in integrating novel information technologies crucial to economic competitiveness. Furthermore, Industry 4.0 enables virtual and physical systems to cooperate (profitably), enabling the operations of smart factories and the redefining roles of humans within industries such as manufacturing [112]. As presented in Figure 3.6, physical systems refer to additive manufacturing, autonomous robots, and wearables, while the cyber environment includes the internet of things, big data, and cloud computing [112], [114].

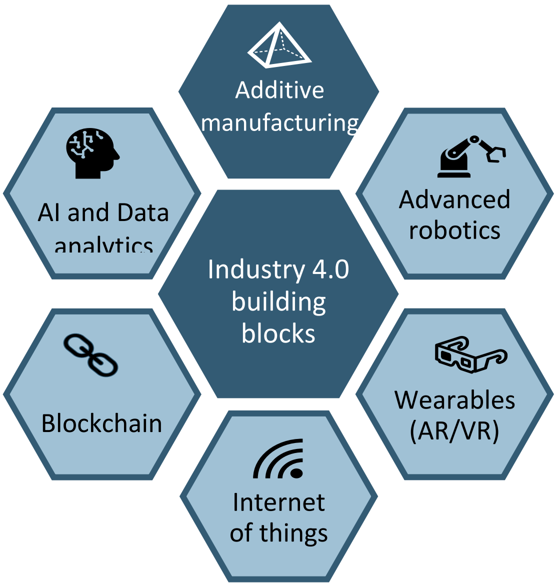


Figure 3.6: Technology trends that form the Industry 4.0 building blocks [114]

Cyber technologies support the effective utilisation of existing information for smart manufacturing [112], [115]. The Internet of things (IoT) is referred to in literature as a network of physical objects such as computer networks, accelerated wireless connections, and mechanical and digital machines embedded with sensors and software to collect and exchange data with other devices and systems through the internet [115]. Furthermore, big data is described as the analysis, process and collection of enormous data volumes growing exponentially with time. The volume and complexity of the collected data sets render big data too complex for traditional data management tools to process or store efficiently [112]. Additionally, cloud computing is described as the delivery of computing services such as databases, networks, storage, software, and analytics via the internet to offer faster innovation, flexible resources, and economies of scale [114].

The use and implementation of additive manufacturing, combined with Industry 4.0's cyber technologies, is producing an evolution in the manufacturing industry towards intelligent production where autonomous, automatic and intelligent systems, machines and networks can exchange information and respond to production management systems [113], [114]. Additionally, additive manufacturing enables the manufacturing of products with limited human intervention, eliminates the need for expensive tools and fixtures, and reduces post-processing and material waste [46], [47]. The technology has therefore been labelled to be fundamental to the manufacturing industry of the future [113], [115], [116]. Furthermore, as material waste is reduced, additive manufacturing technologies support the global movement towards sustainable manufacturing processes with less consumption of resources and generation of waste (part of Sustainable Development Goal 9) [3], [113], [117].

3.3. Additive manufacturing

Similar to the communication, imaging, engineering and architecture industries that have all made the technological advancements to transition from analogue to digital processes, additive manufacturing can bring digital flexibility to the manufacturing industry [115]. Additive manufacturing (AM) is the use of computer-aided design or 3D object scanners to direct hardware to manufacture objects layer upon layer (Figure 3.7). It differs thus from traditional or subtractive manufacturing processes, which often cut and drill away excess material from a solid piece of material [116].

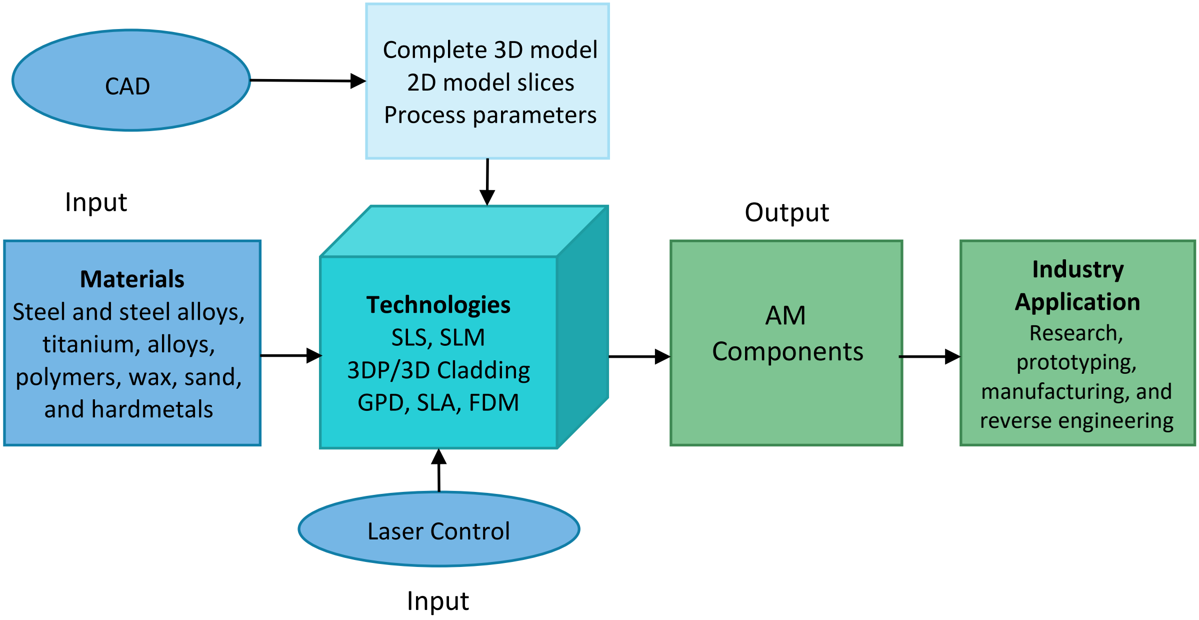


Figure 3.7: The inputs and outputs associated with a general AM process [106]

3.3.1. Additive manufacturing technologies

Although AM only recently became a widely discussed technology topic, the development of AM technology started in 1987 as a rapid prototyping technology when Charles Hull patented Stereolithography and commercialised the first rapid prototyping system [118], [119]. Since then, AM technologies and materials have grown significantly. Today, objects can be additively manufactured from metals, ceramics, plastic, paper, glass and organic materials [118]. The seven AM technologies are listed in Table 3.1, based on the work of De Beer *et al.* [118], General Electronic [105] and Loughborough University [120], along with the materials used in each process.

Table 3.1: Additive manufacturing technologies [118]

Technology	Technology description	Material
Binder Jetting	Binder jetting requires a powder-based material and a binding agent. During the printing process, a liquid binder is selectively deposited onto a thin layer of the powder-based material to join the powder materials.	• Foundry sand • Gypsum • Metals • Polymers
Directed Energy Deposition	Thermal energy is used to melt materials as they are being deposited.	• Metals
Material Extrusion	Material is selectively drawn through a nozzle, where it is heated and then deposited.	• Polymers
Material Jetting	Material jetting works similar to 2D inkjet printers as material droplets are selectivity deposited onto a build platform.	• Polymers • Waxes
Powder Bed Fusion	Thermal energy is used to melt identified regions of a powder bed together. Upon the conclusion of the object, the excess powder can be reused.	• Metals • Polymers
Sheet Lamination	Sheets or strips of material are bound together using an adhesive (for paper) or ultrasonic welding (for metal).	• Metals • Paper
Vat Polymerisation	Ultraviolet light is used to construct an object out of a vat of liquid photopolymer as it selectively hardens the required risen.	• Polymers

All these technologies offer several benefits over traditional manufacturing and have therefore been described as a transformative manufacturing technology.

3.3.2. Additive as a transformative manufacturing technology

The Cambridge English Dictionary defines transformative as *"causing a major change to something or someone, especially in a way that makes it or them better"* [121]. Furthermore, Anvl's CEO Robin Fleming describes an innovative transformation as *"… transformational innovation is changes that shift the entire system into a new framework, that is created to be viable for the future"* [122].

Several authors have described AM as a transformative or disruptive and enabling manufacturing technology [118], [123]–[127]. For example, Tim Shinbara, Vice President of Technology for the Association of Manufacturing Technology, described AM as a transformative technology as it changes a part's manufacturing process and how it is designed. *"Using additive fundamentally changes how you design a part. Additive manufacturing design is not about what shapes are possible to manufacture, but about what is the best possible shape the part could be. Parts that were once machined as solid, straight-edged pieces bracketed together can be printed as a single piece with complex geometries that can reduce weight without losing strength"* [125].

Additive manufacturing has led to the emergence of new business ventures, business strategies and production relocations and led to the possibility of established businesses failing as the number of actors in supply chains was severely reduced [11], [116], [123], [128]. Swaddle [127] described AM as "*the ability to design something in the morning and have a physical representation of the concept in your hand in the afternoon, and that is a priceless step forward in product design*." Khan and Yoga [126] illustrated this in Figure 3.9a and Figure 3.9b by denoting how products are made and delivered to end-users in traditional manufacturing systems and how the system can be simplified by implementing AM technology.

Swaddle [127] and especially Khan and Yoga [126] may seem too ambitious given the technology's current availability and abilities. Given the speedy advancements already made for this technology and the advantages the technology offers, however, Swaddle [127] and Khan and Yoga's [126] predictions may prove to be correct in the near future.

An example includes the Fast Radius Virtual Warehouse [129]. To streamline the power tools producer Husqvarna Group's spare parts supply chain and reduce its carbon footprint, Fast Radius transformed the production of its spare parts into an additive manufacturing solution. As a result, the virtual warehouse enabled the Husqvarna Group to eliminate inventory costs and reduce material waste as spare parts may now be additively manufactured on-demand [129]. Similarly, the US navy has issued six new AM contracts to additively manufacture spare parts on submarines to ease the burden on their strained industrial base [130]. Additionally, the US navy has incorporated 3D Printing training courses at the United States Naval Academy to train the next generation of naval engineers on how to print parts on demand [131].

To enhance and harness the transformative potential of additive manufacturing, studies by the University of Liverpool and Meta Additive Ltd suggest that additive manufacturing technology developers develop the following [132]:

- Broaden the pallet of starting materials and accelerate the transition of innovative materials from research laboratories into additive manufacturing factories.
- Develop industrial-grade additive manufacturing equipment with multi-tool heads so that a range of innovative materials can be directly printed in one build operation.

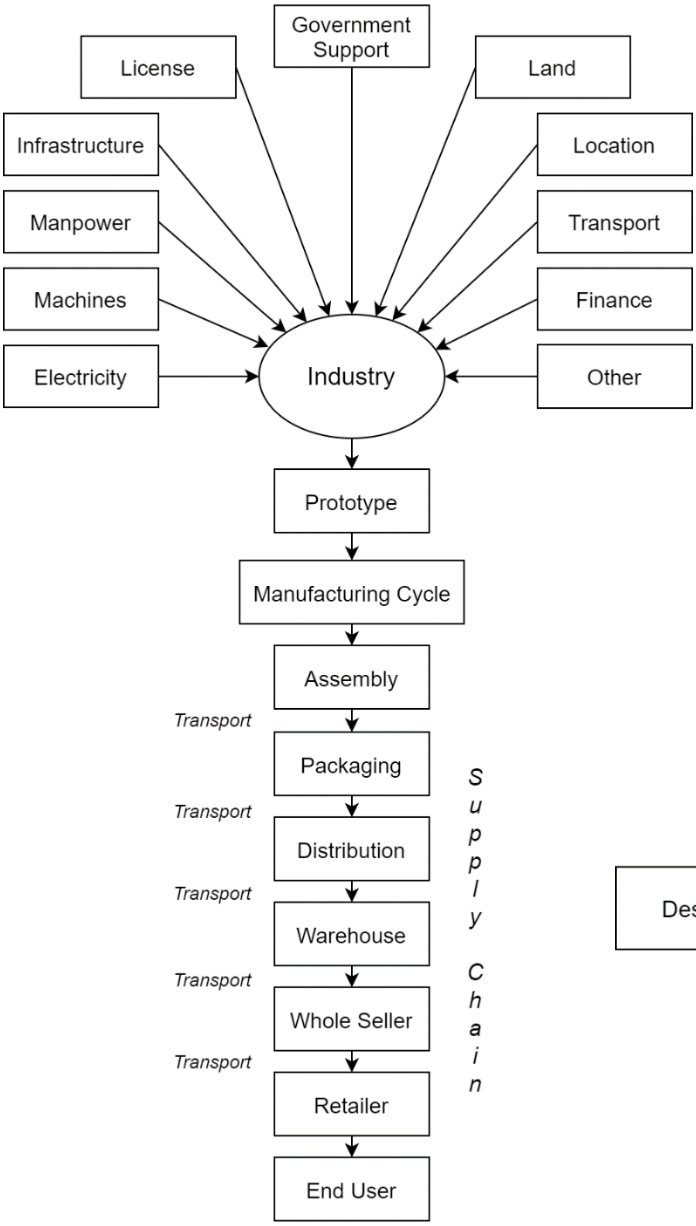


Figure 3.9a: Traditional manufacturing systems [126]

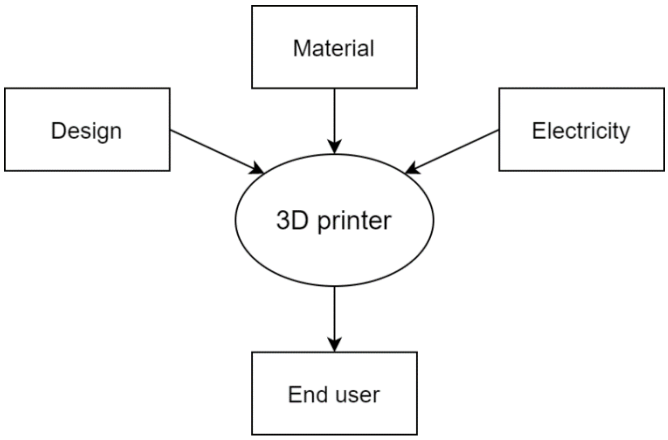


Figure 3.9b: Possible AM manufacturing systems [126]

- Create complex 3D structures with embedded smart functionality, such as direct printing of novel materials for integrated electronic components.
- Monitor processes in-situ to enable investigation and better control of additive manufacturing processes.
- Develop support systems, such as software and machine learning platforms, to enable the printing of multi-materials and facilitate additive manufacturing's true potential.

Furthermore, AM offers several advantages to product designers and consumers that traditional manufacturing methods are unable to offer. In terms of design, AM has enabled the materialisation of part consolidation, intricate designs and primarily designs with complex internal structures for which traditional machining cannot be used [118]. In contrast to traditional machining, AM has also minimised design complexity costs [123]. The technology has also stimulated an increase in engineering design, skills development and customer empowerment as mass customisation can be achieved [123]. In terms of competitiveness, AM has enabled small companies to compete with large companies by using 3D printers to design and manufacture products in-house. The need for long, costly supply chains of manufacturers, distributors, warehousing and retailers, which increase production costs and time-to-market, is thus reduced [119], [123], [133].

In addition, the need for warehouses is reduced as products can be printed on-demand, leading to supply and demand becoming almost perfectly aligned. In terms of the global economy, as AM enables products to be manufactured close to the point of consumption, importing countries will be less reliant on imported goods as they will be able to manufacture their products. This should, in turn, also help reduce global economic imbalance [123].

However, reducing the global economic imbalance and reducing export levels from exporting countries, such as China, could lead to a substantial shift in the global economy [123]. Another adverse effect of AM could be an increase in the implementation of AM technologies, and thus a reduced need for subtractive machining technologies could lead to a reduced need for skilled artisans [133]. Furthermore, it could lead to an increased need for skilled operators, which many developing countries currently do not have [126].

3.3.3. Additive manufacturing in South Africa

South Africa's investment in AM technology started in the early 1990s when the first three rapid prototyping machines were imported by 3D Systems (Pty) Ltd and the Council for Scientific and Industrial Research (CSIR) [118], [134]. The initial adoption of AM was relatively slow until the inception of the RAPDASA in 2000 [118]. The Rapid Product Development Association of South Africa (RAPDASA) is a voluntary association [124] that was established to represent the rapid product development community in South Africa and to encourage the adoption and further development of AM technologies [135]. Through its annual international conference, RAPDASA has provided the government, academic researchers and industry partners an opportunity to connect and collaborate and give them a platform to share ideas [136]. Its international participation has consistently exposed South Africa to the expertise of the international AM world [135].

In 2011 the Aeroswift project was initiated and funded by the South African Department of Science and Innovation (DSI) when limitations were identified in the available 3D metal printers. An opportunity was identified to advance South Africa's global competitiveness. As part of the Aeroswift project, the CSIR and the aeronautical engineering and manufacturing company, Aerosud Innovation Centre, developed an advanced 3D printer for metal components [137], the largest 3D printer in the world [138]. The project focused specifically on titanium material to produce products for the commercial aerospace sector. Since its launch in 2011, the project printed a pilot's throttle lever, condition lever grip and fuel tank pylon bracket [137], [138].

In 2013 the South African Additive Manufacturing Technology Roadmap was developed by the DSI in response to requests from RAPDASA. The roadmap aimed to enable South African companies to become global industry leaders by identifying the market, research and technology development opportunities and guiding development programmes and investment decisions [124], [138]. An initiative established due to the AM technology roadmap is the Titanium Centre of Competence (TiCoC) [138]. The TiCoC, initiated by the DSI, CSIR and the Higher Education Institution as part of the Advanced Metals Initiative, focussed on AM as a manufacturing technology for titanium products [124]. In 2016, the Department of Science and Technology developed the Additive Manufacturing Strategy for South Africa to identify market and technology development opportunities to ensure South Africa's position as a competitor in the international manufacturing market [118]. The strategy identified the aerospace and military, medical and dental, tooling, casting and automotive industry as the prioritised industries for 2014 to 2023 and defined programmes to guide the adoption and increase investment in AM technologies by the public and private sectors of South Africa [118].

South Africa thus has several initiatives supporting both the adoption and the development of AM technologies, which have been described as transformative with the possibility of significantly impacting the world as it continues to mature. Garrett [123], therefore, highlighted that policies are required to facilitate and guide the maturity of AM technology to ensure that it is beneficial to everyone and that the misuse of this technology, and the consequences thereof, are mitigated. Therefore, a scoping review was conducted by McClelland, Grobbelaar and Sacks [41] was conducted to identify available literature on AM policies and the AM literature landscape. The review revealed that no AM literature was explicitly focused on the Latin America, South Asia, the Middle East or North African context and that only 3% of the papers focused on Sub-Saharan Africa [41], [139]. The review also highlighted that the AM policies and the AM literature landscape had not yet been studied through the innovation system and responsible research and innovation perspectives but through the transition theory, digital information, ecosystem, value chain and pedagogy approaches [41], [140]–[143]. Furthermore, the review noted that no studies focused on decision-support frameworks for specific materials using AM technology [41]. Therefore, a research opportunity exists in the AM literature for applying the innovation system framework to the South African AM industry and AM as an additional technology for the hardmetals industry.

3.4. Chapter 3: Summary

The focus of this chapter was cemented tungsten carbide and additive manufacturing. It aimed to present the reader with a contextual understanding of hardmetal and AM as this study studies cases on AM for hardmetals. The chapter started with the properties of hardmetal, its application industries, and its current manufacturing technologies. Thereafter, the hardmetal sector of South Africa was studied. Thereafter the focus of the chapter moved to additive manufacturing. The available AM technologies and their benefits were also discussed, followed by a discussion of the South African additive manufacturing industry. This chapter contributes to objective 1, as mentioned in §1.4.

Chapter 4

Literature review: Industry development

In the previous chapter, this study's application industry and materials were introduced, namely additive manufacturing and cemented tungsten carbide or hardmetal. This chapter provides a literature review on innovation, industry and technology development and frameworks that have previously been utilised to study them. The framework utilised in this study is also identified. This chapter contributes to objective 1, as mentioned in §1.4.

Chapter 4 objectives:

- Reflect on the concept of innovation (§4.1).
- Reflect on the four fundamental theories explaining innovation and change processes (4.2.2)
- Investigate industry development dynamics and phases (§4.2.3).
- Investigate technology development dynamics and phases (4.2.4).
- Reflect on the concept of the valley of death (4.2.5).
- Identify the barriers and enablers of advanced manufacturing technology adoption (§4.3).
- Explore realist evaluation and the CIMO-logic framework (§4.44.4.1).
- Investigate analysis approaches that has been developed to study industry development (§4.4.2).
- Select the analysis approaches utilised in this study (§4.4.2.5).

This chapter starts with a reflection on the concept of innovation and relevant topics in industry development literature. These include process theories and life cycle frameworks. Thereafter, barriers and enablers of advanced manufacturing technology adoption are explored. Section 4.4 reflects on the possible methods and framework through which industry and technology development may be studied and analysed. Thereafter the chapter concludes with the selection of the framework utilised in this study. Chapter 5 will explore the framework in detail.

4.1. The concept of innovation

Innovation is said to play a crucial role in economic development as it leads to technological transformations [144] and large-scale employment opportunities, and job creation [28], [145]. How innovation is understood influences the way it is managed [146].

The literature on innovation is said to draw inspiration from the work of Schumpeter [147]. In the 1930s, Joseph Schumpeter, a prophet of innovation, defined innovation as the economic impact of technological change and the use of new combinations of existing productive products and processes to solve problems. He believed that five types or categories of innovation exist: (a) a product or a qualitative change in an existing product, (b) a new production method, (c) a new market, (d) a new source for raw materials supply, and (e) the establishment of new organisations in an industry or market [147], [148].

In contrast to Schumpeter, Afuah [81] classifies innovations according to technological, market, and administrative or organisational characteristics. These administrative or organisational characteristics involve innovations that pertain to strategies, structure, systems, or people in an organisation [81]. Afuah defines innovation as "*the use of a new knowledge (technological or market) incorporated in products, processes, and services to offer new products or services that customers want*" [81, p.4]. From Afuah's innovation definition and classification, he thus defines innovation from a firm's perspective, while Schumpeter provided a more general perspective.

Twiss and Goodridge [79] include the concept of commercialisation and define innovation as "*a process that combines science, technology, economics and management, as it is to achieve novelty and extends from the emergence of the idea to its commercialisation in the form of production, exchange, and consumption*" [79, p.2].

Similar to Twiss and Goodridge's [79] concept of commercialisation, the Oslo Manual [78], composed by the Organisation for Economic Co-operation and Development (OECD), adopts the concept of implementation in their definition. Additionally, they define innovation from a firm's perspective, similar to Afuah [81]. The Oslo Manual defines innovation as "*the implementation of a new or significantly improved product (goods or services), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations*" [78, 17].

Finally, according to the Business Council of Australia, *"…in business, innovation is something that is new or significantly improved, done by an enterprise to create added value either directly for the enterprise or indirectly for its customers"* [82, p.3]. Similarly, in a management report by Deloitte Australia, innovation is defined as "*the activity of creating and capturing value from doing something new*" [83, p.4].

The concept of *innovation* is said to be rather complex and multifaceted [148]. Consequently, the Oslo Manual [148] and Rogers [153] argue that a generally accepted definition of innovation does not exist in scientific literature. Although these definitions of innovation differ slightly and different classifications of innovation are identified, the authors agree on two aspects of innovation. First, the authors agree that innovation comprises the concept of *novelty,* as they all define innovation as developing something new. This may comprise the use of new entities (for example, new products or processes) or existing entities in a novel manner. Secondly, the authors agree on the concept of *commercialisation or implementation*, indicating that for an entity or idea to be classified as an innovation, it should be released into the market and be useable or implementable. Interventions that are not commercialised may thus not be classified as an innovation.

Finally, in addition to the concepts of novelty and implementation, the Business Council of Australia and the management report by Deloitte Australia include the concept of *value* in their definition of innovation. These authors define innovation as something that adds value, indicating that from an enterprise's perspective, innovations are aimed to add value to its end-user or environment.

Therefore, this study adopts the view that innovation comprises the concepts of novelty, commercialisation or implementation and value creation. For simplicity, the Oslo Manual's [78] definition of innovation is adopted.

Innovation is "*the implementation of a new or significantly improved product (goods or services), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations*" [78, 17].

4.2. Relevant concepts in industry development literature

A primary focus of this study is to support the hardmetal industry to develop and adopt novel manufacturing technologies. Therefore, the literature on industry development and technology adoption may be explored to gain insight into an industry's development and how technology is adopted. According to McGahan [154] and Christensen [155], the development of actor capabilities within an industry is best understood if the specific industry's development is understood. Furthermore, if an industry's nature of change is understood, the how and why of actor capability changes are better understood [154].

4.2.1. Trajectories of industry evolution

The literature on industry evolution presents four distinct change trajectories - radical, intermediating, creative and progressive [154]. *Radical change* has been found to occur when an industry's core activities and assets are threatened with obsolescence [156]. It occurs when an external artefact significantly reduces the relevance of an industry's capabilities and resources, attacks the buyer-supplier relationships and sends some industry companies into crisis [154]. According to McGahan [154] and Christensen [155], an example of such an artefact is the mass introduction of novel technology. Industries experiencing radical change are usually transformed entirely. Radical change does not, however, always occur instantaneously but can take decades [155].

Intermediating change occurs within an industry when the buyers and suppliers gain access to new information and obtain new opportunities [154]. As a result, the core activities within an industry are threatened, while the core assets, such as knowledge, patents, capital, and equipment, remain valuable but must be used differently. An example of an industry on an intermediating change trajectory is the traditional auto sales industry. Not only can auto sales now occur over the internet, but car manufacturers are seeking closer and, in some cases, direct contact with customers [155].

Creative change has been found to occur within an industry when its core activities remain stable, but the core assets are threatened. The companies within such an industry must continuously find new ways to restore their existing assets while customer-supplier relationships must be protected [154]. The pharmaceutical industry is on a creative change trajectory. Companies within the pharmaceutical industry are continuously researching, developing, and testing new medication, which, if proven successful, their administration and marketing departments then commercialise.

Progressive change occurs when incremental innovations occur [156], [157]. Progressive change is similar to creative change, but the industry's assets are not threatened with obsolescence. Therefore, industries on progressive change trajectories tend to be more stable [155]. Christensen and Rosenbloom [156] describe progressive change trajectories as `sustainable' as the progress in an industry, such as new technology development, fits into its existing business framework. The core industry assets are also said to appreciate and not depreciate over time [155]. The commercial airline industry is said to be evolving progressively.

In § 3.3.2, additive manufacturing (AM) was described as a transformative technology that radically changed global manufacturing. For the global hardmetal industry, however, AM is an alternative manufacturing process to the traditional manufacturing processes [158]–[160], as mentioned in §3.3. As the global hardmetal is experiencing incremental manufacturing innovations that do not cause the traditional manufacturing processes to become obsolete, it seems fitting to say that the global tungsten carbide industry is thus on a progressive change trajectory.

4.2.2. Process theories

Explaining how and why industries and organisations change and develop has been a leading and enduring quest of scholars in management and many other disciplines [161]. The sequences of events that unfold in these change trajectories have been challenging to explain and more difficult to manage. To understand these change trajectories of industries and organisations, management scholars have borrowed many concepts and theories from other disciplines, ranging from human development to evolutionary biology.

Two views of change are often used in organisation studies, *variance theory* and *process theory*. When change is studied based on a *variance theory*, change is defined as an observed difference in selected dimensions of an organisational entity over time [162]. Furthermore, change is viewed as a dependent variable resulting from variation in a set of independent variables. *Variance theory* thus seeks understanding based on the relationships between variables [163].

In *process theory*, change is defined as a narrative describing a sequence of events on how development and change unfold over time [161]. It comprises an event-driven approach and focuses on the order in which change events occur, based on a story or historical narrative, to elucidate outputs [162], [163]. *Process theory* studies thus seek an understanding of how change unfolds based on activity flows over time.

Thus, *variance theory* concerns variables and causality, while *process theory* deals with discrete states and time-based events. Furthermore, *process theories* differ from *variance theory* as they consider mechanisms leading to change over time rather than associations that exist at single points in time [162]. Additionally, the process approach addresses questions on how processes unfold over time. Due to the complexity and uncertainty that exist during the development phases of organisations and industries, innovation and management deem *process theories* more appropriate than *variance theory* to explain and understand how and why industries and organisations change and develop [161], [163]–[165].

Van de Ven and Poole [166] developed four fundamental theories explaining innovation and change processes to elucidate and explain organisational development and change. In their note-worthy paper utilised by numerous scholars in management, innovation, and many other disciplines, the four fundamental theories are teleology, dialectic, life cycle, and evolutionary, as seen in Figure 4.1.

The teleological process model describes innovation as proceeding through a cycle driven by an end goal or purpose [161]. The teleological process model comprises goal formulation, implementation, evaluation, and modification of goals. Teleology assumes that an entity, such as an organisation or industry, is purposeful and adaptive. Change occurs through social construction involving actors within the entity who seeks to attain a desired end state, such as a new product or technology [163].

Similar to teleology, the dialectic process model follows a constructed change model. However, the dialectic process relates to change involving numerous entities. In this model, change proceeds through a cycle that comprises a confrontation of different viewpoints, namely thesis and antithesis (Figure 4.1), and their subsequent synthesis. In the next cycle, the subsequent synthesis becomes the thesis [161]. The dialectic process theory's change is a balance of power between different organisational entities or viewpoints [163].

The life-cycle process theory concerns phases of organisational change prescribed, rather than constructed as in teleology and dialectic theory, by an external constraint such as a regulation [161]. Therefore, the life-cycle process theory assumes that an overarching institutional framework may define such steps. Consequently, the organisational change occurring under these circumstances is assumed to be a process of conforming adaptation [163].

The evolutionary process theory also comprises prescribed change. However, this theory assumes that the underlying mechanism of an entity comprises environmental selection. Furthermore, the evolutionary process assumes that change proceeds through a continuous cycle of variation, selection and retention that, over time, leads to an accumulation of small changes [161], [163].

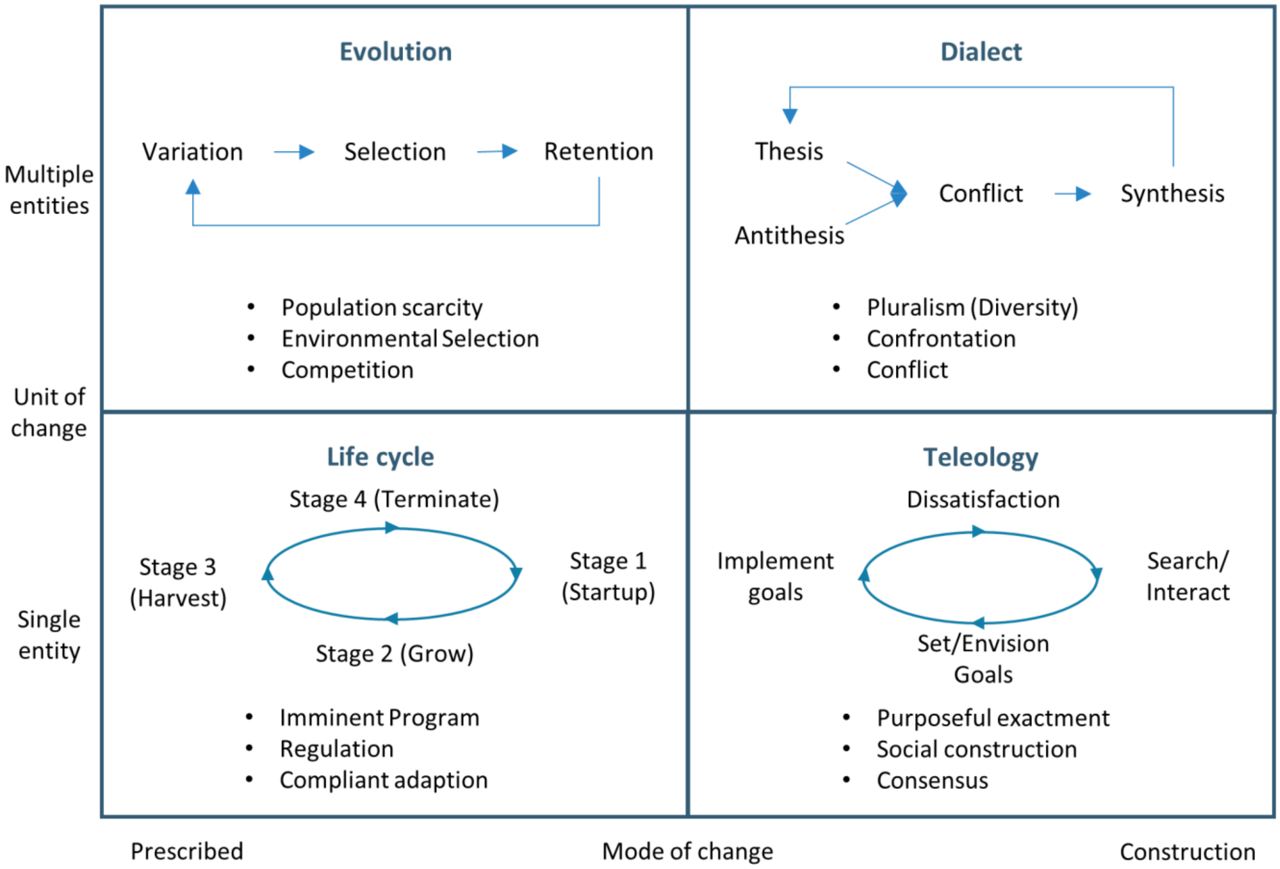


Figure 4.1: Process theories of organisational development and change [166]

The use of any theories should be carefully considered in relation to the aim of the research [161]. It is commonly accepted that combining several theories may enhance understanding of complex phenomena. The use of different theories sheds light on different aspects of a phenomenon and offers a template for extending theory and research [164]. Furthermore, as asserted by Van de Ven and Poole [162], the incompleteness of one of the four process theories of organisational development and change may be accounted for by one of the other theories. Therefore, organisational development and change theories are typically built on two or more basic theories operating at different levels or across different periods [164].

4.2.3. Industry life cycle

It is useful to refer to industry evolution literature to identify and analyse development measures for industries on a progressive change trajectory [22]. Numerous approaches have been developed to analyse industry development and evolution. A particularly useful framework, in line with Van de Ven and Poole's [166] life cycle process theory, is the industry life-cycle (ILC) framework [21], [22], [154].

The essence of the ILC framework comprises the recurring patterns found in the emergence and maturing of industries and the resulting implications for firm strategies [167], [168]. The foundation of the ILC framework is built on the evidence that many industries perform similarly as they evolve. Additionally, the dependence in which these industries develop are driven internally. For example, through the modification from product to process innovation [167], [169]. The literature on the ILC framework is closely related to the literature on the technology and product life cycle frameworks. Scholars such as Framer *et al.* [170] have described these three frameworks as being interchangeable.

The ILC framework suggests that industries typically follow five stages: development, growth, maturity, decline and shrinking [22], [169]. Figure 4.2 schematical represents the first three phases of the ILC framework and provides an overview of the general policy stance typically applied to each phase. Market development illustrated on the y-axis in Figure 4.2 indicates the market capitalisation of companies operating in the industry [21].

During the development phase of the lifecycle, industries emerge in a period of fragmentation with a few actors, ill-defined products and a high level of uncertainty [167]. Companies conduct research and development (R&D) projects, pilot-scale operations and commercial validation tests [22], [154]. These company activities are supported through policies such as R&D tax incentives (expenditure-based and income-based schemes), government-financed business R&D (which includes capital cost support for large-scale demonstration) and patent protection [171].

As awareness of the industry's products slowly increases, the industry moves into the growth period, where profitability rises and value chains form [169]. As the product features continue to improve, a high-cost gap is experienced within the industry. When complementary products become available in the market along with more features and customer benefits, product demand increases, a low-cost gap is experienced, and customer demand increases [169]. These company activities are supported through stable, technology-specific incentives (grants, loans, loan guarantees and procurement contracts) and technology-neutral incentives [22].

Over time, the industry experiences consolidation and reaches maturity. Some companies are naturally eliminated as they are unable to grow along with the industry, while others merge with competitors or are acquired by those who were able to obtain more significant market shares at the growth stage [154], [169]. Sales growth slows, and industry leaders often lock their positions [22]. Technology-neutral incentives continue in the maturity phase. As sales growth declines, policies geared towards demand stimulation are implemented [22].

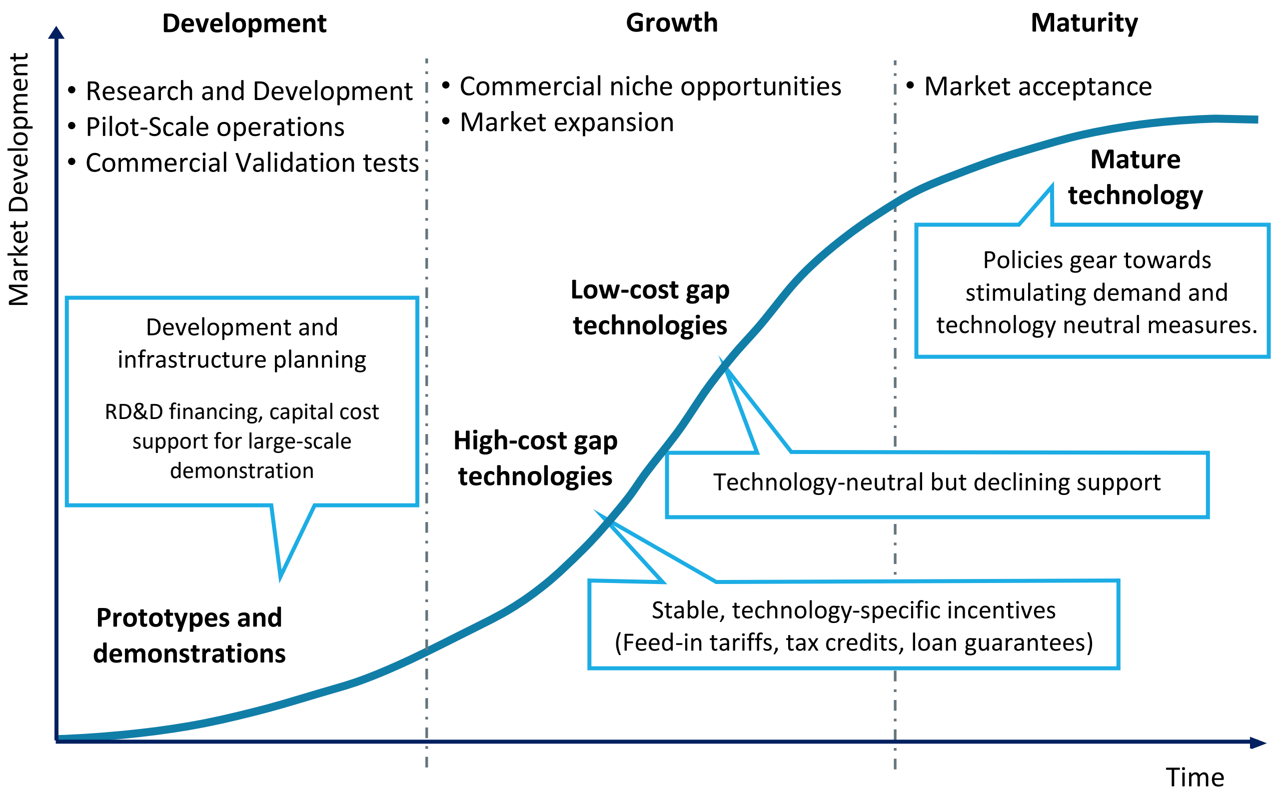


Figure 4.2: Policy focus areas based on maturity [21]

In the analysis literature of the ILC framework, scholars have focused on populations of firms competing in a market. A central explanatory element of the ILC framework is the product life cycle framework and the shift from product to process innovation. The essence of the product life cycle framework is that during the emergent phases of an industry, markets grow rapidly as numerous firms enter the market and product innovation is fundamental. As the industry evolves, output growth and the entry of firms decreases, product innovation becomes less significant, and process innovation emerges.

4.2.4. Technology life cycle

The essence of the technology life cycle (TLC) comprises the regularities in the emergence and maturing of technologies [167], [172]. The literature on the TLC highlights that technological change occurs in response to a complex interaction between political, economic, social, technical, and organisational processes [167].

The technology life cycle depicts a sequence of technological discontinuity followed by an era of ferment. In the ferment era, technology variants compete, technology performance characteristics are unclear, and uncertainty is high [167]. Following the ferment era is the emergence of a dominant design. When a dominant design emerges, both the technological variation and uncertainty decrease. Finally, an era of incremental change occurs. During this phase, key challenges are identified, and performance characteristics are resolved [167].

In TLC literature, scholars focus on firms' technology and strategic actions towards the development of a studied technological field. In this regard, primary analysis indicators include technological performance, technological variation, and innovation magnitude. Dominant designs and technology standards are primary pillars of the TLC framework, and both may be analysed at different levels of aggregation [167]. In addition, S-curves for technology diffusion or performance improvement and the wave model of product and process innovation are additional core elements of the TLC framework [167], [172].

Similar to the ILC, the literature on the TLC is theoretically based on evolutionary theory. However, in contrast to the ILC's primary focus on the competition of firms, TLC scholars focus on a broader range of actors and strategies directed towards establishing a dominant design. Furthermore, although technology standards and dominant designs are central in TLC studies, TLC scholars tend to neglect general institutional dynamics or the effects of different institutional environments [173].

4.2.5. The valley of death

For society to benefit from novel technologies such as AM, the research studies on these technologies must be translated into useful and innovative products, processes and services that are diffused and integrated into industry and the economy [18], [19]. Within the transformation, a discrete segment, referred to as *the front end of product innovation* [174], exists between research (proof of concept) and product development (initial adoption of the product within the industry) and commercialisation [19]. In technology development literature, *the front end of product innovation* segment is known to be rife with roadblocks [18], [20]. The metaphor of the '*Valley of Death*' is used to describe these roadblocks to be the relative lack of resources and expertise in this area of development [18]–[20], [141], [163], [174]. The '*Valley of Death*' (VoD), therefore, suggests that there are relatively more resources on either side of the valley in the form of research expertise and resources, and commercialisation expertise and resources [18], [20], [141], [163], [174], [175], as schematically presented in Figure 4.3.

To date, literature on the innovation processes within the VoD has not reached a consensus on why this phase is difficult to cross [163], [174]. Traditional literature on the VoD ascribed it to a lack of financial

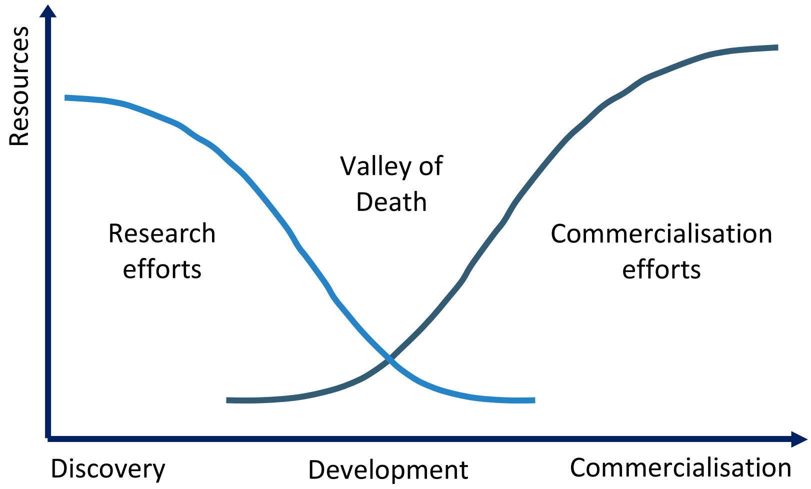


Figure 4.3: Schematic representation of the Valley of Death

support, specifically government financial support [20], [175]. The literature motivated the governmental financial support was too focused on fundamental research and early-stage development (light blue peak, *cf.* Figure 4.3), which resulted in an ineffective distribution of funding throughout the development lifecycle [20], [175]. Therefore, traditional literature suggests that overinvestment in fundamental research leads to inflated scientific output, which does not necessarily correlate with industry needs and resources, thus creating a VoD [20], [175]. Therefore, the governmental support of early-stage research studies does not have the impact on economic growth and competitiveness that it might otherwise have, and many welfare-enhancing discoveries perish in the Valley of Death [18], [20].

The VoD literature that has emerged in recent years has recognised that the VoD is not only ascribed to a lack of funding, but the uncertainty and risk related to investment in untested, unproven or unknown technologies have also been recognised [19], [163]. The risks associated with the novel technologies include addressing the technology challenges, scaling the technology from laboratory to industrial scale, stimulating a market pull for a product and establishing a supply chain to support the manufacturing of products [19].

Since the new understanding of the nature of the innovation process emerged and emphasis was placed on its systemic and interactive character, innovation was seen as an evolutionary, nonlinear and interactive process that required strong collaboration between academia, industry and the government [20], [163], [174], [175]. Therefore, to bridge the VoD of the ineffective distribution of funding and uncertainty relating to especially new manufacturing technologies, the VoD authors encouraged research collaborations between academia and industry [20], [163], [175]. Thus, university-industry knowledge transfer, university entrepreneurship, and the triple helix collaboration model were encouraged to ensure that funding distribution and knowledge transfers are secured and industry-focused research studies are conducted [107]–[111]. It was argued that it would also reduce the uncertainties related to industry investment [18]–[20], [174], [175].

Alternatively, fundamental research at company level is also strongly encouraged [20], [175]. Furthermore, to address the risks associated with technology insertion, a significant body of literature has also been developed on technology readiness levels and the management of technology insertion risks [19]. However, the approaches found in the literature are primarily focused on the management of risk during active project activity and not as well on the risk associated with generic market failure or the development of foundational capability for general use [176]–[179].

Following the literature on the triple helix model, innovation and management scholars increasingly also acknowledge actors beyond the academic-industry-government triple helix [180]. Scholars increasingly recognised the importance of society in co-developing knowledge and innovation and translating technical inventions to social innovations [181]. As seen in Figure 4.5, the quadruple helix includes a societal helix – referring to users and consumers (demand-side actors) and non-profit organisations representing citizens and workers - in addition to the traditional triple helix [181]. Therefore, innovation and management scholars have argued that for inventions to be transformed into innovations and bridge the VoD, research trajectories should be legitimised among relevant societal members, aimed to benefit society and be defined with societies' help [182]. The prospects include that involving societal stakeholders will support the re-alignment of research and development trajectories leading to more welcome, sustainable solutions. The quadruple helix has gained popularity to the extent that it has been placed at the forefront of European innovation policies to strengthen research, technological developments and innovation [181].

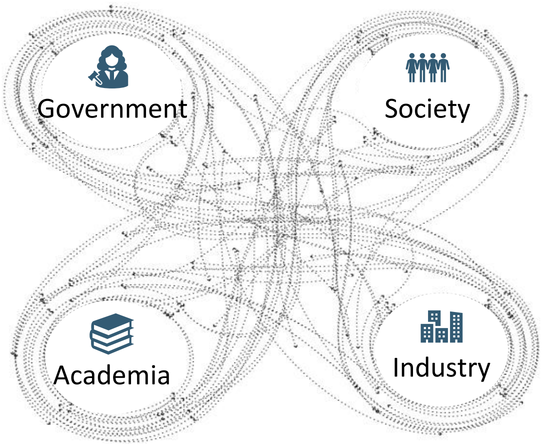


Figure 4.4: Top view of the Quadruple Helix [182]

A quintuple helix also exists. This model includes the natural environment of society [180]. The quintuple helix is, however, less popular than the quadruple helix in empirical studies, as scholars find it extremely challenging to connect the environmental helix to the existing four helices.

The metaphor of the VoD is relevant to this study as the AM technology for the hardmetal industry is still globally being developed and perfected. Consequently, in South Africa, the technology still needs to be scaled from laboratories to industrial scale and thus pass through the VoD to implementation and commercialisation in South Africa. The suggestions mentioned by the VoD authors, such as the triple helix model, will therefore be kept in mind during the continuation of the study.

4.3. Advanced manufacturing technology adoption

The literature on advanced manufacturing technologies (AMT) and technology adoption may be explored to determine the barriers and enablers of advanced manufacturing technologies, such as AM, through the phases of development, particularly in the Valley of Death. Several authors have considered the adoption stages of AM Technologies. Chaudhuri *et al.* [183] adopted three stages, namely pre-adoption (decision phase), adoption (actual installation) and post-adoption (further adaptations). Efstathiades et al. [184] adopt a phase for implementation planning after the decision to adopt AMT and an implementation stage comprising selection, pre-implementation, and transfer activities. Machuca *et al.* [185] also adopt two stages: adoption and implementation. MacDougall and Pike [186] and Chen and Small [187] adopted Voss's [188] three-stage framework of pre-installation, installation and commissioning, and post-commissioning. From these frameworks, Stornelli *et al.* [189] formulated a three-stage model of AMT adoption during the VoD, presented in Figure 4.5.

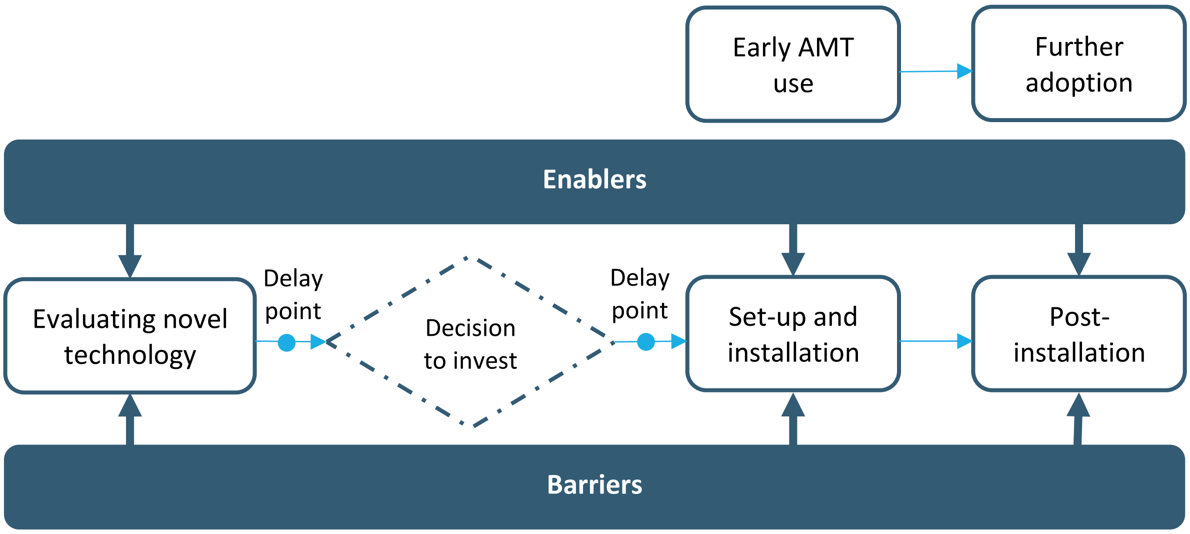


Figure 4.5: Phases of adoption during the VoD [183]–[187], [189]

The framework starts with an *evaluation stage* where initial knowledge is obtained, leading to acceptance or rejection of the AMT adoption [183]. Thereafter the *set-up and installation stage* represents the project's launch, the preparations for installation and the installation of the technology [184], [190]. Finally, the *post-installation* stage entails further adaptations of the technology. Stornelli *et al.* [189] also account for the adoption barriers and enablers influencing each stage. Utilising the three-stage framework, Stornelli *et al*. [189] categorised the AMT adoption barriers and enablers identified in their review according to the three adoption phases of Figure 4.5. The following sub-sections explore the AMT adoption barriers and enablers.

4.3.1. Adoption barriers to advanced manufacturing technologies

Stornelli *et al*. [189] synthesised the most representative themes hindering the adoption of AMT. These include economic, organisational, personnel-related, technology, policy, and regulatory barriers, as presented in Figure 4.5. Organisational constraints refer to challenges experienced during technological change and the communication thereof [88], [99]. It includes the absence of AMT project vision, difficulties in buyer-seller relationships and set-up preparation difficulties (during the installation and post-installation stages of adoption). The absence of AMT project vision comprises the reticence of executives to invest in the technologies, the absence of AMT champions or project-based teams and misaligned team vision. Table 4.1 presents AMT adoption barriers and their relevance stages [183], [186]–[188].

The ATM authors ascribe economic barriers to be relevant to the evaluation, set-up and installation, and post-installation phases of adoption, particularly the evaluation phase [185], [191]–[194]. The predominant economic barrier is the tremendous cost of initial implementation or acquisition of the technologies, although these costs differ by industry sector, ATM and enterprise type [185], [191]. Additive manufacturing acquisition, for example, enquires high-cost system and IT infrastructure acquisition, initial training, and high material and process costs [195], [196]. In addition to the initial liquidity constraints experienced, adaption to the technology may inquire decreased system performance and productivity [193], [194]. Díaz et al. [192] also argued for the ineffective justification of the high-cost initial investment in the technologies when no evaluation methods or long-term adoption plans are employed.

Organisational constraints refer to challenges experienced during technological change and the communication thereof [184], [197]. It includes the absence of AMT project vision, difficulties in buyer-seller

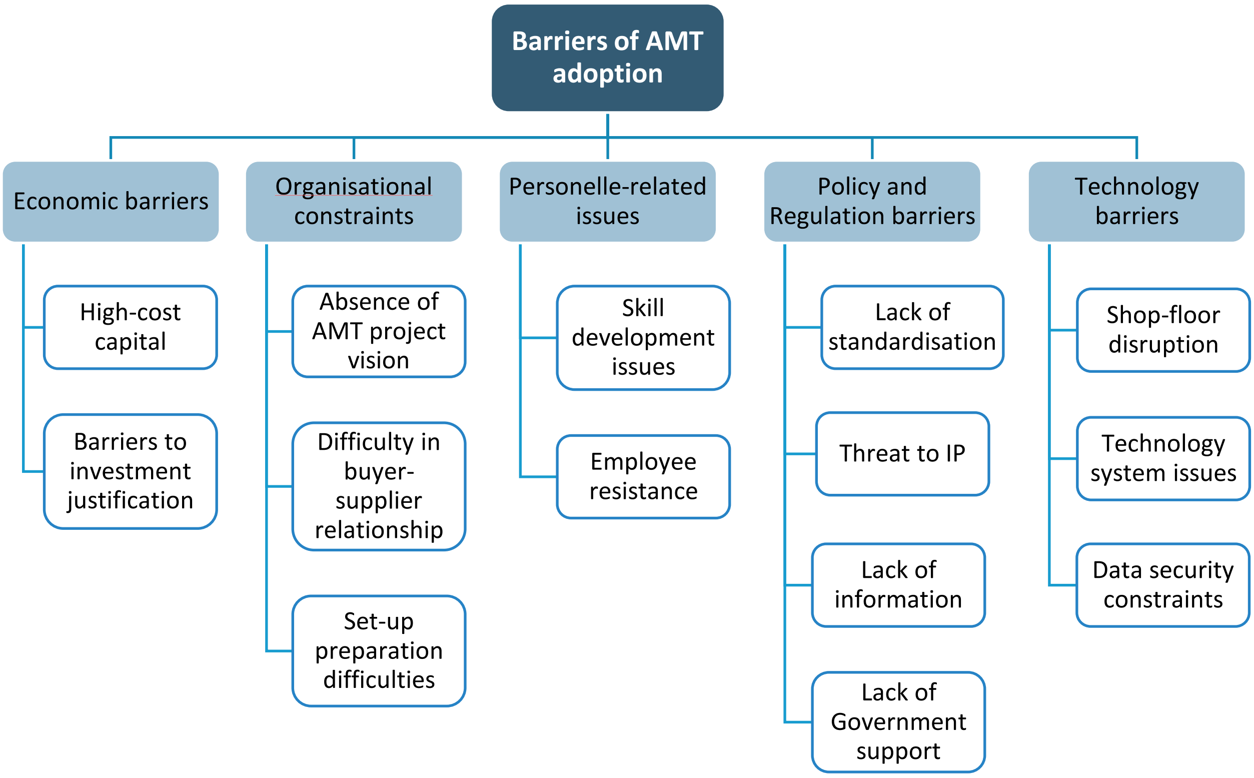


Figure 4.6: Barriers of AMT adoption [189]

relationships and set-up preparation difficulties (during the installation and post-installation stages of adoption). The absence of AMT project vision comprises the reticence from executives to invest in the technologies, absence of AMT champions or project-based team, misaligned team vision, difficulties in creating a business case and reorganising production routines [184], [186], [192], [197], [198]. According to Machuca *et al.* [185] and Efstathiades *et al.* [184], managing buyer-seller relationships is also challenging, especially when adopters do not trust suppliers (difficulty in contractual agreements), as it may impact the entire adoption process. Similarly, the uncertainty of technological needs may delay the adoption process. Set-up preparation difficulties may also be experienced during the implementation and post-installation stages when an implementation plan is absent [185].

Table 4.1: AMT adoption barriers and their relevance stages [183], [186]–[188]

		Process stage		
		Evaluation	Set-up and Installation	Post Installation
Economic Barriers	High cost of capital			
	Barriers to investment justification			
Organisational Constraints	Lack of AMT project vision			
	Difficulties in buyer-supplier relationships			
	Set-up preparation difficulties	Not Significant		
Personnel-related Issues	Skills development issues			
	Employee resistance			
Technology Barriers	Shop-floor disruption	Not Significant		
	Technology system issues			
	Data security constraints			
Policy and Regulation Barriers	Lack of standardisation			
	Threat to intellectual property			
	Lack of Government support			
	Lack of information			
	Higher relevance to stage			
	Lower relevance to stage			

Personnel-related issues are said to be most relevant during installation and later stages [199], although some authors have argued for their relevance as evaluation criteria. These issues refer to skill development issues and employee resistance. Authors found that as a shortage of AMT skills may exist in the manufacturing industry, manufacturing enterprises that adopted strategic training programmes achieved higher technology acceptance and productivity outcomes [200]. For AMT, such as additive manufacturing, training designers and engineers on the use and benefit of additive manufacturing is necessary, similarly developing Big Data analysis competencies to manage the Industrial Internet of Things [201], [202]. Employee resistance also comprises fear of job loss in unionised industries [197], [199], [203], psychological resistance to routine change and envisioned threat to established competencies [198] and finally, insufficient employee training leading to months of installation delays [204].

Stornelli *et al*. [189] found that *policy and regulation barriers* impact the entire adoption process, particularly the evaluation stage before technology acquisition and implementation. A primary barrier to AMT adoption is regulatory initiatives that fail to incentivise industry standards and diffuse knowledge on AMT applications and costs [195]. Studies by Harrington et al. [97] and Wagner and Walton [108] found an absence in safety, material properties production methods and design standards which severely delayed enterprises' adoption of AMTs, particularly for AM and electronic data exchange. Chan *et al.* [196] found that AM adopters feared threats to their IP and the risk of infringing copyrights for the design and printing of certain products. On a policy level, several authors identified shortages in government support regarding inconsistent adoption policies [197], tax credits [194], and shortage of knowledge diffusion between research institutes and SMEs [197], especially towards AM technologies and their readiness [141], [195], [205]. Similarly, Baldwin and Lin [197] highlight the market impacts of irregular and insufficient technical and scientific AMT information as awareness of AMT's potential is reduced.

Technology barriers are said to exist due to the programmable nature of AMTs and are relevant during the installation and post-installation phases of adoption [189]. These barriers are prominent in the form of system malfunctions and data security issues impacting operations as well as integration problems of AMT components with existing information systems during installation [204], [206], [207]. Integration problems often experienced include the integrating of CAD/CAM software, changing batches on automated machines, prototyping inaccuracies as well as AM limitations designers and engineers were unaware of [193]–[195], [201], [205], [208]. As the possibility of these integration challenges leading to unproductivity is high, they often keep enterprises from adopting the technology, as productivity is always necessary, especially for smaller enterprises [209]. Furthermore, data security constraints link with *organisational and personnel-related constraints* as employees are alert to the risk of stolen proprietary information, the responsibility of managing different data sources, the challenges associated with sharing data across supply chains and insufficient knowledge of possible data security [193], [202], [210], [211]. Studies also provide evidence of shop-floor disruptions such as connection malfunctions between interconnected machines, excess data analysis for decision-making and difficulties in data integration as barriers to the adoption of AMTs [193], [198], [206].

4.3.2. Typical enablers of advanced manufacturing technology

In contrast to AMT adoption barriers, Chaudhuri *et al.* [183] and Stornelli *et al*. [189] synthesised the most representative themes enabling ATM adoption. These include technology selection and strategy, policy and government programmes, capability enablers, and corporate structure, as presented in Figure 4.7.

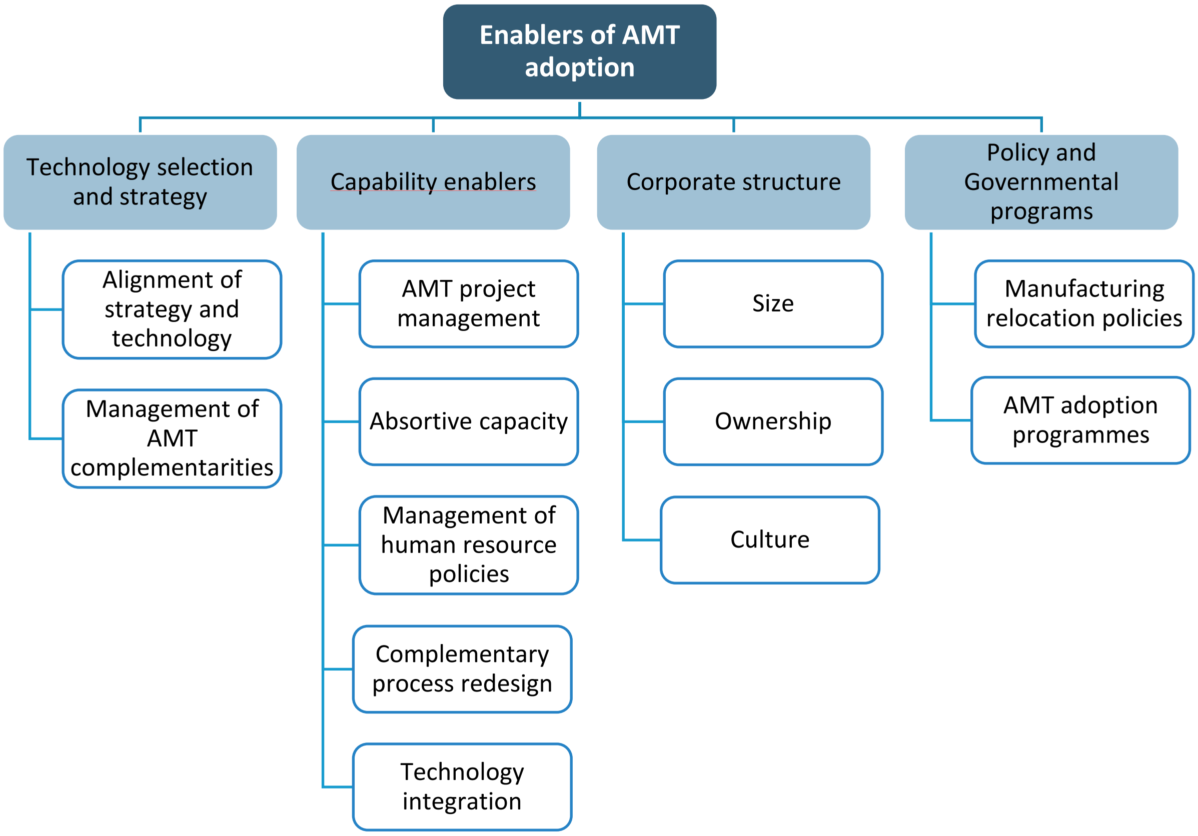


Figure 4.7: Enablers of AMT adoption

Several authors have explored *technology selection and strategy* as an enabler of AMT adoption and performance, particularly through the alignment of the manufacturing strategies and the selected AMT components. This enabler is highly relevant during the evaluation stage, although strategic objectives may change during later stages when manufacturers analyse the business and technical benefits offered by the AMTs [186], [189]. For example, innovation or differentiation strategies integrate different AMT components, while cost leadership strategies require enterprises to adopt high-volume automation technologies [212]–[216]. Other *technology selection and strategy* studies have highlighted the importance of the management of AMT complementarities. For example, studies by Percival [217] and Spanos and Voudouris [218] have found that enterprises with aggressive technology strategies likely invest in AMT following a sequential trajectory with different utilisation patterns between industries. Furthermore, the studies indicate that experience with a single AMT eases the adoption of complementary AMT systems leading to enhanced innovation performance.

Corporate structure, an enabler relevant to all three phases of adoption, entails the moderating roles of size, ownership and culture [189]. The size of enterprises has been explored in several studies as a contextual enabler of adoption [219], [220]. Larger enterprises are more likely to invest in AMTs due to experience, accessibility to assets and training, organisational policies and adoption process management strategies [219], [220]. Ownership facilitates access to the knowledge base of parent or subsidiary enterprises, leading to higher performance and supported AMT adoption [216], [221]. Finally, culture in AMT adoption is related to the willingness to change and shift from a product-oriented culture to a software-orientated culture [202], [210]. As cultural values may be flexible or hierarchical, they may enable efficient vertical and horizontal data integration for service deployment and efficient adoption decision-making [175], [198].

A few studies have highlighted the enabling role of *policy and government programmes* throughout the adoption process. For example, studies have shown that governmental support towards back shoring and local investments through tax incentives supports the adoption of AMTs as enterprises and academia may leverage these market advantages and exploit local resources [193]. Similarly, governmental assistance towards different levels of AMT implementations supports SMEs in the adoption process [189]. Furthermore, Samford *et al.* [141] highlight the empowering impact of AMT adoption programmes that support and guide organisational changes, develop adoption plans, and offer training. These studies often also facilitate the development of product, process, and service adoption capabilities. Table 4.2 presents the AMT adoption enablers and their relevance stages according to the systematic review of AMT literature sources Stornilli *et al.* [189] explored.

Table 4.2: AMT adoption enablers and their relevance stages [189]

		Process stage		
		Evaluation	Set-up and Installation	Post Installation
Technology Selection and Strategy	Manufacturing competitive priorities			
	Management of AMT complementarities			
Policies and Government Programmes	Manufacturing relocation policies			
	AMT adoption programmes			
Capability enablers	AMT project management			
	Absorptive capacity			
	Management of human resource policies			
	Complementary process redesign	Not Significant		
	Technology integration			
Corporate structure	Size			
	Ownership			
	Culture			
	Higher relevance to stage			
	Lower relevance to stage			

4.3.3. Enabling capabilities of advanced manufacturing technology

Capability enablers refer to the organisational and inter-organisational capabilities relevant to project and human resource policy management, deployment of best practices, absorptive capacity and technology system integration [189]. The AMT *project management capability* enabler is a multiphase enabler with high relevance during the evaluation phase of adoption, when projects need to be planned, developed, and communicated [189]. The necessities of the *project management capability* are as follows. First, studies highlight the need to visit trade fairs, engage with suppliers to test technologies and exchange information within internal manufacturing councils to identify and gain preliminary knowledge on the AMTs [190], [222].

Planning the adoption and technology change is a primary capability to reduce pressures from employee resistance, achieve higher productivity, and reduce performance gaps after implementation [223], [224]. Therefore, the need for management support and AMT champions is emphasised to guide the change [225]–[227]. Similarly, engagement with employees and establishing and managing supplier relationships are necessary for the formulation of an AMT strategy and business case [194], [206], [208], [228]–[230]. Ordoobadi and Mulvaney *et al.* [231] and Saleh *et al*. [232] highlight and demonstrate the usefulness of decision attribute frameworks in developing an AMT strategy and stimulating a higher implementation performance.

In consort with the AMT *project management capability* enabler, *absorptive capacity*, the capability and capacity to absorb knowledge, is a critical multiphase adoption enabler [209], [218], [220]. Serval studies argue that absorptive capacity is a prerequisite to AMT adoption and is measured through the education level of the workforce, their ability to obtain and use new knowledge and experience with prior AMTs[216] [209], [218], [220].

To reduce the personnel-related adoption barriers, the *management of human resource policies has* predominantly been stressed in literature [204], [226], [233]–[235]. Although the anticipated impact of the AMT adoption on working conditions is considered during the evaluation stage, human resource policies are said to be particularly important during the installation and post-installation stages [184]. The policies typically include training between operators and managers, processual and cognitive competencies development, customisation of training for job variants, on-the-job training and worker assessment development strategies [204], [226], [233], [234]. Furthermore, as continuous monitoring of workers is said to be crucial in AMT skill development [235], worker assessment development strategies and high-performance work systems may increase performance and reduce employee adoption resistance [185], [236].

A capability enabler, particularly important during post-installation, is c*omplementary process redesign.* It comprises two levels, namely internal routines and inter-organisational capabilities. Internal routines refer to the procedures, such as design-manufacturing integration and virtualisation, that should be redesigned to facilitate the organisational integration of the AMTs and the integration of processes that enable high-level technology use and performance [217], [221], [237], [238]. Inter-organisational redesign comprises the reconfiguration of workflows to incorporate the new AMTs, ensure plant efficiency, enable product improvement and effective customer and supplier collaborations [239], [240]. Within the context of, for example, IoT adoption, product data is used for dynamic product and service improvement [202], [241], [242]. However, within the context of additive manufacturing, a higher supply chain integration is necessary as customers may be positioned as co-producers [196], [209], [243].

In line with c*omplementary process redesign* is the *technology integration* capability. As seen in Table 4.2, this capability is highly relevant in the set-up installation and post-installation stages. This capability comprises the ability to structure *technology layers* to ease the integration of new AMT into an enterprise's existing infrastructure [197], [210]. To structure these layers, the authors suggest the utilisation of scalable solution platforms, technology-service structure architecture, IoT business units, and interdepartmental data integration [228], [241], [244]. Another study suggests data integration across factories to enhance manufacturing plant performance [245].

4.4. Methods and approaches to study industry dynamics and evolution

To study the dynamics involved in science commercialisation and bridging the Valley of Death (VoD), noteworthy management papers by Rasmussen [164] and Ellwood *et al.* [163] utilised Van de Ven and Poole's [161] process theories. Additionally, they utilised the realist evaluation approach, a well-established approach for evaluating programmes and projects [163], [246].

In line with *process theories* that seek to understand *how* change unfolds based on activity flows over time, the realist approach seeks to understand why certain outcomes are delivered by studying the underlying interventions and mechanisms that led to the outcome [247]. Realist evaluation authors Rogers [248], Mathison [249], and Pawson *et al.* [246] have argued that realist evaluations are best suited to complex systems where several social processes may be functioning. Due to the complexity of the innovation dynamics involved in science commercialisation and the VoD, Rasmussen [164] and Ellwood *et al.* [163] argued for the suitability of the realist approach. In addition to the process theories, the authors argued that the realist evaluation approach guided the manner in which they thought about evaluation as it provided them with an evolution logic.

Based on the utilisation of the realist evaluation approach by science commercialisation authors Rasmussen [164] and Ellwood *et al.* [163], this study also employs the approach to guide the evolution logic of this study. It is believed that the approach will shed light on how change and development unfold during the VoD and through which mechanisms resulting outcomes are delivered.

4.4.1. Realist evaluation approach

According to Tilley [55], traditional evaluation approaches follow the natural science approach of experimental testing. This comprises constructing equivalent experimental groups and assessing the influence of intervention implemented in certain groups. Evidence would then typically be produced to answer evaluation questions such as "*What works*?" or "*Does this work*?". Traditional evaluation approaches thus focus on understanding what underlying mechanisms produce regularities under specific conditions, as presented in Figure 4.8.

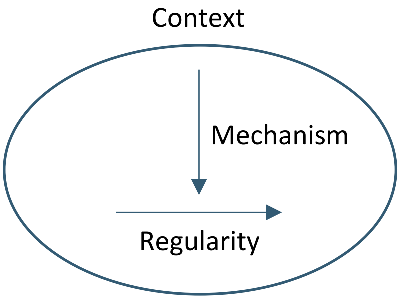


Figure 4.8: The Context-Mechanism-Regularities of traditional evaluation approaches [55]

Consequently, traditional evaluation approaches are described as having a 'Black Box' stance of evaluation as the reasons why specific outcomes occurred are not considered outside the experimental environment [247]. Instead, only inputs and outputs are considered to determine whether innovation actions (known as interventions) worked.

In 1997, Pawson and Tilley [247] argued for the shortcomings of traditional experimental evaluation approaches as they focus on observed programme outcomes and mitigate the nature and context of innovative actions or interventions causing the outcomes. In response, Pawson and Tilley developed the realist evaluation approach. Realistic evaluations aim to determine and improve the merit of innovation actions while considering a programme's context in its practical application [247].

In contrast to traditional evaluation approaches, realistic evaluation proposes a 'clear box' approach. This approach moves beyond the evaluation question of "*What works*?" as it is recognised that the question is merely a starting point that might never be fully answered but should be strived towards. The realistic evaluation's 'clear box' approach instead considers all the mechanisms and context contributing to regularities and changes in the overall open system where interventions are applied [247]. Tilley and Pawson [250] and Kazi and Rostila [247] therefore suggest that realistic evaluation's main evaluation question is "*What works for whom, how, in which circumstance, and to what extent?*".

A realist approach assumes that programmes embody theories. Thus, whenever a program is implemented, it tests a theory about what might cause change, even though that theory may not be explicit. Therefore, the task of realist evaluation is to make the theories within a programme explicit by developing clear hypotheses about how and for whom the programme might work. The implementation of the programme, and the evaluation of it, then test those hypotheses. Realist evaluation, therefore, requires data collecting about the programme impacts, the programme's implementation process, and the aspects of programme context, interventions and mechanisms that might be creating change.

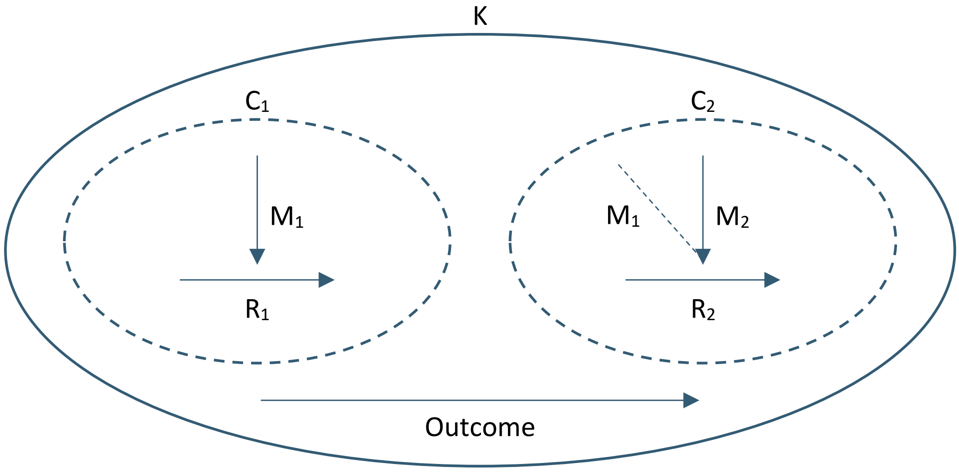


Figure 4.9: Context Mechanism Outcome Configuration of Realistic Evaluations

In social sciences, realistic evaluations aim to inform and contribute to social policy and practice development [55]. Realistic evaluation authors such as Kazi and Rostila [247], Tilley and Pawson [250], and Westhorp *et al.* [54] believe that the 'Black Box' stance of traditional experimental approaches miss out on practical lessons and insight required to inform social policies and practices. Therefore, in contrast to the Context-Mechanism-Regularities focus, realist evaluation is concerned with understanding how regularities are altered when causal mechanisms are changed (M_1) or new mechanisms are introduced (M_2) in response to an alteration in the project context (C_1 to C_2), as presented in Figure 4.9. The change in regularities (from R_1 to R_2) thus describes the outcome of a programme. As social programmes are concerned with the change that occurs, they consider the programmes and their context part of the broader social setting, an overall open system (oval K). Realist evaluation thus considers the wider social setting in which different contexts and programs occur, linking to the Design Science Research methodology applied by this research study.

From these factors, Tilley and Pawson [55] developed the programme theory known as the Context Mechanism Outcome Configurations (CMOC), a configuration that captures the linkages between the context mechanism and outcome. Following this configuration, realistic evaluation is thus based on deriving, refining and testing the understanding of the specific CMOC [55], [251]. Therefore, to understand any program or intervention in realist terms, Tilley and Pawson [55] defined evaluation questions that link to the CMOC components. These questions are presented in Table 4.3.

Table 4.3: Realistic evaluation questions proposed by Tilley and Pawson [55]

Realistic element	Evaluation questions
Context	Which conditions are required for a measure to trigger mechanisms to produce particular outcome patterns?
Mechanism	What about a measure may lead it to have a particular outcome pattern in a given context?
Outcome	What are the practical effects of causal mechanisms triggered in a given context?
CMOC	How are the changes in regularity (outcomes) produced by measures introduced to modify the context and balance of mechanisms triggered?

Tilley and Pawson's CMOC programme theory was later expanded by authors such as Klerkx [252] and Denyer [253]. These authors argued that as it is the interventions performed in patterns that cause the mechanism, the interventions should form part of the CMOC programme theory. These authors extended the CMOC to include the interventions and developed the programme theory known as the Context-Intervention-Mechanism-Outcome logic (CIMO-logic) structure. In line with the Design Science Research methodology applied by this research study, the CIMO-logic structure enables a systematic structure for developing design propositions [163], [252], [253]. Similar to the CMOC, the structure combines a problematic *context* with certain *intervention* types to develop *mechanisms* to deliver specific *outcomes* [253]–[255] (Figure 4.10).

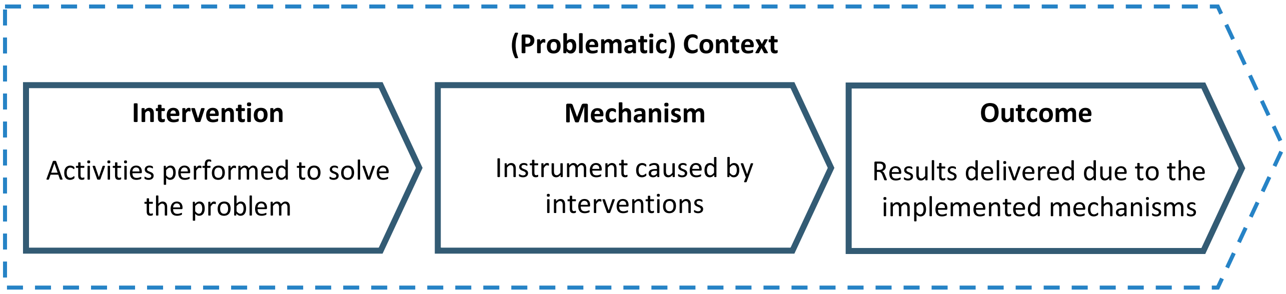


Figure 4.10: Schematic representation of the CIMO-logic structure

Design principles formulated according to the CIMO-logic structure indicate which activities to perform and in which situations to obtain specific desired results and offer an understanding of the present system dynamics [253], [254]. Table 4.4 describes the CIMO-logic components and considerations for constructing design propositions [254].

Table 4.4: Components of the CIMO-logic structure [250], [253], [254]

Component	Description
Context	• Context refers to the surrounding, external and internal environmental factors and the nature of humans that influence behavioural change. These factors include geographic and community setting, culture, politics, historical period, events, organisational setting, politics and power, age, experience, competency, the nature of the technical system, organisational stability, uncertainty, and system interdependencies. • Interventions are continuously embedded in a social system. Consequently, they will be affected by at least four contextual layers: the individual, the interpersonal relationships, the institutional setting, and the broader infrastructural system. • It is essential that all factors – internal, external, individual, interpersonal, institutional wider infrastructural – are considered when propositions are analysed.
Intervention	• Interventions are the purposeful actions or measures (products, processes, services, or activities) formulated by the designer or design team to solve a design problem or need and influence outcomes. • It is essential to examine the nature of the intervention, how it is implemented and by whom it was implemented.
Mechanisms	• Mechanisms relate to causation. The interventions of a specific context trigger patterns of events that can be defined as causal mechanisms which indicate why the interventions produce a particular outcome. Mechanisms can explain the cognitive processes (reasoning) actors use to choose their response to the interventions and their ability (resources) to put them into practice. • It is valuable to note how and why mechanisms were triggered and what effect each intervention had on the mechanisms.
Outcome	• Outcomes are the various aspects of the results interventions cause, such as performance improvement, cost reduction or low error rates. • It is valuable to view the various influences of the outputs the mechanisms achieved.

Realist evaluation authors Rogers [248], Mathison [249], and Pawson *et al.* [246] have argued that realist evaluations are best suited to complex systems where several social processes may be functioning. In line with their argument, realist evaluation has increasingly been used to evaluate complex health care interventions and facilitate a more profound understanding of "*What works for whom, how, in which circumstance, and to what extent?*" [163], [246], [256]. The analytical routine of realist studies aims to identify programme theories underlying the interventions [256]. As a programme theory explains how and why interventions are expected to work within a programme, the CIMO-logic structure is frequently followed to structure data gathered on a programme. In Ellwood *et al.'s* [163] notable paper, the realist evaluation and the CIMO-logic structure were utilised to collect, structure and compare the findings of six medical research projects. The study aimed to explain the innovation processes for crossing the Valley of Death. As in many other realist evaluation studies, the CIMO-logic programme theory supported Ellwood *et al.* [163] in successfully synthesising a framework to guide projects to cross the Valley of Death.

In summary, realist evaluation is a well-established logic guide for evaluating projects and programmes [246], [256]. It supports the identification of *What works for whom, in which circumstance, and to what extent?*" in evaluation studies. Furthermore, realist evaluation does not seek generalisation regarding the relationships between variables but the role and impact of generative mechanisms that diffuse over time. It has also been argued that the approach best suits complex systems where several social processes function. Therefore, its CIMO-logic programme theory has been utilised in numerous studies, particularly in health case studies. It has also successfully been utilised to develop a framework for the VoD [163].

As mentioned in §4.2.3, the dynamics that exist during industry development, particularly the VOD, are known to be very complex. Therefore, cases operating within different contexts may vary regarding the support mechanisms and innovation activities that lead to positive outcomes and bridging the VoD. It is, therefore, empirical to elucidate the context in which innovation actions or mechanisms were (un)successful, the extent to which they were (un)successful, and the roles innovation actors fulfilled. As the realist approach emphasises context and does not seek generalisation in terms of the relationships between variables but the role and impact of generative mechanisms that diffuse over time, it may be considered a feasible approach to study the VoD dynamics. Furthermore, the CIMO-logic structure supports the analysis of the dynamics of the VoD as it enables the categorisation of data in terms of context, innovation actions and actors. Moreover, it supports the identification of event triggers and the analysis of cumulative causation as it traces the development of action sequences (mechanisms) over time to elucidate why specific outcomes were achieved (or not achieved). Therefore, the realist evaluation approach and the CIMO-logic programme theory are deemed warranted to be utilised to guide the evaluation logic in this study.

4.4.2. Analysing the dynamics of evolution and industry development

In industry evolution literature, numerous approaches have been developed to analyse the dynamics of evolution and industry development [22]. Three primary constructs have been designed to assist the analysis and operationalise industry support measures [21]. These constructs include the value chain approach, cluster approach and innovation systems approach. From these constructs, four analysis frameworks or heuristics have been derived. They include Value Chains, Clustering, Business ecosystem perspective, and the Innovation systems framework [21]. In research studies similar to this study, due to time constraints, these frameworks are used independently and studied in-depth. However, authors have motivated the unison use of these frameworks as they are complementary.

4.4.2.1 Value Chains

The value chain construct was popularised in the 1980s. The construct has been used in literature to analyse inter-firm relationships and their relations in producing a particular product for customers [257]. The value chain construct provides a holistic approach to studying supply and demand management. It studies the integration of business processes to enable supply management and incorporates concepts that enable product and service improvement, management of production networks and managing collaborative relationships to satisfy consumer demand [258]. Value chains involve various stakeholder groups – suppliers, processors, producers, companies of all sizes, knowledge institutes of all levels, environmentalists, financial organisations, intermediaries, non-profit organisations, and public sector players - with diverse backgrounds and perspectives [259]–[262]. Actors are typically by linkages of value exchange. Actors performing similar value-adding activities are connected with horizontal relationships, while vertical relationships connect actors performing different roles

4.4.2.2 Clustering and its mechanisms

The construct of clusters and clustering was developed in 1990 by Harvard Business School professor Michael Porter [263]–[265]. Porter [263] regarded a cluster as geographically focussed groups of interrelated companies, suppliers, service providers, knowledge institutes, and organisations of all relevant activities (for example, agencies for standardisation and trade associations) that cooperate and compete [264]–[266]. Thus, a cluster comprises geographically neighbouring interrelated companies and organisations that collaborate and co-evolve around shared resources. Consequently, the construct of clustering incorporates multiple value chains, focussing specifically on the overall sector or industry within which the value chains exist and the comprehensive resources and inputs involved within the sector or industry [21], [267]. The cluster approach thus provides the broadest strategic perspective on a sector and therefore requires an understanding of the various value chains and relationships that exist within the sector [21], [267].

4.4.2.3 The business ecosystem perspective

The notion of an ecosystem was coined in the 1930s by botanist Arthur Tansley to refer to a localised community of living organisms interacting with each other and their environment [268], [269]. These organisms cooperate, compete, and co-evolve with and within their terrain and adapt together to external influences [269]. A business ecosystem is a network of actors (businesses, suppliers, market intermediaries, customers) who interact and co-evolve around an innovation and depend on each other to survive and succeed [270]. The distinguishing characteristic of business ecosystem actors from the sector and supply networks is the explicit modelling of the mutual dependence of the actors. Therefore, the business ecosystem perspective provides a powerful lens that captures the dynamic transformation in the business landscape by highlighting the growing importance of actor relationships, partnerships, networks, alliances, and collaboration [268].

4.4.2.4 Innovation systems

The innovation system approach was popularised in the 1980s. The construct is built on the foundation that innovation and technology diffusion are individual and collective acts [271]. The innovation system construct allows for an understanding and analysis of components within a system, their roles, presence, nature, quality, capabilities and competencies and how they interact to achieve the principle system functions [21], [33], [272]. Furthermore, the construct allows a functional analysis to identify the range of functions and activities that support an effective innovation system towards its goal of developing and diffusing innovations. The systems studied through this approach may comprise individual firms, collaborations, projects, programmes, and initiatives, all of various sizes and contributions to a sector of industry. It should be noted that not every innovation system studied contains a complete value chain, but that borders of the system may be defined as large or small according to a researcher's preference. As a result, the innovation system approach provides the most fundamental perspective on a sector of all the industry development analysis constructs [21], [33].

In a notable paper by Markard [167], the innovation system approach is selected for use in conjunction with the life cycle perspective as it is a conceptually sound systems approach well suited to pertain to institutional, technological and organisational changes and their interactions. Furthermore, the innovation system approach, specifically the technology innovation system approach, can be linked to a particular technology while considering the broader industries and supply chains linked to the selected technology. Furthermore, innovation system literature has already started to engage with the global dimension of innovation systems and the complex relationship between local and global technology dynamics [273]. Finally, the TIS approach has proven fruitful when informing policymakers about targeted interventions to foster technology development [167].

4.4.2.5 Chosen methodology: Innovation systems

The South African hardmetal industry is only starting to develop AM technologies. Therefore, the study aims to identify the activities and actor capabilities the South African hardmetal industry requires to stimulate the adoption and implementation of novel manufacturing technology. Subsequently, it is not of value to the author to adopt a high-or mid-level approach such as the value chain, clustering, or ecosystem approach as the ground-level and system-level innovation components and functions required to adopt the AM technology, are still to be identified. Therefore, the innovation system approach is most appropriate for this study. Together, as presented in Figure 4.11, the innovation system framework and the realist evaluation approach comprise the method through which this study will study and analyse the dynamics and evolution of industry development and the logic of evaluation that is followed.

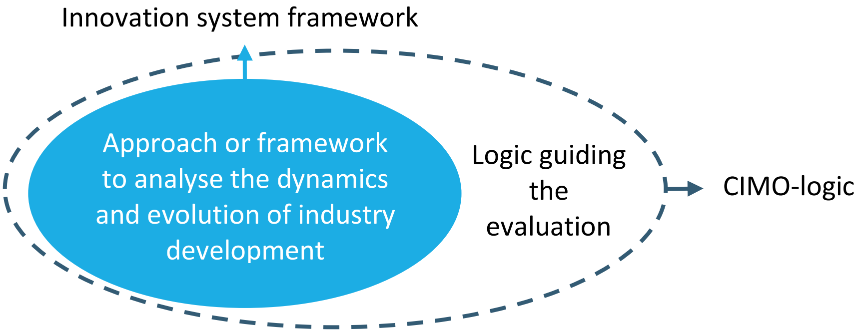


Figure 4.11: The innovation system framework and the realist evaluation's CIMO-logic structure comprise the method through which this study will study and analyse the dynamics and evolution of industry development and the logic of evaluation that is followed

4.5. Chapter 4: Summary

This chapter provides a literature review on innovation, industry and technology development and frameworks that have previously been utilised to study them. This chapter first reflected on the concept of innovation and the four fundamental theories explaining innovation and change processes. The chapter reflected on how industries develop and investigated industry and technology development dynamics and phases. The concept of the valley of death was also introduced. Thereafter, the chapter reflected on technology adoption and the enablers and barriers thereof. Next, the chapter explored realist evaluation and the CIMO-logic framework as a lens to guide evaluation in this study. Finally, analysis approaches developed to study industry development were investigated, and the innovation system framework was selected for this study. This chapter contributes to objective 1, as mentioned in §1.4.

The following chapter explores the literature on the innovation system framework in more detail.

Chapter 5
Literature review: Innovation Systems

A literature review on industry and technology development was presented in the previous chapter. This chapter presents a literature review on innovation systems. The chapter starts with an introduction to innovation models. Thereafter innovation systems and their main components and functions are discussed. The methodologies used to analyse innovation systems are also discussed. The chapter then concludes with a detailed discussion of the analysis methodology used in this study. This chapter aims to gain an understanding of innovation systems, their functions, and the analysis thereof. This chapter contributes to objective 1, as mentioned in §1.4.

Chapter 5 objectives:

- Present an introduction to innovation models and the different types of innovation systems (§5.1, 5.2).
- Explore the components and functions of the innovation system framework (§5.3).
- Relate the IS framework to the life cycle phases of development (§5.4).
- Explore innovation system evaluation approaches (§5.5).
- Explore the systemic innovation policy framework (§5.6).
- Explore innovation system deliverables (§5.7).
- Explore the concept of motors of innovation (§5.7.2).
- Present the Event History Analysis method and previous applications thereof (§5.8).

5.1. Introduction to innovation models

Innovation plays a crucial role in economic development as it leads to technological transformations [144] and large-scale employment opportunities [28], [145]. How innovation is understood influences the way it is managed [146]. Since the first `innovation as a process' perspective was developed in 1950, the perception of innovation has evolved. To date, six generations of innovation processes have been documented in literature.

The first and second generations of innovation processes saw innovation as a linear sequence of activities and were therefore known as the *linear model of innovation*. In 1950, fast economic growth and scientific breakthroughs led to the assumption that innovation started in science and research [274]. Subsequently, the first-generation model, known as the *technology push*, postulated that science and research were followed by product development, refinement, production and eventually diffusion into the marketplace [275], [276]. The second generation, known as *market pull*, started in the mid-1960s and was characterised by increased competitiveness to gain market share, which induced companies to shift focus from research and development (R&D) to market need [146], [274], [276]. The linear innovation model received criticism as it disregarded feedback loops, the relationships between groups involved in the innovation process and considered R&D an innovation [275]–[277]. It was also criticised as the first-generation technology-push model led to the development of products that were not adopted in the marketplace. Additionally, the second-generation market pull model led to short-term projects [146], [274]. Consequently, the criticism led to the development of the third generation of innovation.

The third-generation model, known as the *chain-linked model*, was developed in the mid-1970s as an improved version of the linear model [278]. The chain-linked model combined the *market pull* and *technological push* approaches from the linear model as it understood that innovation was not the result of pure technology push or market pull forces [274], [277]. Although this model was still consecutive and relied on existing knowledge, it allowed feedback between stages and acknowledged that innovation leads to knowledge creation [276],[277].

In the early 1980s, the fourth-generation innovation model, *the parallel model*, was developed. Innovation was no longer seen merely as a sequential process but as a parallel process of development that required relationships between process actors [274], [276]. This model accentuated concurrent learning between process actors and that R&D was merely one of the many functions of the innovation process [274]. As this model and its preceding models did not offer a holistic approach to innovators to advance the entire innovation process, the fifth-generation innovation model came about [276].

5.2. Innovation systems

The fifth-generation innovation model, known as the *innovation system* or *systems of innovation* model, was developed with a specific focus on systems integration and networking models that guarantee flexibility and continuous development [276]. Freeman [25] defined an innovation system (IS) as *"networks of institutions, public or private, whose activities and interactions initiate, import, modify and diffuse new technologies"*. Therefore, an IS framework could be used to identify and map linkages and engagements between actors and institutions and map how knowledge is shared between them to develop, produce, and diffuse innovations [25]. It is also a framework through which the complex interactions between elements are acknowledged, and the feedback loops and non-linear behaviour resulting from various actors' activities in these systems are acknowledged [26], [27].

A system is defined as a group of objects, parts or components that work together to serve a common purpose [279]. The core components in an IS are actors and institutions [173]. The actors include, amongst others, governments, firms, financial organisations, universities, research institutes, customers and suppliers [280], while institutions include norms, habits, routines, rules, practices and laws that regulate the interactions between actors [173], [278]. The relationship between actors and institutions is essential for innovation and the overall performance of the IS. Institutions influence and are embedded in actors, and both tacit and codified knowledge is shared during actor interaction to develop, diffuse, and utilise innovations [32], [281]. Knowledge is the centre focus of ISs [282]. Therefore, the networks between actors are necessary as they provide knowledge channels for knowledge flow and learning processes.

It is important to note where the conversion of knowledge to value creation occurs within an IS, namely, firms [173], [282]. Firms fulfil a central role in ISs as they influence the direction and degree of innovation that occurs [282]. Firms interact with other firms and knowledge infrastructures such as research institutes and thus create learning processes within and around them. These learning processes lead to the development of the capabilities required to develop products and services, among others [173], [282]. Due to this interactive learning process, innovation literature recognises that innovation is not developed and implemented in isolation. Instead, innovation is developed and implemented in a system where actors and institutions influence the knowledge and capabilities generated and the value created [278], [282], [283].

The IS and its actor interactions occur within a specific environment [281] shaped by history, social relationships and cultures [276]. The ISs, therefore, change over time as variations occur within social, economic and political environments [281], [284]. The study of these changes is known as the `evolutionary approach' [28], [278]. The evolutionary approach studies the changes that occur within actors and institutions as they, in turn, change the interaction and innovation processes [284]. As a result of these changes, diversity is caused across sectors, regions and countries [278]. To support the transformation process where knowledge is turned into value, it is necessary to understand the various innovation processes within the micro-structures and between micro- and macro-structures so that the required editions can be made to actors and institutions [25], [282].

Several IS perspectives have been developed in IS literature as variants of the generic IS framework. Each perspective is focused on a different unit of analysis, and all perspectives complement each other [30]. The perspectives include the national, regional, sectoral, and technological perspectives. From these perspectives four types of ISs have been developed, namely the National Innovation Systems [26], [284], [285], the Regional Innovation System [286], [287], the Sectoral Innovation Systems [24], [272] and the Technological Innovation System [23], [33], [272], [278]. A schematic representation of the boundary relationship between these ISs is given in Figure 5.1. A short reflection of each of these ISs follows.

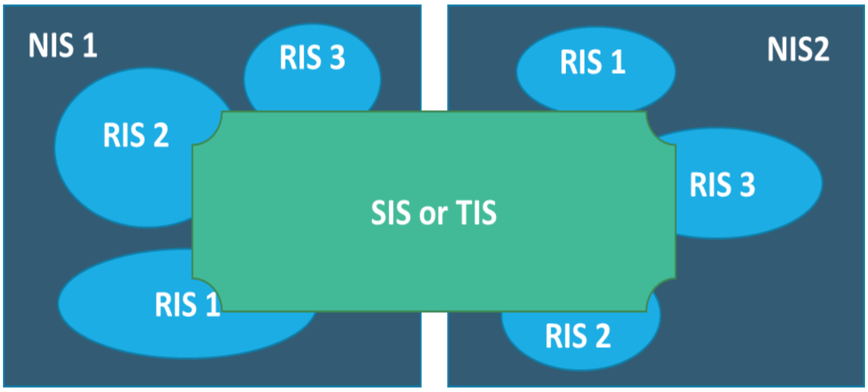


Figure 5.1: Schematic representation of the boundary relationship between the NIS, RIS, SIS and TIS [31]

5.2.1. National innovation system

Freeman [25] defined a national innovation system (NIS) as a "*network of institutions in public and private sectors whose activities and interactions initiate, import and diffuse new technologies*". The NIS, the oldest delimitation of the ISs, is used as a framework to analyse and compare the innovative success and economic growth of a variety of countries [23], [26], [173]. The NIS framework recognises that a county's innovative performance depends on the ability of the involved actors and the relationships and interactions among them to form a system where knowledge is created and shared, which leads to innovation and technological change [26]. The actors within a NIS mainly include the national government, private enterprises, public research institutes and universities [26], [288]. These actor interactions include patent sharing, joint research, worker exchanges, university-industry collaborations, and equipment procurement [33]. The macro-perspective of the NIS makes it sound as a heuristic tool for policy analysis and the derivation of policy recommendations but is not useful as a research framework as the number of actors in a nation as well as the relationships and interactions amongst them are too complex to study [23], [272].

5.2.2. Regional innovation system

The regional innovation system (RIS) was developed in the early 1990s as a subsystem of the NIS [286], [287]. The RIS reduces the scope of the NIS to a region of a nation or a collective region that includes small regions of different countries [173], [289]. Therefore, the RIS aims to analyse a region's innovative performance [23]. Chung [286] defined the regional innovation system (RIS) as *"a complex of innovation actors and institutions in a region that are directly related with the generation, diffusion, and appropriation of technological* *innovation and an interrelationship between these innovation actors"*. Regions are generally smaller than provinces and cover metropolitan areas [287]. The geographical distance between actors in a RIS affects the region's innovative performance [23], [33]. The actors in a RIS include private enterprises, public research institutes, universities, and regional governments [290]. The RIS approach is more micro-oriented than the NIS and includes analysis on the organisation- and firm-level [23]. The RIS approach is, therefore, more dynamic.

5.2.3. Sectoral innovation systems

Generally, the NIS and RIS frameworks do not perform a detailed analysis of technological innovation processes [33]. For that reason, the sectoral innovation system (SIS) and the technological innovation system were developed [290]. The SIS focuses on the dynamics of technological development and flows between actors in a sector [33]. Therefore, the SIS can be used as a framework to measure the performance of technology change in the industrial sector [287]. Breschi and Malerba [271] defined the SIS as "*the specific clusters of the firms, technologies, and industries involved in the generation and diffusion of new technologies and in the knowledge flows that take place amongst them".* The actors within an SIS include individuals and organisations. These individuals include scientists, entrepreneurs and consumers, whereas the organisations include enterprises, universities and technical associations [290]. The SIS offers a dynamic perspective as industries and technology evolve over time. A well-defined industry or industry branches are usually taken as departure point in SIS literature which therefore limits the dynamic perspective [23].

5.2.4. Technological innovation systems

In IS literature, the unit or analysis of a technological innovation system (TIS) is a specific technology or technological field [23]. Hekkert *et al.* [33] defined the TIS as *"a combination of interrelated sectors and firms, a set of institutions and regulations characterising the rules of behaviour and the knowledge infrastructure connected to a specific technology"*. The TIS framework was developed to study and evaluate the processes and structures that support and hinder the development of technological innovation [23], [291]. The TIS approach is also specifically used to derive policy development recommendations to support a specific technology's innovation processes [27], [291]. The TIS can therefore be seen as a more micro-oriented approach to the SIS, and as a result, the SIS can be seen as a collection of interrelated, overlapping TISs [23], [33], [292]. A feature of the TIS that differentiates it from the other IS approaches is its focus on system dynamics and knowledge and (economic) competence [23]. The TIS approach emphasises the need to generate and share knowledge within the system and fully exploit and recombine knowledge to create new business opportunities [23], [293]. TIS actors are similar to SIS actors; they may be connected across multiple industries and countries [288]. A summary of the differences between these IS delimitations, as derived by Gao and van Lente [289], is listed in Table 5.1.

5.2.5. Comparison of the innovation system types

The NIS and RIS frameworks analyse and compare various countries and regions' innovative success and economic growth. As the scope of this study is the hardmetal and additive manufacturing (AM) industries of South Africa, the NIS and RIS frameworks will not be appropriate for this study. The SIS and TIS frameworks, both very similar frameworks, enable detailed analysis of technological innovation processes; therefore, both frameworks are considered. As AM is a manufacturing technology that can be used to manufacture hardmetal products, the TIS framework is strongly considered. The TIS will enable the study and evaluation of the processes and structures that support and hinder the development of additive manufacturing technology as a manufacturing technology for hardmetal products. Additionally, the framework enables the performance analysis of technology change within an industrial sector and offers a dynamic perspective of how industries and technology evolve. The TIS will thus enable the analysis of the adoption of AM technology into the South African hardmetal sector, which forms part of this study's objective. As the incorporation of AM technology into the hardmetal sector is still in the feasibility phase, the risk of a limited dynamic perspective due to a well-defined industry or industry branch departure point is eliminated. Therefore, the TIS framework will be used in this study.

Table 5.1: Summary of the different delimitations of innovation systems [31]

	NIS	RIS	SIS	TIS
Unit of analysis	• National state	• Region	• Industrial sector	• Technological field
Main actors	• Industry • Government • Academic and • research • organisations	• Universities • Industrial enterprises • Research organisation	• Firms • Non-firm • organisations • Individuals	• Technology developers • Technology adopters
Institutions	• National policies • Laws • National finance supports	• Informal institutions dependent on trust and reliability among the actors	• Formal and informal institutions	• Formal and informal institutions
Main interactions	• Joint industry • activities • R&D collaboration • Technology diffusion • Personnel mobility	• Inter-firm interactions • External interactions for firms with research organisations • R&D collaboration	• Inter-industry • interactions • Interactions among firms and non-firm organisations	• Private-public actor interactions • Technology developer-adopter interactions

An IS perspective that has grown in popularity in the more recent years is the innovation for inclusive development (I4ID) perspective [288], [294]–[297]. Foster and Heeks [298] define the I4ID as "The means by which new goods and services are developed for and, or by those who have been excluded from mainstream development; particularly the billions living on the lowest incomes". As the TIS and RIS frameworks focus on technological fields or regions, the I4ID perspective focuses on the marginalised in the process or outcome of innovation [294].

The I4ID authors have described the perspective to comprise a broad range of actors, including intermediaries, marginalised groups and innovators [288], [298]. The primary focus is to include the marginalised as individuals and communities to promote participation [281], [294]. Scholars have found institutions essential in forming regulations that enable novel innovations to be implemented. Therefore, a complex combination of formal and informal institutions exists within the I4ID perspective [296]. Informal and social relationships are also said to exist between conventional and non-conventional actors, often on a deeper level than typical business relationships [294]. Due to the marginalised focus of the I4ID perspective, I4ID have also adapted the IS activities, the IS functions § 5.3.2, described in IS literature to be more marginalised specific.

Although the I4ID perspective is not related to the technological focus of this study, the tools I4ID scholars have developed to study the I4ID projects through the IS framework are fruitful, particularly for deriving policy suggestions. They are therefore also explored in this literature review as part of the IS literature.

5.2.6. Unit of analysis

The empirical operationalisation of the different ISs is often complex [32]. Consequently, innovation analysts are faced with several choices to determine the scope or unit of analysis as these choices influence the particular IS captured in terms of the components and activities of the system.

Bergek [32] and Van der Hilst [29] note that TIS boundaries may be defined around a single product, service, technology, particular sector or sub-sector, or specific target group. They may also be defined around groups of products, services, technologies, sectors, or sub-sectors. According to Van der Merwe [281] and Suurs [24], boundaries may also be defined around a geographic region. However, geographical boundaries are not strictly defined by the actors present within the boundaries [29]. Lundvall [282] notes that all actors involved in the development and diffusion of a specific innovation or whose activities are orientated towards the innovation within a geographically defined area are included within the system's boundary. Therefore, Van der Hilst [29] and Lundvall [282] argue that these actors, not present within the boundaries, may still interact with the system's actors and even influence the system, but must be noted as exogenous influences on the system.

Bergek *et al.* [32] suggest that analysts make deliberate choices when defining an IS's boundary and re-evaluate the choices throughout the analysis. Van der Merwe and Grobbelaar [281] suggested that the boundaries may eventually be broadened as a better understanding of the systems is obtained to include aspects that indirectly influence the system. Bergek *et al.* [32] suggest that conclusions are drawn about how the choice of starting point has affected the analysis and clearly communicate the unit of analysis to the analysis recipients. Bergek *et al.* [32] also noted that system boundaries may eventually be broadened as the system is better understood.

5.3. Structures and functions of innovation systems

In IS literature, the building blocks and most essential elements of an IS are said to be the IS structures [23], [26], [284]. These structures are the components of an IS and are found to be relatively stable over time [23]. The activities that are performed by these structures are known as the system functions. The system functions were introduced by TIS literature to shed light on the system dynamics [24], [27]. A key purpose of an IS is to encourage innovation processes and to create and diffuse innovations. The system structures perform these activities through the system functions [27]. The fulfilment of the IS purpose is thus dependent on the performance and presence of the system structures and functions.

This section presents an overview of an IS's structural and functional components. The knowledge regarding the IS components and functions obtained from this section will be used to satisfy the objective of this study, to develop a method to analyse the evolution of ISs.

5.3.1. Structures of innovation systems

The four building blocks of an IS, namely the system structures, are found in IS literature to contribute to the overall development, functioning, diffusion and utilisation of innovations [32]. The four system structures, as defined by Bergek *et al*. [17], Freeman [20] and Suurs [28], seen in Figure 5.2, are discussed in this section.

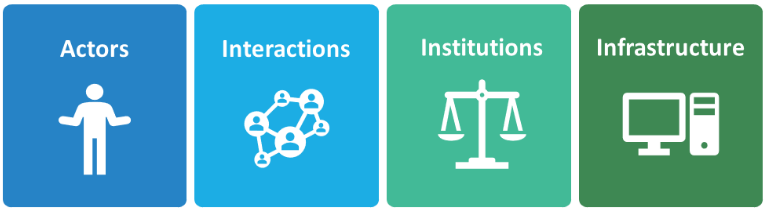


Figure 5.2: Structures of an innovation system

5.3.2.1 Actors

Innovation system literature recognises actors as the key structure of ISs as they are the component who perform the innovation activities through their choices and actions [23], [27]. The IS's development has been found to mainly depend on the presence, skills, motivation and interrelation between its actors [23], [27]. As the IS framework can be scoped on the levels mentioned in §5.2, several different actors may be found in each IS. The actors include civil society, the government, non-governmental organisations (NGOs), companies, knowledge institutes, legal organisations, financial organisations, intermediaries and consultants (Table 5.2) [32], [33]. Companies include start-ups, SMEs, multinationals and large firms, whereas knowledge institutes include research centres, technology institutes, universities and schools [27], [288].

Suurs [23] argued that a contrast could be drawn between the roles actors fulfil within ISs and divided actors into two categories: enactors and selectors. Each actor's involvement is explained by their type [23]. Enactors are those actors actively involved in the innovation development process and depend on the success thereof, such as a small technology developing company. In contrast, selectors are actors involved in the innovation at a distance, such as financers (Figure 5.3). The enactor-selector scheme is beneficial as it allows IS analysts to quickly identify an actor's role in the IS based on a few characteristics [23].

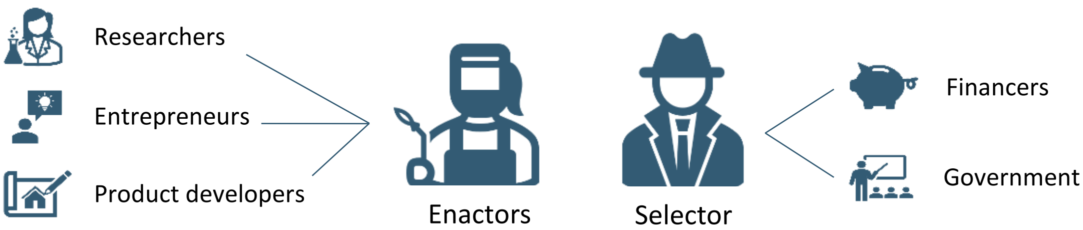


Figure 5.3: Example of innovation actors - Enactors and Selectors

5.3.2.2 Interactions

Relationships and linkages are said to exist between the actors, institutions and infrastructure within an IS [32]. As these interactions are dynamic, it is difficult to consider them stable structural elements [27]. Therefore, interactions are often studied in networks [23], [27]. Networks are said to develop when the structural components and the relationships among them form a configuration [32]. These networks are necessary to enable knowledge development and diffusion, thus, the learning process [24]. However, during the beginning stages of an IS's development, networks of actors do not exist yet, but relationships between actors exist. Interactions thus exist on both network-level and individual levels (Table 5.2) [27].

5.3.2.3 Institutions

The institutions or institutional structures of an IS are defined by Edquist and Johnson [271] as a set of "*common habits, routines, established practices, rules, or laws that regulate the relations and interactions between individuals and groups*" [211, p.6]. Institutions are the people-oriented constraints developed to shape the interactions between actors [23]. Formal and informal institutions exist [278]. Formal institutions are rules implemented by authority figures, such as government laws, contracts, and policies. Informal institutions are normative and cognitive rules, such as norms, values and collective mind frames, established through actor interaction [32]. Institutions are at the core of any ISs and institutional alignment across the IS, although it is not an automatic process, is essential [23], [32]. Institutional structures such as tax incentives and support programmes influence both enactors' and selectors' presence, skills, motivation and interrelation [23]. From an intervention perspective, institutional structures are, thus, vital as they are the focus points of governments and business strategies [288].

5.3.2.4 Infrastructure

Three types of infrastructures have been found in IS literature, namely physical, knowledge and financial infrastructures [27], [288], [294]. Physical infrastructure includes, amongst others, buildings, roads, machines, equipment, and networks. Knowledge infrastructure refers to system knowledge, expertise and strategic information, whereas financial infrastructure includes, amongst others, all forms of financial support such as financial programmes, subsidies and grants [27].

Several IS authors, such as Suurs [24], Hekkert *et al.* [299] and Wandera [300], refer to this IS structure as technological factors instead of infrastructure. These authors define technologic factors as artefacts and technological infrastructures in which they are integrated.

As the classification of the fourth IS structure as infrastructure, comprising physical, knowledge, and financial infrastructures, is most prevalent in IS literature, this structure classification will be used in this study. This classification is believed to be more comprehensive and inclusive of all infrastructure types than the technological factors classification.

Table 5.2: Structural components of an IS [23], [27], [297]

IS structures	Subcategories
Actors	• Companies: start-ups, SMEs, large firms, multinational companies • Knowledge institutes: universities, technology institutes, research centres • Government and NGOs • Civil society and other parties: legal organisations, financial organisations/banks, intermediaries, knowledge brokers, consultants
Networks	• At the level of networks • At the level of individual contacts
Institutions	• Hard: rules, laws, regulations, instructions • Soft: customs, established practices, traditions, ways of conduct, norms, expectations
Infrastructure	• Physical: instruments, machines, tools, buildings • Knowledge: knowledge, expertise, strategic information • Financial: subsidies, financial support programs, grants

5.3.2. Functions of innovation systems

Functions are the key activities performed within an IS to develop, diffuse and use innovations [23], [34]. They are the dynamic aspects of the IS that can be mapped over time [27]. The functions interact and are interdependent [23], [35]. The seven system functions identified by Bergek et al. [32] and Wieczorek and Hekkert [27], as seen in Figure 5.4, are discussed in this section. In a system, all functions need to show a certain level of development and quality for the system to perform well. Scholars have developed performance indicators (Table 5.3) for the functions to identify system weaknesses and inform policymakers on how to foster the development of a particular technology [167].

Figure 5.4: Functions of innovation systems

5.3.2.5 F1: Entrepreneurial Activities

In IS literature, entrepreneurs are said to be essential to ISs. Without them, innovation would not occur, and ISs would not exist [33], [34]. Entrepreneurs are the IS actors responsible for transforming the IS knowledge, interaction networks, and infrastructure into beneficial business opportunities. Entrepreneurs are thus dependent on the other system functions, and when entrepreneurial activities are underperforming, the causes can be traced to the other functions [33]. Innovation system entrepreneurs are found in both the private and public sectors and often in a combination of both [23], [36]. They can also be new companies wanting to take advantage of market opportunities or established companies diversifying their brand to capitalise on market opportunities [33]. This function's performance can be analysed by mapping the number of experiments conducted with the innovation, the number of new entrants in the IS, and the diversification of incumbent actors [32], [33]. Indicators of entrepreneurial activities include the entry of firms or other actors within the innovation system, portfolio expansions to diversify business strategy [299], manufacturing and or installing technology [301] and starting innovation projects with commercial aims [302].

5.3.2.6 F2: Knowledge Development

Knowledge is at the core of innovation systems [32], [33], [36]. Lundvall [26] explained this when he said, *“the most fundamental resource in the modern economy is knowledge and, accordingly, the most important process is learning”.* Research and development (R&D) are thus also fundamental to ISs [23], [33]. This function captures the breadth and depth of an IS’s knowledge base [32]. Different types of knowledge can be identified within an IS, including technological, scientific, market, design, production and logistic knowledge, amongst others [32]. New knowledge can be developed through R&D, learning-by-doing, learning-by-searching, learning-by-using and experimentation [34], [36]. Three indicators that can be used to map the knowledge developed over time include investment in R&D projects, investment in R&D, and the number of patents obtained [32], [33]. Indicators of knowledge development activities include academic research and studies [303], market surveys, pilot projects [304], feasibility studies, developing promotional materials, developing prototypes, development of models, testing performance of models, and adapting models [301] and learning activities, particularly learning-by-doing [299].

5.3.2.7 F3: Knowledge Diffusion

The purpose of the interactions and networks within an IS is to exchange information [293]. Information exchange is particularly essential in a heterogeneous context where R&D, government, competitors, and other actors interact. Within an IS, knowledge diffusion include partnerships between actors, meetings, workshops and conferences [23]. Networks where knowledge continuously diffuses allow policy decisions based on the latest technological insights and changes regarding values and norms to quickly take effect in R&D agendas [170]. Knowledge diffusion can be analysed by mapping the number of diffusion activities related to a specific innovation and the network sizes and interaction intensities over time [33]. Indicators of knowledge diffusion include training activities, demonstrations [301], conferences, workshops, seminars and meetings, alliances between actors and exchange of information [299] and joint ventures [23].

5.3.2.8 F4: Guidance of Search

In IS literature, guidance of search refers to the IS activities that shape actors' needs, expectations and requirements regarding innovation [36]. It can refer to individual choices regarding innovation and institutional components such as policy directives [23]. Natural resources are known to be limited. It is, therefore, important that specific focus areas are chosen within an IS. Guidance of search is also necessary from a system functional perspective as entrepreneurial activities **[F1]** and knowledge development and diffusion **[F2 and F3]** are bound to lead nowhere without proper guidance [23]. Guidance of search can be satisfied through actors such as governments, industries, technology producers and users, as well as NGOs sharing information, goals, and promises and creating expectations for the innovation [36]. This function's performance can be analysed by mapping the targets set by industry or the government and the number of publications regarding the innovation, both positive and negative, available. Publications studying the benefits of innovation are likely to stimulate the development thereof [23]. Guidance of search indicators include setting policy targets, standards and research outcomes, defining expectations, providing directions or showing interest, communicating research outcomes to the public [299], designing favourable regulations and policies and communicating vision and expectations [299].

5.3.2.9 F5: Market Formation

It is often difficult for new technologies to be accepted in the market due to the competition from existing technologies [35]. It is thus necessary to create a protected environment such as a temporary niche market for the application of the new technologies [33], [35], [36]. Protected environments will provide customer actors with the opportunity to learn about the new technologies **[F2 and F3]** and develop expectations **[F4]** for them [33]. Other possibilities include the creation of temporary competitive advantages for innovations such as minimal consumption quotas and tax regimes [34]. The market formation function of an IS can be analysed by mapping the number of niche markets and opportunities created for the innovation [33]. Market formation indicators include subsidies to finance investment [301], reforming regulations and market regulations, implementing regulations supporting niche markets and setting tax incentives and tax exemptions [299].

5.3.2.10 F6: Resource Mobilisation

The allocation of financial, material and human capital resources are necessary as inputs to ISs [34], [36]. Innovation systems can also require resources for the development of knowledge activities such as R&D programmes, which thus indicates that resource mobilisation is a prerequisite to **[F2]** knowledge development [33], [34]. Typical resource mobilisation activities, which any IS actor may perform, include investments, subsidies and funding for the testing of innovations with niche markets [33], [34]. Resource mobilisation can be analysed regarding the increase in seed and venture capital, volume and quality increase in human resources and changes in complementary resources [32]. Resource mobilisation indicators include financial incentives, infrastructure developments, acquiring complementary assets [301], subsidies, investments and recruiting human resources (including consultants and technical staff) [299].

5.3.2.11 F7: Creation of Legitimacy

In IS literature, the creation of legitimacy is the formation of institutional compliance and the conception and support of social acceptance for innovations to overcome the obstacles associated with `newness' within a market [288]. Legitimacy is not easily obtained, but forms due to the conscious decisions made by various IS actors [32]. Demand stimulating **[F5]** and the mobilisation of resources **[F6]** support the creation of legitimacy [32]. This function is typically fulfilled by private actors such as industries and NGOs [23]. The creation of legitimacy can be analysed by mapping the size and progression of relevant IS actors and stakeholders and their lobby actions [33]. The creation of legitimacy indicators includes advocacy coalitions and all lobbying activities [299]. A summary of the indicators and typical activities associated with each system function are listed in Table 5.3 [23], [299], [301], [302], [304].

Table 5.3: Indicators of functional fulfilment o the IS functions [23], [299], [301], [302], [304]

Function	Description	Indicators
F1: Entrepreneurial Activity	The transformation of knowledge, interaction networks and infrastructure into beneficial business opportunities	• Projects with commercial aims • Demonstrations • Portfolio expansions • Entry of firms • Manufacturing, constructing, or installing technology
F2: Knowledge Development	All activities associated with learning and the obtainment of information	• Academic research and studies • Market surveys • Feasibility studies and pilot projects • Developing promotional materials and or prototypes • Testing of model performance and model adaptions • Assessing the availability of raw materials for the production of technology • Conducting impact analysis • Technology literacy of entrepreneurs • Learning by doing and using
F3: Knowledge Diffusion	All activities, channels and networks through which knowledge is shared among actors	• Training activities • Alliances between actors • Joint ventures • Setting up branch organisations • Awareness campaigns • Conferences, workshops, seminars, and meetings • Demonstrations
F4: Guidance of Search	The direction of people and resources towards appropriate opportunities and the provision of clarity, visibility and understanding	• Setting policy targets, standards, and research outcomes • Designing favourable regulations and policies • Defining expectations • Promises • Communicating vision • Providing directions or showing interest • Communicate research outcomes to the public
F5: Market Formation	All factors influencing the market adoption of an innovation	• Subsidies (i.e., cost-sharing of investment) • Market regulations • Regulations supporting niche markets • Setting tax incentives and tax exemptions • "Obligatory use" and public procurement • Reforming regulations • Expectation
F6: Resource Mobilisation	The alignment of resources to enable the development, diffusion, and use of innovations	• Financial incentives • Subsidies and investments • Infrastructure developments • Recruiting human resources • Providing equipment
F7: Creation of Legitimacy	The creation of institutional compliance and support of social acceptance for innovations to overcome the obstacles associated with `newness' within a market	• Lobbying activities • Advice • Advocacy coalitions

5.4. The life cycle of technological innovation systems

In a recent innovation study by Markard [167], the TIS framework was placed in relation to the industry and technology life cycles (discussed in § 4.2.3 and §4.2.4). This section explores the relation of the TIS framework to the industry and technology life cycles. First, the similarities and differences between industries and TISs are presented. Thereafter, the foundation of the TIS's development is reflected. Finally, the section presents the technology innovation system compared to the industry and technology life cycles.

5.4.1. Industries vs technological innovation systems

In TIS literature, more and more studies have been conducted on novel technologies that are associated with the formation of new industries, such as wind and photovoltaic energy studies [34]–[36], [305]. These authors, along with Markard [167], have argued that industries and TISs are similar as they both focus on a specific product (industry) or technology (TIS) and can be defined at a similar level of aggregation. However, they found that industries and TISs differ conceptually as industries typically comprise enterprises that produce the same product. In contrast, TISs represent institutional structures and interrelatedness and typically comprise a broader range of actors such as universities, NGOs, suppliers, and associations. These authors, therefore, concluded that a TIS may overlap and interact with several industries [167].

As a TIS may include actors directly involved in a technology's development and actors indirectly involved who form part of the more extensive network that supports the focal technology, such as service providers, a TIS may overlap the industries these services form part of. An example that supports this argument includes the TIS of online streaming technology as it overlaps with the film, television, games, publishing, music, and radio industries. These authors' argument is thus deemed warranted as it seems that TIS may overlap and interact with several industries.

5.4.2. Foundation of the technology innovation system's development phases

The early-stage technology innovation system (TIS) comprised the study of existing industries intending to evaluate these industries' abilities to generate novel technologies and arrive at policy suggestions to improve their performance [32], [40]. Innovation scholars implicitly assumed that the underlying system structures were stable over time and already positioned at the time of analysis.

More recently, a new dimension of the TIS concept developed as TIS scholars began to study the development of novel technology and thus the formation of new industries [24], [40], [299]. Within this new dimension, specific organisations, institutions, and networks that support the technology develop alongside the novel technologies. Co-development of the TIS and its underlying focal technology thus occurs.

According to Markard [306], the concept of co-development of a TIS and its underlying focal technology is essential to the understanding of the TIS life cycle perspective. The TIS life cycle perspective is built on the foundation that the TIS and its underlying focal technology emerge simultaneously and develop, mature, and decline together [167]. Thus, when the technology or product in which it is incorporated is not produced or used anymore, the TIS discontinues as the former suppliers or customer segments have ceased to exist or turned to other technologies. This, however, does not mean that all former suppliers of customer segments cease to exist; they merely exit the focal TIS and turn towards other technologies [167].

The concept of co-development thus contrasts with the early-stage technology innovation literature assuming that structures were stable over time and mobilised by firms to survive significant technological changes [32], [40], [167]. However, in a paper by Bergek and Jacobsson [305], the IS authors built on the industry and technology life cycle literature and distinguished two phases in a TIS's development. The first phase comprised experimentation with competing technology variants, frequent entry and exit of products, low market volumes, and a high degree of uncertainty. The second phase comprised a growth phase in which technology was said to diffuse widely, and the market rapidly expanded. A paper by Bergek *et al.* [32] later defined these phases as the formative and growth phases. According to Bergek *et al.* [32], the formative phase is characterised by a rudimentary structure that is formed as the entry of firms and organisations starts, and institutional alignment and the formation of networks are initiated. In contrast, Bergek *et al.* [32] describe the growth stage to be focused on system expansion and large-scale technology diffusion through the construction of connecting markets and subsequent mass markets. Furthermore, Bergek *et al.* [32] and Jacobsson and Bergek [35] defined the growth phase as developing self-sustainingly due to positive feedback loops causing cumulative causation. The early phase distinctions identified by Bergek *et al.* [32] and Jacobsson and Bergek [35] laid the foundation for the TIS life cycle perspective that goes beyond the formative and growth development phases to include maturation and decline.

5.4.3. Life cycles and technological innovation systems

The literature on the industry and technology life cycles report regularities in the emergent and maturing phases of industries and technologies [306]. The emergent phase is characterised by a high degree of variation and uncertainty, followed by a more rigid maturing phase characterised by incremental innovation, lower uncertainty and high entry barriers [167]. These regularities form the foundation of the phases of the TIS life cycle. The formative (or emergent) and growth phases correspond with the existing TIS literature and reflect the ILC framework's high uncertainty and variety phase, followed by a rapid growth phase. Similarly, a mature TIS parallels an ILC's phase of stabilisation and a TLC's phase of incremental changes [291].

Table 5.4: Comparison of the Industry life cycle, Technology life cycle and Technological innovation systems approaches [167]

	Industry lifecycle	Technology lifecycle	Technological innovation systems (TIS)
Focus	• Firms • Patterns in industry development	• Technology • Patterns in technology development	• Technology dynamics • System performance
General interest	• Understand and survive industry change • Suggestions for management	• Understand and survive discontinuities • Suggestions for management	• Understand technology dynamics • Sustainability • Suggestions for policy
Key concepts	• Industry • Entry/exit, shakeout • Three stages of the industry lifecycle	• Technology • Discontinuity • Dominant design • The era of ferment vs incremental change	• Actors, networks, institutions, technology • TIS functions • Policies
Key mechanisms	• Economies of scale in R&D • Shift from product to process innovation	• The emergence of dominant design (including struggles over dominant design)	• Interaction of TIS elements • Positive feedback effects
Actors	• Firms in the same market	• Firms in the same market along with suppliers and customers	• Firms, associations, NGOs, policymakers, consumers
Tends to miss	• Institutions, contexts, inter-industry dynamics	• Institutions, context	• Interaction of different technologies

According to Markard [167], it is noteworthy to realise that the ILC and TLC strands of literature are well-matched and have overlapping theoretical roots in evolutionary economics. They also share a common interest in the fate of firms with respect to both industrial change and technological discontinuities. However, Markard [167] suggests using the TIS approach in the context of sustainable development instead of adapting the existing life cycle approaches. First, Markard [167] argues that although institutions are central to sustainable development and transition studies, the ILC and TLC framework neglect their influence. The TIS framework, however, awards equal weight to actors and institutions. Furthermore, the TIS framework focuses on the role of public policies (central to addressing technology change associated with sustainability targets) as the framework explicitly targets policymakers rather than managers, such as the ILC and TLC frameworks [299]. Additionally, the TIS framework highlights social mechanisms such as collaboration between actors based on shared visions which studies have proven relevant to the context of sustainability transitions [24], [167], [299]. Table 5.4 compares the industry life cycle, technology life cycle, and technological innovation system approaches.

5.4.4. Phases of TIS life cycle development

Markard [258] distinguished four TIS development phases similar to the industry life cycle. These phases include the formative phase, growth phase, mature phase, and phase of decline, as presented in Figure 6.12. A mature TIS corresponds to the industry life cycle's stabilisation phase and the technology life cycle's incremental changes.

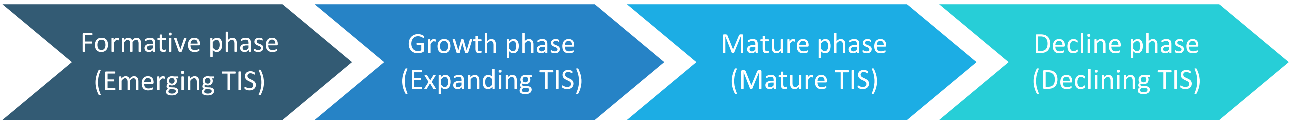


Figure 5.5: Phase of the TIS life cyle

This section reflects on the TIS life cycle phases identified in IS literature. It is important to interpret these phase descriptions as mid-phase variances as a TIS in the middle of one phase differs significantly from a TIS in the middle of a more mature phase. In addition, the changeovers between phases may be relatively smooth, making it challenging to elucidate definite boundaries between phases [167].

5.4.4.1 Formative phase

The formative phase of a TIS is characterised by very few actors, low structuration, a small number of sales and very little growth. Actors of the merging TIS are primarily focused on research and development, experimentation and developing prototypes [167]. Numerous competing ideas and a large variety of technology designs exist. Applications and performance parameters are still ill-defined. Consequently, it is uncertain which conceptualised ideas will develop through the Valley of Death and whether there will be profitable applications or customer demand. Financial resources are primarily obtained from R&D funding, often from public agencies. Vertical integration is high because no specialised suppliers or vendors are available yet [307]. Informal technology-specific institutions exist, and cognitive institutions play a crucial role [168]. Furthermore, an emerging TIS is highly dependent on context structures such as academic institutions and research programmes, societal trends and sustainability challenges and utilises them to create advocacy. Consequently, TIS actors establish relationships with the context structures [167].

5.4.4.2 Growth phase

The growth phase of a TIS is said to be characterised by high growth and entry rates [167]. It may also comprise a shakeout with high exit rates. In this phase, the sales volumes are much higher but still below the market's potential. The expanding TIS contains an increasing number of actors in various roles with increasing levels of specialisation. Intermediary actors, such as technology-specific associations and standardisations, are established. Institutional structuration increases, and formal institutions such as interoperability standards, norms or safety regulations develop. According to Bergek *et al.* [32], value chains are established, and actors regularly collaborate. Performance parameters and technology applications are also more formalised and widely accepted. Consequently, a dominant design may emerge. The relationships or affiliations between the TIS and its context also multiply, resulting in conflicts that may arise [167].

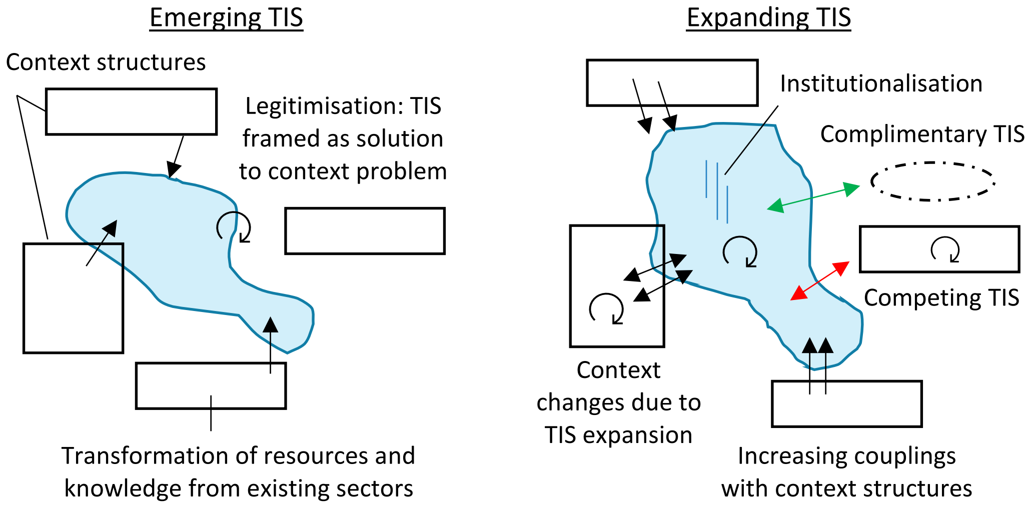


Figure 5.6: TIS-context interaction during the formative and growth phases [167]

5.4.4.3 Mature phase

A TIS's mature phase comprises high sales, slowed growth, and low firm entry and exit rates. Its actor base has been found to be characterised by a high degree of specialisation and a high stability degree of structuration and institutional. Numerous service-providing organisations exist, and complementary products are available for the focal technology. Products and applications are clearly defined, and the technology is widely known. Value chains and inter-firm networks are well established and stable. Technology performance is high and might branch into new application fields. The TIS and its context are co-dependent, and a vast number of affiliations exist between the TIS and its suppliers, end-users, and infrastructures in its context. The TIS' close affiliations with its context and the high degree of structuration results in a mature TIS that is path-dependent and relatively resistant to change.

5.4.4.4 Decline phase

During the decline phase, sales decline rapidly, and more actors leave the TIS. As a result, intermediaries are no longer relevant, and established value chains, networks and technology-specific institutional structures disassemble. Technology designs and performance parameters may be examined, and lobbying might increase in a mitigation attempt. Conflict amongst actors also increases. Finally, in response, established affiliations with the context structures disassemble, and complementary industries may also decline.

Table 5.5 summarises the four TIS development phases. These descriptions of the TIS life cycle phases assume ideal conditions, which may not hold for every TIS. For example, there may be rapidly growing technological ISs in which there are still competing designs. Due to the rapid expansion, these TISs may also be confronted with significant resistance in the growth phase [32]. Furthermore, not all TISs will develop through each of the four phases. For example, an emerging TIS may never develop beyond the formative phase due to the hurdles in the Valley of Death [36].

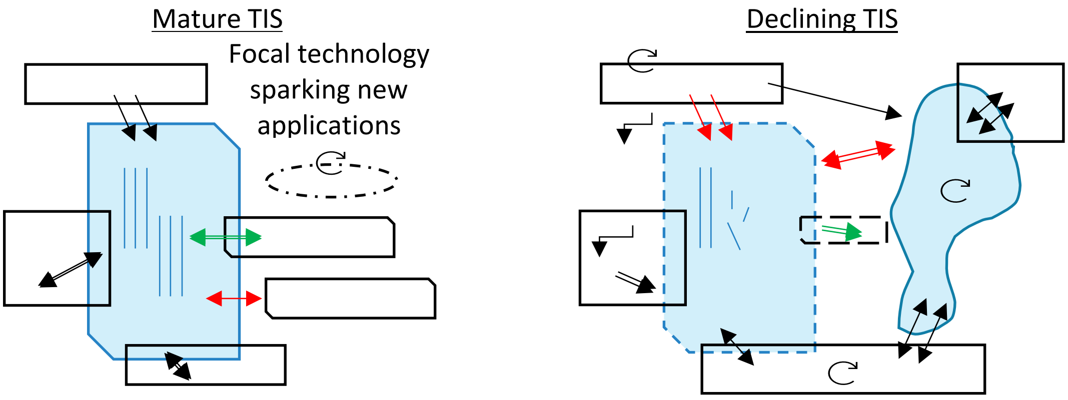


Figure 5.7: TIS-context interaction during the mature and declining phases [167]

Table 5.5: Phases of a TIS life cycle [167]

	Formative phase	Growth phase	Mature phase	Decline phase
Size and actor base	• Sales close to zero • Little growth • Small number of actors • High degree of vertical integration • Low entry/exit rates	• Sales are moderate at first but grow rapidly • Medium to large number of actors in different roles • Specific associations and intermediaries emerge • High entry rates • Strong competition and struggles over standards	• Sales are high • Low growth • Medium to large number of actors • High degree of specialisation • Low entry/exit rates • Potentially dominant players • Little conflict	• Sales below maximum and declining • High exit rates • Intermediaries lose influence • Increasing conflict
Institutional structure and networks	• Low structuration • High degree of uncertainty • Cognitive institutions central • Loose networks, incomplete value chains	• Increasing structure • Markets take shape • Technology-specific institutions emerge • Increasing formalisation • Collaboration in networks	• High degree of structuration • Uncertainty low • Established markets, value chains and networks	• Structural destabilisation • Norms/designs questioned • Struggles over institutions • Networks break up
Technology performance and variation	• Performance parameters unclear • Performance low compared to existing TISs • Technology has a high degree of variation	• Performance parameters clear • Performance increasing • Variation decreasing • Potential emergence of dominant design	• Performance increasing • Potential branching of technology to new application contexts	• Performance parameters potentially questioned
Context and TIS-context relationship	• TIS depends on its context and adapts to it • First affiliations emerge	• Affiliations to context multiply and formalise • TIS has an increasing impact on its context • Potential conflicts arise • Co-dependence	• High number of close affiliations • Interaction of TIS and context • Co-dependence	• Affiliations break up • Dependent context structures decline

5.5. Innovation system evaluation approaches

In IS literature, IS scholars have utilised and developed several approaches to evaluate their ISs or the dynamics within the systems. This section reflects on eight of the popular evaluation approach IS scholars have used.

5.5.1. Component-based approach

The *component-based (structural) approach* focuses on the four system structures discussed in §0. This approach argues that as the system structures perform the innovation activities within the IS, the system structures have the most significant influence on the system's performance [308]. The performance of an IS can therefore be evaluated according to the presence and quality of its system structures and their capacity to stimulate innovation [27], [32], [33], [296].

Within this approach, all the structural elements within the IS are first identified. Thereafter IS failure matrixes are developed to identify system failures or blocking mechanisms within the system [308], [309]. Within the IS failure matrixes, different IS actors, such as company actors, demand actors, knowledge institutes and third-party actors, are placed against systemic failure types to identify where and why failures have occurred [309]. These failure types include infrastructure, institution, interaction, capability, market structure, policy coordination and demand articulation failures. The approach is therefore useful to researchers and policymakers as it can be used to analyse where system failures occur, identify which actors are hindered, justify the policy choices of actors or failures and analyse existing governmental policies to identify if the right actors and failures are addressed [309].

To support the identification of the IS structures in the component-based approach, Hekkert *et al.* [299] suggested questions to guide the identification of the system structures in the application of the component-based approach. Furthermore, authors such as Chinseu *et al.* [310], Lizuka [311], Arora [312] and Lundvall [282] have utilised the component-based approach in their TIS studies. Their applications range from agriculture to renewable energies and inclusive innovation.

Table 5.6: Questions suggested by Hekkert *et al.* [299] to guide the identification of the system structures

IS structures	Questions to guide the identification of the system structures
Actors	• Who are the actors? • Industry - describe the value chain of the different technological trajectories • Which parties develop knowledge and where are the knowledge producers located? • How much knowledge is developed? • Are the education needs met? • What are the types of organizations involved in knowledge production? • What does the market look like?
Networks	• Which parties try to engage in collaboration between different parties? • What does the network look like?
Institutions	• What are the policy goals related to the TIS?
Infrastructure	• What are the technological trajectories?

This approach has, however, received criticism from IS authors [27], [32], [309]. Authors have stressed that this approach alone constitutes an inefficient basis for the evaluation of ISs as the activities performed by the system structures also largely contribute to the IS performance as they make the structures meaningful [27], [32], [309]. Bergek *et al.* [32] have also noted that it is almost impossible to evaluate the effectiveness of a structural element or groups of elements without referring to its influence on the IS functions [32].

5.5.2. Function-based approach

The *function-based approach* emerged as a result of the critique *component-based approach* received. This approach highlights the seven system functions discussed in § 0 [27], [32], [308] as the dynamic aspects of the IS that are important for the performance of the system. Therefore, this approach argues that the performance and overall functioning of the IS is best indicated in terms of how well the individual system functions are fulfilled [27], [313]. The approach is therefore focused on what is achieved in the system rather than by whom it is achieved [32].

Within this approach, the functions of an IS is first mapped to obtain a clear indication of the current fulfilment of the functions, known as the *functional pattern* [32], [33]. Secondly, desired functional patterns are developed against which the current state of the functions are then evaluated to determine how well the functions are being fulfilled [32]. Thereafter the mechanisms that induce or hinder the development of the functions towards the desired patterns are identified [32], [38], [308]. Important policy issues can then be identified, and recommendations can be derived with regards to the functional patterns [23], [32], [33], [39].

However, this approach has received critique as authors have also argued that this approach alone constitutes an inefficient basis for evaluating ISs. Critique includes the argument that IS structures make IS functions meaningful, and that structural alterations are always necessary for function improvement [27], [32], [33]. Wieczorek and Hekkert [27] explained this argument by noting the necessity of, for example, actors for the knowledge diffusion function (F3) to occur.

Despite the criticism, the functional approach has been utilised in numerous TIS studies [27], [33], [314], [315]. More recently, it was utilised in two TIS studies on developing and adopting renewable energies in developing countries such as Iran and Kenya. In the studies, authors Esmailzadeh *et al.* [316] and Wandera [300] utilised the IS functional indicators, as listed in Table 5.3, to score the fulfilment of each TIS function. For example, if their TIS fulfilled five out of a function's ten indicators, the function scored a value of 50%. Policy recommendations were then derived to support the TISs in improving their functional ratings.

In addition to the criticism that the function-based approach alone constitutes an inefficient basis for the holistic evaluation of ISs, authors Esmailzadeh *et al.* [316] and Wandera [300] reduce the effect of the function-based approach. Although the scoring of the functional indicators identified in the studied TISs presents the author with a current-state view of the studied TIS, the perspective is limited as the interrelatedness of the functions (and their indicators) is not captured. Therefore, suboptimal mitigation strategies may be developed for the to-be state of the TISs as the underlying dynamics of the TISs are not captured or considered. Consequently, this approach is not merited in this study.

5.5.3. Component-function approach

As the critic of both the component- and function-based approaches indicated that IS structures and functions are mutually dependent, the component-function-based approach was developed as an integrated, comprehensive approach to analyse ISs and derive policy suggestions that improve IS performance. It provides system analysts with a comprehensive overview and explanation of the system's operations and elements that influence innovation trajectories [27], [32], [308]. This approach is, therefore, said to provide a more accurate and all-inclusive basis for policy suggestions than the two separate approaches [27].

Similar to the component-based approach, this approach starts with identifying all the IS's structural elements and their capabilities. Thereafter, the IS's functions are mapped and evaluated based on their performance so that a clear indication of the IS's *functional pattern* can be obtained [27], [32], [33]. Next, each IS function is examined from the perspective of each of the four IS structures (Table 5.7) [308]. Finally, analysing the functions through these perspectives then provides insight into why a specific function is absent or weak in relation to a specific actor, interaction, institution or infrastructure [27], [296].

Table 5.7: The component-based approach where the IS functions seen through structural elements of IS [27]

System function	Structural element
F1: Entrepreneurial Activities	Actors
	Institutions
	Interactions
	Infrastructure
…	…
F7: Creation of Legitimacy	Actors
	Institutions
	Interactions
	Infrastructure

This method was introduced by Wieczorek and Hekkert [27] and has since been utilised by numerous authors. For example, Lamprinopoulou [308], Hornum and Bolwig [317], and Reichardt [318] have used in studies on the field of agriculture, Grobbelaar *et al.* [22], van der Hilst [29] and van der Merwe *et al.* [281], [288] in the field of inclusive innovation. Different variants of this approach are often found in literature as IS scholars identify different approaches to integrate the two approaches and conduct the component-function-based analysis.

5.5.4. Other methodologies also described in literature

The *triple-helix model* focus on three IS actors: universities, industry, and governments. This model assesses the ISs through these actors' presence, quality and activities and focuses specifically on the relations and interactions between them [296].

The *data envelopment analysis* method is one of the most mature efficiency evaluation methods. This method uses mathematical techniques capable of managing various variables and constraints to evaluate the relative efficiency of Decision-Making Units [319]. It has been utilised by IS authors as the evaluation is objective, and the analysis of the IS's influence on the system outputs provides managers with useful decision information [296], [319].

The *system failure framework* presents an alternative view ISs of analysis by identifying the types of failures associated with the elements of ISs [309]. These pertain to, among others, the IS structures, the adoption of innovations (transition failures) and market failures. The framework aims to analyse an IS's systemic performance and design innovation policies to address inadequacies [320]. Therefore, the framework analysis the system to identify what kind of systemic failures occur, justify IS-based policy choices the actors or failures focus on and then evaluate the current relevance and sufficiency of the existing governmental policies before deriving policy support suggestions [309].

The *system dynamics approach* comprises a perspective and set of conceptual tools that enable understanding the structure and dynamics of complex systems [321]. It aims to conceptualise the complex behaviours in systems through qualitative and quantitative models and to model the expected behaviour of systems [322]. It, therefore, embraces the construction of causal loop diagrams that describe a system's causal assumptions and often includes quantitative modelling through stock and flow diagrams. The *system* *dynamics approach* has been found to be particularly useful in improving the understanding of IS's nonlinear behaviours of ISs [294], [296].

Although the *component-based approach, function-based approach, triple-helix model,* and *data envelopment analysis method* have been utilised in IS literature, they will not be utilised in this study. The separate use of the *component- and function-based approaches* do not present a comprehensive analysis of ISs. Therefore, the component-function approach will be utilised. Furthermore, as the triple helix model only focuses on universities, industry, and governments as innovative actors, valuable contributions by other innovation actors may be lost. Therefore, this study argues that all the enactors and selectors involved in the IS be included in IS analysis. Finally, although the *data envelopment analysis* method is one of the most mature efficiency evaluation methods, the aim of this study is not to evaluate the relative efficiency of decision-making units. The focus of the study is to develop a method that enables an understanding of the IS structures, functions and deliverables that develop in systems over time.

Consequently, the component-function approach seems to be the most comprehensive approach to analyse the structures and functions of ISs as it comprises the study of the actors and the innovative activities they perform along with the relationships, institutions and infrastructure that influence their activities. However, the *system failure framework* and the *system dynamics approach* may also be used to complement the component-function approach. As the system dynamics approach enables an understanding of the structure and dynamics of complex systems through causal loop diagrams that describe causal assumptions of a system, the approach may be used to visually demonstrate the IS functions each actor performs. Additionally, the literature pertaining to the *system failure framework's* system failures may be utilised to identify why the components or functions of the component-function approach are not performing as aimed.

5.6. The systemic innovation policy framework

In IS literature, factors hindering the development have often been labelled systemic problems, weaknesses, or failures [24], [27], [309], [313]. Consequently, a consensus has been reached between IS scholars that systemic failures may be used as an innovation policy rationale to support IS development [299]. Although limited research exists on defining and classifying these problems, the foundation for policy interventions has been argued to be necessary when a systems failure exists [24], [27], [271], [309], [313].

In literature, IS failures have very often been viewed as process failures caused by an uncertain articulation of market demands, overemphasis of risk perception, or a lack of strategic capabilities among actors leading to innovations not being produced or implemented or being insufficient and ineffective for their proposed purpose [288]. Failures have been found to also occur in the output of the innovation, where the innovation is produced and implemented but is not returning its intended social value [299]. Authors have therefore argued that it is necessary to understand and define the underlying principles of systemic problems from the systems perspective.

Wieczorek and Hekkert [223] developed the systemic innovation policy framework to address the critique of the component-based and function-based approaches and address systemic problems. This framework introduced the component-based approach (§5.5.3), where the IS functions are seen through structural elements of IS. Building on the component-based approach, the authors identify systemic problems. To address the literature on systemic problems, the authors developed a typology of the various systemic problems found in IS literature. Wieczorek and Hekkert [27] found that the systemic problems could all be classified as either presence, quality or capability problems. The systemic problems related to actor barriers were awarded to presence and capability problems, while presence, capacity and quality problems were associated with interactions, institutions and infrastructure barriers (Table 5.8) [27], [33], [309].

Additionally, the framework comprises goals and policy instruments to solve the systemic problems identified. The systemic problems, goals and instruments provide analysts with a standardised method to determine why a system is not functioning well and who the responsible IS functions and structures are.

Table 5.8: Typology of the various systemic problems found in IS literature [27]

IS structure	Type of Systemic problem
Actor problem	• Presence? • Capabilities?
Network problems	• Presence? • Capacity or quality?
Institutional problem	• Presence? • Intensity or quality?
Infrastructure problems	• Presence? • Capacity or quality?

5.6.1. Steps of the systemic innovation policy framework

The systemic innovation policy framework comprises five steps, as presented in Figure 5.8. The first step of the framework comprises the identification of the four IS structures along with their capabilities. Stage 2 identifies the functions and related indicator activities in the studied TIS. Next, each IS function's performance is evaluated and scored based on indicators and diagnostic questions collected from the literature, such as, "Are there enough entrepreneurs? What is the quality of entrepreneurship? What types of businesses are involved?" [3, p.84]. Thereafter, the component-function based approach is utilised, and the IS components that caused insufficiencies or the absence of the functions are identified.

Stage 3 then determines why the IS structures caused the insufficiencies or absence of the functions by utilising Table 5.6's typology of the systemic problems and determining the systemic problems of the IS components. In stage 4, the identified systemic problems are then aligned with eight systemic instrument goals and policy suggestions to indicate how the development of the IS should be supported. Finally, in stage 5, systemic instruments are designed from existing literature to fulfil the goals of the systemic instruments. In addition to Figure 5.8, Table 5.9 presents the steps of the systemic innovation policy framework along with the typology of the systemic problems, the systemic instruments goals, and the systemic instruments to solve the systemic problems.

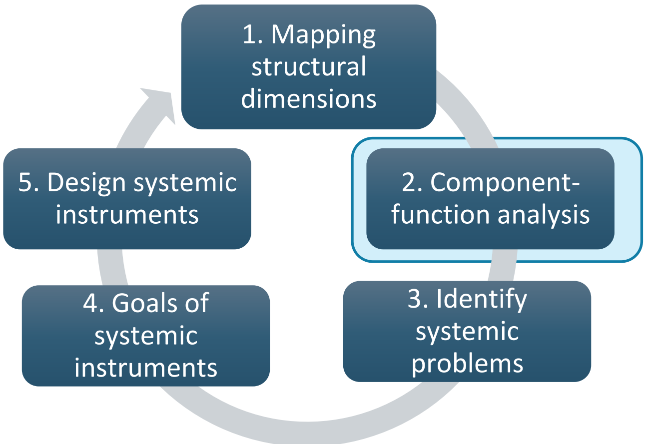


Figure 5.8: The generic systemic innovation policy framework developed by Wieczorek and Hekkert [27]

Table 5.9: The systemic innovation policy framework adapted from Wieczorek and Hekkert [27]

2. Functional dynamics analysed	**3. Reason for functional dynamics**			**4. Goal of systemic instruments**	**5. Systemic instruments**
The IS functions' indicators guide the functions' evaluation	Systemic problems are identified by exploring components, their capabilities and intensity or presence			Evaluation questions for establishing systemic instrument goals	Design systemic instruments
F1: Entrepreneurial activities F2: Knowledge development F3: Knowledge diffusion F4: Guidance of search F5: Market formation F6: Mobilisation of resources F7: Creation of legitimacy	Actor problems	Presence	• Missing actors	• Are we encouraging the involvement of a wide variety of influential actors?	• Focus groups, feedback sessions, and workshops. • New types of partnerships. • Interactive actor involvement techniques.
		Capability	• Weak learning capacity • Weak competency to articulate needs and or develop strategies	• Are we establishing spaces and methods for actor capability development?	• Training and education sessions, workshops, pilot projects, focus groups, and feedback sessions.
	Interaction problems	Presence	• Weak or missing interactions	• Are we motivating interaction opportunities between diverse actors?	• Innovation platforms, collaborative research programmes, and conferences. • Bridging institutions (community liaison, local NGO).
		Capacity	• "Strong" or "Weak" network problems	• Are we avoiding networks that are either too strong or too weak for the specific requirements?	• Training and education sessions, workshops, pilot projects, focus groups, and feedback sessions. • Programme assessment and monitoring.
	Institution problems	Presence	• Missing institutions	• Do we have the appropriate presence of (hard and soft) institutions for the specific innovation in focus?	• Presence of (hard and soft) institutions the specific innovation in focus;
		Intensity	• Insufficient or poor institutions hindering innovation	• Are we avoiding institutions being either too strong or too weak for the specific requirement?	• Avoid institutions being either too strong or too weak for the specific requirement;
	Infrastructure problems	Presence	• Missing infrastructures	• Do we have adequate physical, financial and knowledge infrastructure?	• Motivate physical, financial and knowledge infrastructure;
		Quality	• Insufficient or poor infrastructure	• Are we effective at ensuring infrastructure quality to be sufficient?	• Ensure infrastructure quality to be sufficient.

5.6.2. Previous applications of the systemic innovation policy framework

Several innovation authors have utilised the systemic innovation policy framework and the typology of systemic problems for fault finding in IS analysis [32], [40], [272], [285], [323]–[325]. It has also been utilised in the field of inclusive innovation, where authors have used the framework to either analyse their inclusive ISs or have developed new systemic innovation systemic goals and instruments specifically focused on inclusivity [29], [285], [288], [297].

De Oliveira and Negro [279] adapted the first two stages of the systemic innovation policy framework to address these shortcomings of the systemic innovation policy framework and address the context-specific criticism. They aimed to utilise the framework to examine contextual structures and interaction dynamics of the Brazilian biogas TIS.

To achieve their aim, De Oliveira and Negro [325] adopt the understanding of technologies as a bundle of value chains to explain how biogas technologies interact with and overlap distinct contextual dimensions. The authors argue that by explicitly describing the value chains of a TIS and exploring their most relevant interactions with distinct contextual structures, it is possible to select the relevant contextual structures to analyse. Additionally, they claim that the approach addresses the analytical challenges of the boundary definition for contexts and that the first two stages of the systemic innovation policy framework should be adapted, as presented in Figure 5.9.

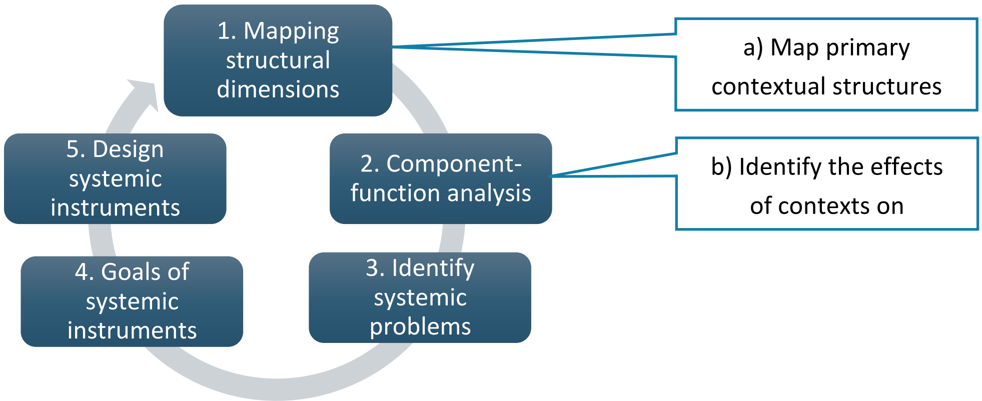


Figure 5.9: The systemic innovation policy framework adapted by De Oliveira and Negro [325]

De Oliveira and Negro [325] argue that the first stage of the systemic innovation policy framework should comprise the definition of the boundaries of the analysis for the focal TIS and the contextual structures. These authors argue that specific agents typically perform value chain activities under certain conditions, which may be institutional, infra-structural, political or geographic. Therefore, identifying these agents and conditions enables understanding how these value chains relate to the TIS contexts. Therefore, in addition to defining the boundaries of the focal TIS, the context should also be determined by considering the agents and activities of the delineated value chains. Furthermore, for stage two, the authors argue that examining how the contextual structures evolved is necessary. This means the analysis must investigate the dynamics of the elements of contexts and their influence.

Additionally, Kushnir *et al.* [324] utilised the TIS and systemic innovation policy framework to systematically explore the Swedish steel TIS's capacity to adopt renewable energy and identify the barriers hindering the adoption. To support the analysis of the IS functions, specifically the F2: Knowledge Development and F3: Knowledge Diffusion functions, and identify the knowledge contributors of the TIS, Kushnir *et al.* [324] utilised node analysis to deepen their quantitative empirics. To identify the knowledge contributions in their studied TIS, the authors gathered all the scientific and patent literature applicable to their TIS. Thereafter, they developed nodes for each document's actors, authors, institutions, and patent assignees. They then indicated the documented collaborations and knowledge-sharing activities amongst the identified nodes as edges to indicate connections. In this manner, the edges between actors, authors, institutions, and patent assignees who often collaborate are thick. Figure 5.10 presents the node analysis conducted by Kushnir *et al.* [324].

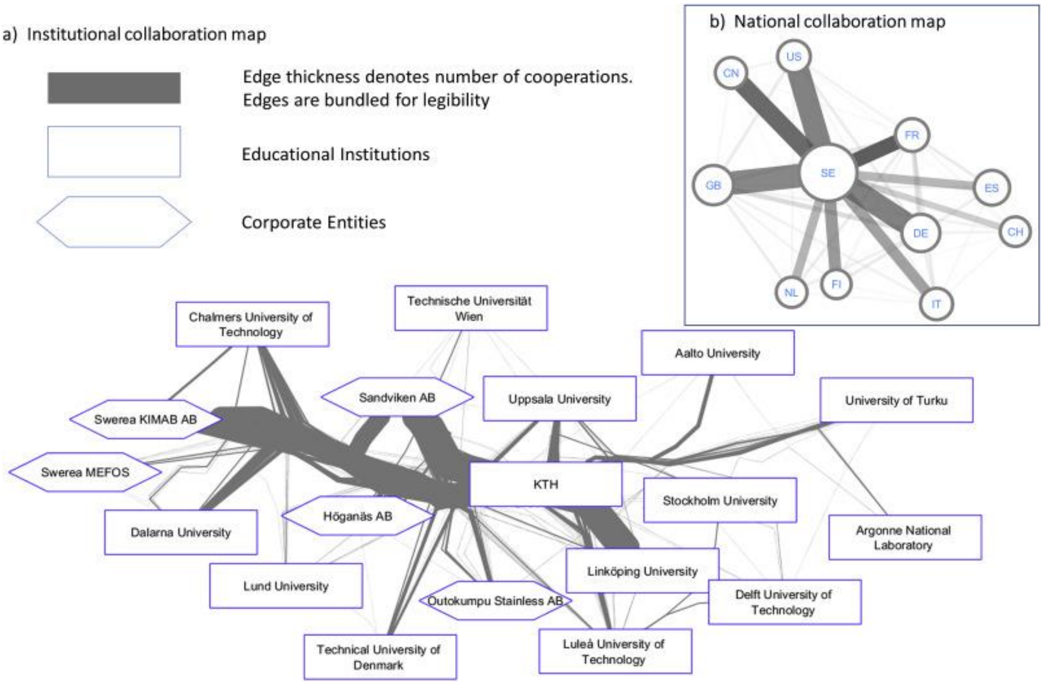


Figure 5.10: Node analysis conducted by Kushnir *et al.* [324]

Although very popular amongst IS scholars, Coenen [326] praises the systematic identification of systemic problems but criticises the generality of the systemic goals and instruments. Coenen [326] argued that a set of eight predefined, broad systemic goals for each IS function does not enable the obtainment of the valuable qualitative data that describes context. Schmidt and Dabur [327] argued that although the generic systemic goals are justifiable, they do not contribute to context-specific interventions or provide analysts with guidance to design and implement other interventions. Additionally, De Oliveira and Negro [325] argue that although TIS scholars have suggested useful generic types of contextual structures such as surrounding TISs, specific geographic sectors, and political contexts, the TIS scholars still struggle to define structural coupling and an external link as the distinction between the focal TIS and different context structures are often blurred [325]. The distinction has therefore been found to be subjected to the IS scholar's opinion.

Furthermore, the systemic innovation policy framework's goals and instruments are often generalised to suit all ISs. Similarly, De Oliveira and Negro [325], Bergek *et al.* [328] and Coenen [326] argue that innovation scholars often overestimate the functioning of a TIS and disregard the influence of the surrounding context on the success or failure of innovations. In line with Markard's studies on the life cycle of a TIS, the authors argue that competing ISs and generic political processes are often disregarded, although they are important factors to consider during TIS analysis.

5.7. Innovation system deliverables

The previous two sections reflected on the approaches IS scholars have utilised to analyse their ISs. This section reflects on the approaches IS scholars have utilised to define or conceptualise the deliverables of their ISs. Some scholars have adopted the notion of outputs and outcomes, while others have adopted the concept of motors of innovation.

5.7.1. Innovation system deliverables as outputs and outcomes

In an inclusive innovation study by Botha *et al.* [297], the need to explicitly define the outcomes studied ISs delivered was argued. They argued that when outcomes are not defined, it is difficult to express and measure how the performance of an IS changes over time. Therefore, they argue that it is necessary to define objectives at the start of a study, define the outcomes ISs deliver and compare old and new outcomes when interventions have been implemented.

Additionally, Botha *et al.* [297] classified the outcomes their studied ISs deliver as outputs and outcomes. Given their emphasis on inclusive innovation, their objective was to define both the results their ISs delivered and the impact the ISs had on their surrounding communities. They defined each as follows.

- Outputs: The measurable and tangible results of the activities conducted.
- Outcomes: The effect (beneficial or adverse) the IS had on the economy, society, the environment, quality of life culture, or public policy service. It is expressed in terms of `capitals', `market' and `non-market' related outcomes.

In their work, Botha *et al.* [297] described outputs to be specific to each IS studied. Outcomes were described to be generalised and serve as a classification typology to determine the type of value an IS creates, both for itself and its surrounding context. Botha *et al.* [297] exploited the literature on capitals, predominantly used in the sustainable development literature, as conceptualised by Sen [329], as classification typology. In their study, Botha *et al.* [297] related the development of the capitals to the IS actors and categorised the capitals according to the actors who contributed to them.

According to the Chartered Institute of Management Accountants' Integrated Report [330], traditional business decision-making focuses primarily on the financial aspects, namely tangible assets and liabilities. However, in recent years, the definition of value creation has relied increasingly more on intangible, socio-economic factors [297], [330]. Therefore, the concept of `capitals' was conceptualised to describe the broad range of resources and relationships ISs used and delivered by an IS [329], [330].

A *capital* may be defined as any resource capable of producing other resources. Bebbington [331] and Sen [329] describes capitals as being more than only resources utilised to deliver other resources but also as assets that enable the *capability* to exist, develop other resources and engage with the surrounding value chain and environment. For example, following this definition, money can be classified a financial capital as it could be invested in an activity that produces desired outputs, such as a product or more money. Table 5.10 lists the capitals found in literature [297], [330], [332], [333].

Authors have found that all capitals are related to and depend on one another [297], [333]. Produced and financial capitals are products of and dependent on human, social and intellectual capital, which in turn are products of and dependent on natural capital. Similar to the cumulative causation generated by the motors of innovation, capitals influence each other and cause cumulative causation (or *upward and downward spirals* as labelled by Emery and Flora) [333], [334]. If financial and produced capital is built at the expense of human, social, intellectual or natural capital, the resource base is cumulatively depleted, leading to imbalance and eventually crisis [333], [334]. According to Sasol [333], during the period of adoption and development, value creation is said to be critical. Therefore, adoption processes that nurture and enhance natural, human, social and intellectual capital, on which the financial and produced capitals depend, are highly valued.

Table 5.10: Capital outcomes [297], [330], [332], [333]

Capital	Description
Business	The establishment of spin-out businesses or corporations
Financial	The financial resources available for investment support, businesses and entrepreneurship, development, and wealth accumulation for future company development.
Cultural	Traditions and shared identity, ethnicity
Human	The skills, knowledge, and capabilities people utilise to enhance other capitals and acquire more skills, knowledge, and capabilities.
Intellectual	Intellectual property, such as patents, copyrights, and licences. `Organisational capital' such as tacit knowledge, systems, procedures, protocols, a brand, and reputation
Natural	The assets, resources, and ecosystem services of the natural world.
Political	The ability to voice needs and have the influence to achieve certain aims.
Produced	The physical assets produced by applying human capital to natural capital to provide a flow of goods or services.
Social	Connections within communities, networks, and the sense of trust, mutual understanding, shared values and socially held knowledge.

Although the use of the development capitals to define IS delivers has not often been utilised by IS scholars, the utilisation thereof is merited. However, Botha *et al.'s* [297] process of relating the development capitals to the IS actors at the end of an IS's analysis may be limited as insight on why particular capitals were or were not delivered may be lost. The development of the capitals may also be related to the IS institutions, interactions and infrastructure that enable or support them. Therefore, similar to identifying each IS structure's influence on the IS, their influence on the capitals may also be studied. However, as the capitals do not have explicit indicators such as the IS functions, the classification of the capitals is subjective to the beliefs of the IS analyst. Triangulation on the classification of the capitals is thus suggested.

5.7.2. Innovation system deliverables as cumulative causation and motors of innovation

In IS literature, IS functions are said to strengthen or support each other over time [23], [24], [33], [35]. A specific function's fulfilment influences another's [33], [36]. For example, completing a feasibility study on additive manufacturing (AM) as a manufacturing technology for hardmetal products contributes to the development of new knowledge **[F2]**. The new knowledge leads to high expectations **[F4]** for AM in the hardmetal industry, which could lead to funding programmes **[F6]** for further research studies on the topic **[F2]**. Therefore, a non-linear model of multiple interactions between functions is expected to positively or negatively affect an IS's overall performance. Hekkert *et al.* [33], therefore, considered the positive interactions and influences the functions have on each other necessary for structural change and systematic

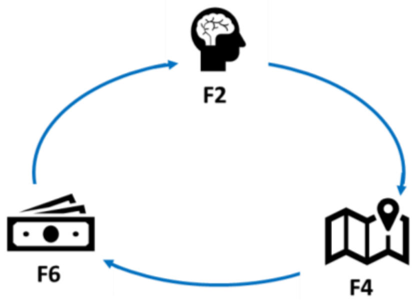


Figure 5.11: Example of a positive feedback loop of the IS functions

innovation. Jacobsson and Bergek [35] went further to explain that these interactions and influences of the functions could lead to positive feedback loops or virtuous cycles of processes of change. In these loops or cycles, the system functions reinforce each other, which leads to the accumulation of momentum, producing a process of creative destruction within the incumbent system [335]. The positive feedback loop of the AM as a manufacturing technology for hardmetal products is illustrated in Figure 5.11.

Negro [36] and Suurs [23] acknowledge that functions could also strengthen each other `backwards', leading to conflicting developments and negative feedback loops or even vicious cycles that reduce the performance of the IS. According to Suurs and Hekkert [24], Suurs [23] and Negro [36], the negative feedback loops include steady-state mechanisms that stabilise development within the IS and eventually stabilise the entire IS. Negative feedback loops are generally said only to become dominant when the sector or technology has started to grow [24]. At the same time, the development stage of an SIS or TIS is predominantly influenced by the positive feedback loops that enforce virtuous and vicious cycles [23], [335].

The virtuous and vicious cycles of interactions between the system functions lead to cumulative causation, also known as motors of innovation [23], [24], [34], [37]. Many forms of cumulative causation or types of motors of innovation may exist within an IS. Myrdal [37] explained that the motors of innovation, therefore, lead to accelerated development or destruction of the IS. Myrdal [37] and Suurs and Hekkert [24] explained the effect the motors of innovation have on the IS by noting that it is not merely the system functions that are influenced by the motors. Instead, they noted that the context within which motors of innovation emerge, the system structures, influence the motors and are influenced by the motors. This means that the motors of innovation emerge from a configuration of IS structures and, in turn, continuously change to reinforce the system functions within these cycles [23], [24]. According to Suurs [23], the development of motors of innovation can only be understood when they are related to the IS structures. By relating the motors of innovation to the system structures, a basis for understanding is provided of how and why specific structural drivers and barriers exist and contribute to the performance of an IS.

The concept of cumulative causation and motors of innovation is very fruitful as it presents IS scholars with the opportunity to identify the mechanism or significant events that caused change or development within a TIS. It thus supports TIS scholars in gaining insight into why specific configurations of IS structures and IS functions led came about and led to specific outcomes. A combination of the cumulative causation approach and the systemic innovation policy framework's identification of systemic problem's step will thus be very fruitful to IS scholars as it sheds light on a system's deliverables due to specific IS structural and functional configurations and the events that led to the configurations, providing a more holistic explanation of a TIS's deliverables.

Additionally, the classification of the motors of innovation and the definition of TIS deliverables as outputs and capital outcomes may perhaps be combined to enrich the insight gained from TIS deliverables. In this regard, the progress of the development capitals may be traced alongside the progress of the IS functions throughout a TIS's development. In this way, a more holistic perspective may be gained on the capitals delivered by an IS. Although this may not be desired by all IS scholars, it may be considered in this study.

To monitor and gain insight into these loops and cycles, the accumulation of momentum and the motors of innovation, Suurs [24], Negro [34] and Hekkert [33] suggest that a flexible, systematic research approach should be used. They argued that during IS analysis, the approach should consider the IS structures, functions and the sequence and contribution of all relevant processes. The method they proposed and united in their studies on renewable energies [24], [33], [34], [36].

5.8. The method of Event History Analysis to study innovation systems

Event history analysis is a qualitative research approach derived from the narrative research design [77]. In narrative research, in-depth insights are gained into a complex phenomenon through the study and analysis of a case [78], [336]. The cases typically studied through this approach are bounded by time and activity and can refer to a programme, system, sector, industry, or one or more individuals. In narrative research, the case information is broken up into activities, referred to as events, which are then reconstructed into a chronological narrative of events [336].

The event history analysis (EHA) methodology was developed as a process approach to conceptualise the changes and development that occur within a system as sequences of events [36], [337], [338]. The foundation on which this methodology has been developed is that events link forward to outcomes and that these outcomes are events themselves that lead to subsequent outcomes, forming a causal network [294], [339].

Therefore, if the sequence through which development and change occur over time is followed, significant insight can be obtained into the paths followed within a system and the dependencies formed [24], [337]. A narrative developed based on the insights obtained can therefore explain the flow of events through the system, the significance of each event, the causal factors influencing the flow of events, the sequence in which the causal factors occurred as well as the amount of time the causal factors operated within the system [36], [337]. Therefore, the narrative provides an overview of how forces initiated as events, how they diffused to subsequent events, and how combinations of events led to the development or destruction of the system [337]. The EHA methodology is thus beneficial as it provides insights into the underlying mechanisms that influence the development and change that occur within a system over time [33].

5.8.1. Event history analysis steps

This method has been utilised in the IS domain to analyse the dynamics and development of specific innovation systems. The application of EHA in conjunction with the IS framework has been applied by several authors, most notably by Negro [34], [36] and Suurs [23], [24], [33]. The EHA steps followed by these authors in their studies on sustainable energies are presented in Figure 5.12 and discussed below.

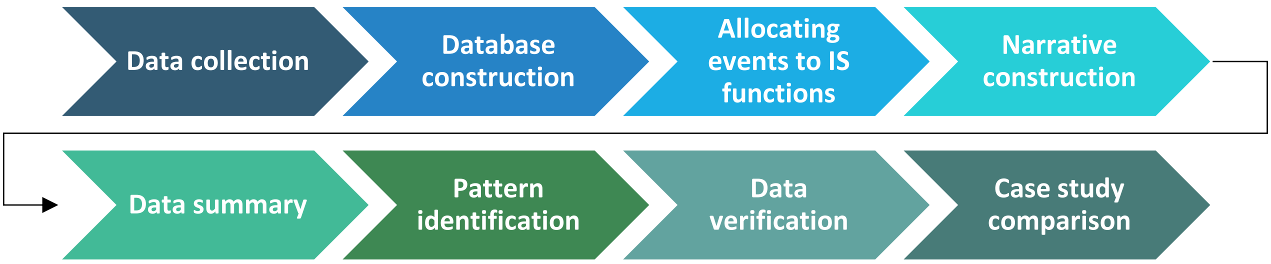


Figure 5.12: Steps of the Event history analysis method

5.7.1.1 Data collection

The first step of EHA is to conduct a comprehensive literature study to find all relevant information on the studied case [34], [36]. Various literature sources may be utilised, including professional journals, periodicals, reports, national strategies, and websites [24].

5.7.1.2 Database construction

When all the available literature applicable to the case study under investigation is found, the literature must be studied and analysed to identify imperative or influential events. As this approach operationalises the system functions by relating them to events, the definition of the system functions and the indicators associated with the functions, as seen in Table 5.2, are used to guide the identification of the events. All the influential events must be identified, not only those directly related to the seven IS functions, as unrelated events could indicate a need for additional system functions [24]. It is also essential that the events are not chosen too `broadly' as `broad' events will be associated with several IS functions, which may lead to confusion [23]. Once the events have been identified, they are stored chronologically in a database table. Negro [34], [36] suggests that the events be awarded event IDs to indicate the sequence in which the events took place.

5.7.1.3 Allocating events to innovation system functions

When all the necessary and influential events have been identified, a database of events in chronological order exists. It is then necessary to group the events into event types corresponding to the functions. It is important to note that the events can have either a positive or a negative influence on the functioning of the IS and that these influences must be indicated in the event database [33].

5.7.1.4 Construction of a narrative

As previously mentioned, the foundation of EHA is the construction of a narrative [23]. Therefore, the development of a narrative is the foundation of each case study. The case narratives are developed from the chronological events documented in the database. The narrative details how the events unfolded over time and influenced or triggered subsequence events. Consequently, the narrative enables an in-depth understanding of the key milestones that occurred in the case that led to particular outcomes and provides valuable insights that could be of use to future cases [294].

5.7.1.5 Data summary

To gain insight into the IS functions' development and their influence within the case study, the fulfilment of the case functions should be tracked over time. To track these fulfilments, Hekkert et al. [27] suggest that the event typology with each event's numerical values be used to develop a timeline graph for each IS function. Therefore, it is suggested that each function is assigned a value of zero at the start of the study. Thereafter, the numerical value of the events can be added to the specific function's numerical value as the timeline of events progresses, and a graph can be drawn of the development over time. In this study, the graphical representation provided an overview of the functional development of the narrative.

5.7.1.6 Pattern identification

After the narrative is constructed and the development of the IS functions are summarised, the event data can be analysed for patterns. Based on the ideas of Poole et al. [195] and Suurs [41], the event data may be subjected to two types of pattern analyses: trend and interaction analysis.

Trend patterns are associated with the fulfilment of the individual system functions and are used to identify important developments in the narrative [23], [24]. Qualitative content analysis may be used to identify the important developments and changes, while qualitative analysis may be used to interpret the change and derive insights from it. To identify the trend patterns, the cumulative number of events associated with each IS function may be plotted on time-based graphs. The graph's slope indicated the number of events associated with the IS functions. Changes in the graph's slope indicate changes or turning points during the case development. To gain insight into what caused the change, the narrative events associated with the time point of the changes should be studied. The graphs then provide an overview of the development of the IS functions over time and indicate the effect of the interaction patterns identified.

Interaction patterns offer possible explanations for the trend patterns identified in each case as they focus on the sequences in which functions occur [23],[36]. If the order in which the functions occur repeats, it indicates an interaction pattern, a causal linkage, that implies a motor of innovation. Therefore, repetitive sequences of events reinforcing their associated IS function are indicative of virtuous cycles. Similarly, repetitive sequences of adverse events are indicative of vicious cycles.

The application of the trend and interaction pattern analyses was not conducted in a specific order as the two analyses strengthened each other. The trend patterns identified change and turning points in the case narratives, while the interaction patterns explained why the changes occurred.

5.7.1.7 Data verification

As only a small amount of quantitative data is used in the narratives, the interpretation of the events and the functions' development is based on the researchers' interpretation. Therefore, although the analysis may be conducted as objectively as possible to minimise bias [23], [24], [36], the event identification, narrative and pattern recognition should be verified using triangulation.

5.7.1.8 Case study comparison

The final step of the EHA is synthesising and comparing the outcomes of the different cases. This is done to present a general insight into the functional dynamics present in different cases.

5.8.2. Previous applications of event history analysis

Innovation system literature has utilised the EHA method previously, particularly in the field of sustainable energies [24]–[27], [33], as it enables the identification and mapping of linkages and engagements between actors, how knowledge and resources are shared and the innovation sequences that over time enable the bridging of the Valley of Death. This section reflects how IS authors have utilised EHA to study their ISs.

5.7.2.1 Event scoring and functional timeline graphs

To document and illustrate how functions developed over time in studied TISs, authors such as Furtado [340], Maarsingh *et al.* [294], Negro [34], [36], and Suurs [23], [24] have utilised a similar scoring method for the TIS events. These authors acknowledge that events may have a favourable or adverse effect on a TIS; therefore, their influence should be noted. For example, the provision of funding benefits a TIS in relation to the suspension of funding. Therefore, these authors utilised the following '+1, +0, -1' scoring method where

- +1 – are allocated to events with favourable effects on the fulfilment of the system functions [23], [34], [294],
- 0 – are allocated to events included in the database to provide context for other related events [23], [34], [294], and
- -1 - are allocated to events with adverse effects on the IS.

Following this scoring method, the authors developed functional time graphs, as presented in Figure 5.13, of the functions' development over time to identify the trend and interaction patterns. The authors also suggest that the studied TIS be divided into phases to support the identification of the trend and interaction patterns.

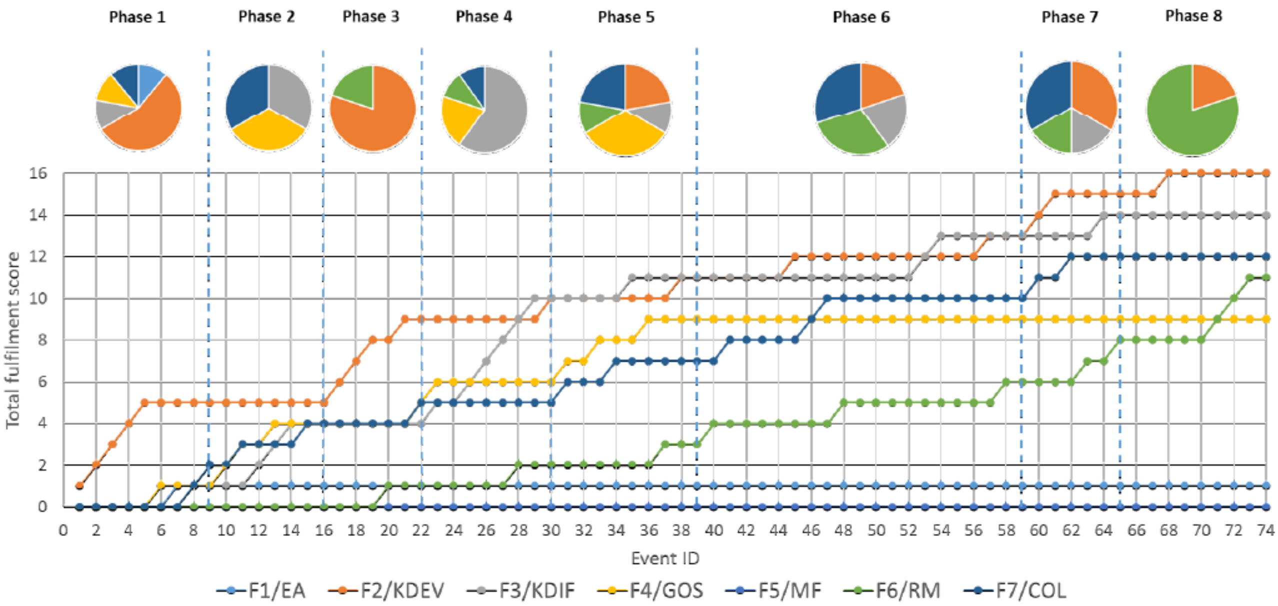


Figure 5.13: functional fulfilment timegrapgh developed by Maarsingh *et al.* [294]

Although the scoring method these authors utilised provides valuable insight into the development of the IS functions over time, these authors did not capture or trace the actors who performed each of the '+1, +0, -1' events. As indicated in Table 5.2, different actors may exist within an IS. Therefore, if the '+1, +0, -1' notation is followed to score events and the actors participating in the events are not captured, valuable insights regarding each actor's contribution are lost as events, and their impacts are unrelated to the actors performing them. The accuracy of the (policy) suggestions derived by the above-mentioned authors may then be questioned as the contributions of different actors are not considered nor studied. Therefore, it may be argued that the insight generated from the combination of the EHA method and the IS framework may be much richer if the actors performing or involved in events are noted.

Additionally, EHA authors tend to either define the outputs of systems in terms of their system-specific outcomes or in terms of the inadequate fulfilment of an IS function. However, the development capitals utilised by Botha *et al.* [297] to define the output of IS may also be utilised in the EHA method. As the development capitals represent value creation in systems in addition to monetary value raised, they are, as motivated by Botha *et al.* [297], useful to the definition of ISs' outputs. Therefore, as the EHA method already captures how systems develop over time in terms of the IS functions, the development of the development capitals may also be traced to define system outputs accordingly in addition to the system-specific outcomes delivered.

5.7.2.2 Process tracking

In a study by Tziva *et al.* [341], the method of event history analysis and the TIS framework are used to understand the dynamics of the Dutch food processing sector. To support the pattern identification step (§5.7.1.6) of the EHA method and analyse whether motors of sustainable development could be identified, the IS scholars utilised the process tracing method.

Process tracing is described as an analytical tool designed to support scholars in drawing descriptive and causal inferences from chronological qualitative data events [342]. According to Brady and Collier [342], an essential step of process tracing is developing detailed descriptions of significant events at several points. While Tziva *et al.* [341] acknowledge that it is impossible to present these descriptions fully, the development of the process tracking chains (Figure 5.14) significantly contributes to the understanding of the processes unfolding within a TIS and analysing its change. Consequently, the study used the process tracking method to highlight the findings relevant to the TIS dynamics and to show the presence of motors of innovation. Furthermore, larger bubbles were used to indicate functions of significant contributions or importance [341].

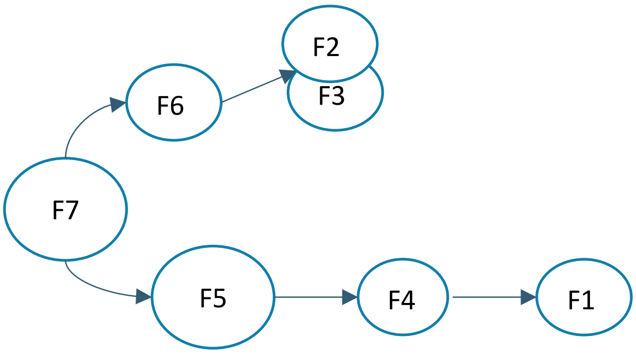


Figure 5.14: Example of a fucntional process chain developed by Tziva *et al.* [341]

As the cases or TISs studied through the EHA method may comprise numerous functions and become quite complex [23], the use of process tacking to support pattern analysis and the identification of motors of innovation has merit. Furthermore, although the interpretation of the bubble sizes may, in particular instances, be subjected to an IS scholar's perspective, the development of functional process chains is very fruitful in defining qualitative data in a quantitative manner. The use of process tracking is thus noted.

5.7.2.3 Causal loop diagrams

Maarsingh *et al.* [294] utilised the functional timeline graphs used by Negro [34], [36] as well as the concept of motors of innovation used by Suurs [23], [24], [33]. Similar to Tziva *et al.* [341], Maarsingh *et al.* [294] used an analytical tool to illustrate the dynamics of their studied ISs. However, Maarsingh *et al.* [294] drew from the literature on feedback loops studied in system dynamics during their application of EHA. To help identify the interaction patterns and thus the causal linkages between the IS functions in the case study, Maarsingh *et al.* [52] suggest using causal loop diagrams. Causal loop diagrams (CLD) are a "*systems-thinking tool that aims to understand systemic relationships over time*" [52, p. 51]. These diagrams helped identify virtuous and vicious cycles as they graphically illustrate cause-and-effects and simplify the dynamic behaviour in terms of its components and the relationships found among them [343].

Similar to process tracking, CLDs indicate feedback through loops of arrows. The arrows represent the relationships between variables of the modelled system, for example, the IS functions, and the arrow tips the direction in which the variables are influenced [280], [343]. Furthermore, as the influence or relationship between variables may be positive (+) or negative (-), the loops indicate the + or - at the upper end of an arrow. Figure 5.15 presents an example of a CLD.

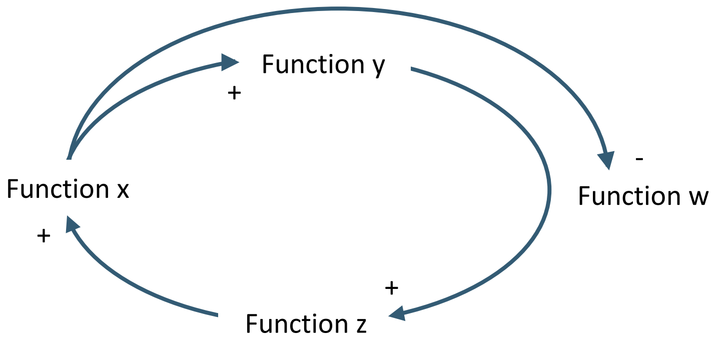


Figure 5.15: Example of causal loop diagram [294]

Similar to process tracking, the use of causal loop diagrams to support pattern analysis and the identification of motors of innovation has significant merit. However, this approach does not include the interpretation of the bubble sizes, which may influence the conclusions drawn from identified motors of innovation or causal loop chains. Thus, although causal loop diagrams may also comprise a form of user bias, the method offers a solution slightly less dependent on user interpretation. Therefore, in this study, causal loop diagrams are the preferred analytical tool to support the drawing and identification of motors of innovation.

5.7.2.4 Typology of motors

In addition to the functional timeline graphs, Suurs [23], [24], [33] utilised EHA to develop the concept of motors of innovation to label the cumulative causation IS functions may cause. Furthermore, Suurs [23] applied the TIS perspective to study the development phases of four sustainable energies in two countries through the IS framework and EHA to determine which motors of innovation were present during each development phase. Although the context and influences of the four energy sources differed, he discovered that similar patterns and results could be identified among renewable energies that were developed in similar contexts.

Suurs [23] identified four motors of innovation. The first motor identified, the *science and technology push motor*, comprised the development of scientific knowledge on technology in various application fields to create positive expectations of the technology leading to government-supported R&D programmes and resource allocations to support further scientific knowledge for the emerging technology. This motor is said to exist during the emerging phases of a TIS [322]. This motor may, therefore, be related to Markard's [167] formative phase of a TIS. The second motor identified is the *entrepreneurial motor.* The *entrepreneurial motor* comprises converting created knowledge into operational artefacts, creating new business opportunities, and enabling enterprises to contribute to developing the technology [23], [322]. The third motor identified is known as the *system building motor.* This motor comprises firms and other actors venturing into innovative projects and establishing platforms to share knowledge, coordinate further technological development, and lobby for resources. The fourth motor identified, the *market motor* (Figure 5.16), comprises the establishment of structures that facilitate demand for the emerging technology and the increase in expectations of the model. Furthermore, the motor comprises the increasing availability of resources, followed by the entrance of new actors into the TIS and the development of market strategies [23].

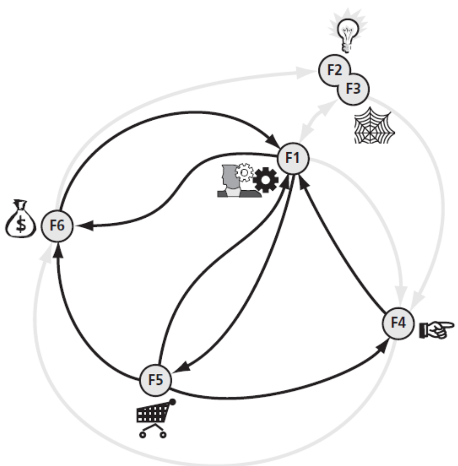


Figure 5.16: Suur's [23] typology of motors with the *market motor* highlighted

For each of the motors, Suurs [23] identified the structural drivers and barriers that influenced the motors and their impacts on the motors' development. This enables the identification of the support required for each motor to be sustained and enables subsequent motors.

Additionally, as it was found that the motors could be placed in relation to the inducts life cycle, Suurs [23] developed a typology of motors. Finally, Suurs derived guidelines for innovation practitioners developing sustainable energies to proceed from one motor to the next, as presented in Figure 5.17. These guidelines were specific to system actors and differentiated between enactors and selectors (*cf. §5.3.1*).

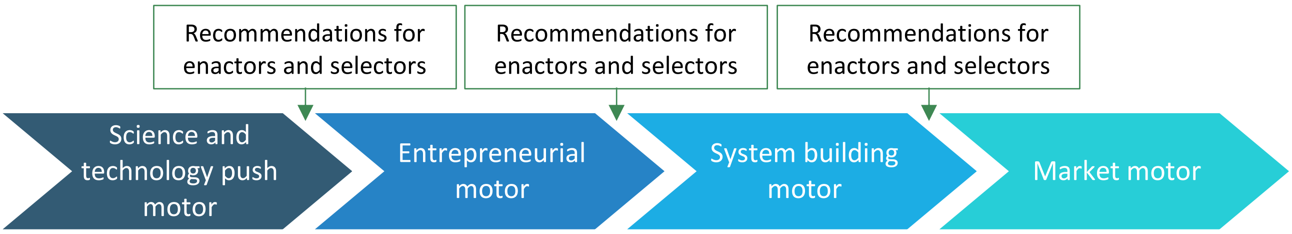


Figure 5.17: Suur's typology of motors of innovation [23]

5.7.2.5 Modelling motors innovation through system dynamics

Building on the motors of innovation studies conducted and Suurs' [23] typology of motors, a recent study by Azad and Ghodsypour [322] developed a system dynamics model to analyse the entities exchanged between the functions of the motors of innovation. These authors argue that the deliverables exchanged and transferred between the IS functions of motors of innovation are of the same importance as the final deliverable of the overall motor as they shed light on the cumulative causation that led to the motor's final deliverable.

In their study on the Iranian petrochemical sector, the authors argued that between each function of a motor of innovation, knowledge (K), a product (P) or resources (R) is either transferred from one function to another or converted to a different form. Additionally, each function's role is related to its purpose of either transferring knowledge, a product or resources or converting knowledge into products or resources. They, therefore, argue that each IS function has an input and output element and an internal conversion process. Their description of each function's input and output element and internal process is presented in Table 5.11.

Table 5.11: Azad and Ghodsypour's [322] performance breakdown of the IS functions in motors of innovation

Function	**Input** Knowledge (K) Product (P) Resources (R)	Output	Internal process
F1: Entrepreneurial activities	R, K	P, R, K	Converting knowledge and resource to product
F2: Knowledge development **F3: Knowledge diffusion**	R	R, K	Converting resources to knowledge
F4: Guidance of search	R, K	R, K	Converting resources to knowledge
F5: Market formation	P, K	R, K	Converting product and knowledge to resource
F6: Mobilisation of resources	R, K	R	Converting knowledge to resource
F7: Creation of legitimacy	R	R, K	Converting resources to knowledge

Azad and Ghodsypour [296] utilised Suur's [235] four motors of innovation to present their model. Figure 5.18 presents Azad and Ghodsypour's [322] model in relation to Suur's [23] *market motor*. Figure 5.18 indicates, following Table 5.11, that between the functions F6 and F1, knowledge is converted to resources. From F1, the resources are transformed into a product for F5, which is translated into knowledge for F6.

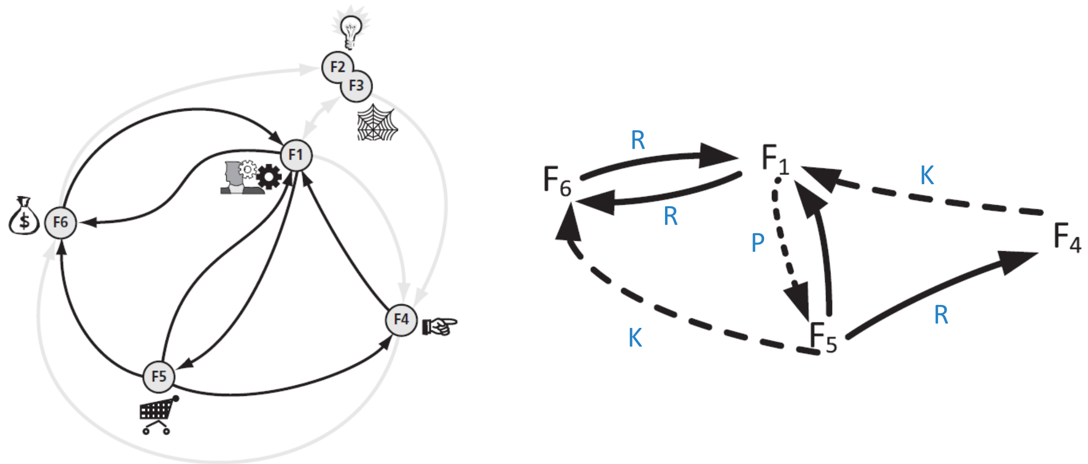


Figure 5.18: Azad and Ghodsypour's [322] system dynamics' model to demonstrate the entities exchanged between functions

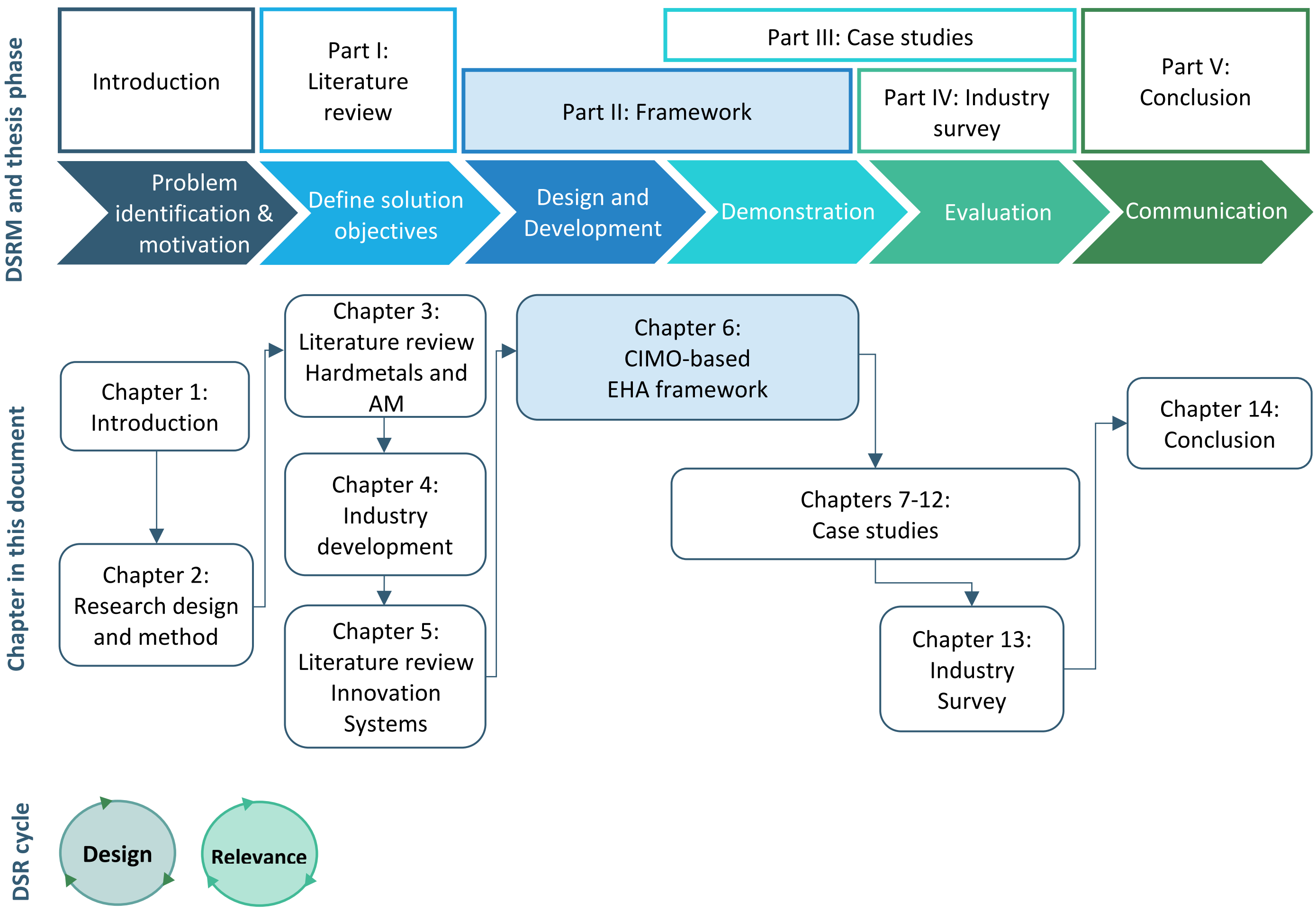
5.9. Chapter 5 summary

The focus of this chapter was innovation systems. The chapter started with an introduction to innovation models and the different types of innovation systems. Next, the components and functions of the innovation system framework were explored. Thereafter, the literature pertaining to the IS framework in relation to the life cycle phases of development were explored. Next, innovation system evaluation approaches were presented, and the component-function approach was identified as the most comprehensive and suitable IS evaluation approach. Subsequently, the systemic innovation policy framework, a popular IS analysis framework, was studied in depth. Additionally, innovation system deliverables and the concept of motors of innovation were explored. Finally, the Event History Analysis method, a time-based evaluation approach often applied to the IS framework, and previous applications thereof were presented. This chapter contributes to objective 1, as mentioned in §1.4.

The subsequent chapter presents Part II and documents the development and validation of the analysis framework.

Part II

Framework



Chapter 6

CIMO-based EHA analytical framework

The previous four chapters introduced the research study and methodology and documented the literature reviews. In this chapter, the analysis framework proposed in this study is presented in some detail. An overview of similar existing frameworks from the literature is first presented. Thereafter, a description of a generic innovation system paradigm within which the proposed framework is set is given. Finally, a high-level overview of the proposed framework is given, followed by a detailed description of its primary components. This chapter was accepted for presentation and publication at the 28th IEEE ICE/ITMC & 31st IAMOT Conference [71]. This chapter satisfies objective VI, as mentioned in §1.4.

Chapter 6 contribution:

- The proposal of a generic innovation system framework paradigm
- The relation of the generic innovation system framework paradigm to the components of the CIMO-logic structure
- The development of a CIMO-based EHA framework to analyse the evolution of innovation systems.

Chapter 6 objectives:

- Introduce similar existing frameworks (§6.1).
- Present the generic innovation system paradigm (§6.2).
- Detail the proposed CIMO-based event history analysis analytical framework (§6.4 and 6.5).
- Present the framework validation and evaluation (§6.6).
- Present the refined CIMO-based event history analysis analytical framework (§6.7).

6.1. Similar existing frameworks

Several frameworks for innovation system (IS) analysis have been proposed in the literature. This section provides an overview of the existing frameworks, highlighting, in particular, those aspects that these frameworks have not adequately addressed.

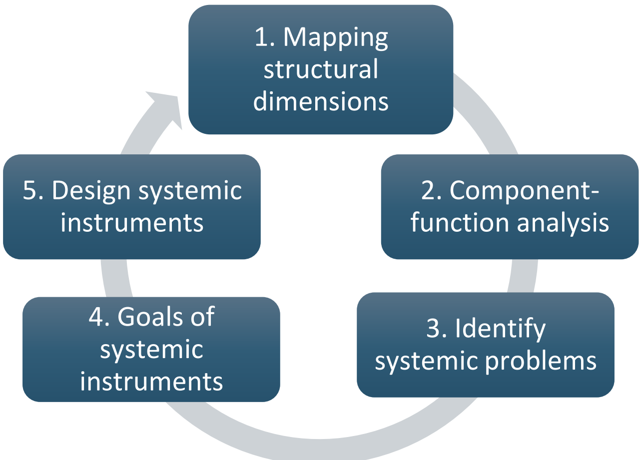


Figure 6.1: The generic systemic innovation policy framework developed by Wieczorek and Hekkert [27]

In a notable paper, Wieczorek and Hekkert [27] presented the systemic innovation policy framework to analyse ISs and solve systemic innovation problems. This approach became popular amongst IS scholars as the core of the framework comprises the *component-function-based approach*, discussed in §4.4.1, and *systemic instruments* to solve systemic innovation problems [27]. As presented in Figure 6.1, in stage 1 of the framework, the IS' structures, namely the actors, institutions, interactions, and infrastructure and their capabilities are identified. Subsequently, each IS function's performance is evaluated and scored based on indicators and diagnostic questions collected from the literature, such as, "Are there enough entrepreneurs? What is the quality of entrepreneurship? What types of businesses are involved?" [3, p.84]. Thereafter, the IS components that caused insufficiencies or the absence of the functions are identified. Stage 3 then determines why the IS structures caused the insufficiencies or absence of the functions by determining the systemic problems of the IS components. For example, whether the IS structures were ineffective, inefficient, or absent. In stage 4, the identified systemic problems are then aligned with the systemic instrument goals and policy suggestions to indicate how the development of the IS should be supported. Finally, in stage 5, systemic instruments are designed from existing literature to fulfil the goals of the systemic instruments. The steps of the systemic innovation policy framework (Figure 6.1) have been utilised to analyse various ISs in the fields of environmental sciences [40], [260], [291], agriculture and biological sciences [308], [344]–[346], as well as the field of inclusive innovation [285], [294], [295], [297].

Although being the leading IS framework [296], [347], the systemic innovation policy framework has received recurring critique. Van der Hilst [29] argues that the evaluating and scoring of functions based on generic indicators from literature does not enable the obtainment of the valuable qualitative data that describes context but instead leads to eight predefined broad systemic goals for each function. Van der Hilst [29] argued that although the generic systemic goals are justifiable, they do not contribute to *context-specific* interventions or provide analysts with guidelines on designing and implementing other interventions.

Following Van der Hilst [29], Markard and Truffer [306] argue that the framework is inward-oriented, not paying attention to the surrounding environment. Additionally, Smith and Raven [348] argue that it primarily regards the innovative success of an IS due to the performance of the system itself. Furthermore, Coenen [326] argues that although innovation scholars often disregard the influence of the surrounding context, the systemic innovation policy framework's systemic goals and instruments are often generalised to suit all ISs. Consequently, Coenen has argued that IS scholars regard the distinction between an IS and context as an analytical choice. He furthermore argued for scholars to pursue a *situationist* boundary-setting approach that empirically traces the IS structures and influential context systems on a case-by-case basis [326].

Additionally, critiques have argued that too much emphasis is placed on institutions and networks between innovation actors within ISs. As the systemic innovation policy framework identifies systemic problems related to the IS components, emphasis has been placed on the necessity of strong networks and institutions between actors. However, Broekel and Boschma [349] and Hekkert *et al.* [33] have argued that strong connections between agents do not ensure enhanced innovative performance but that it may perhaps also harm it.

Therefore, Broekel and Boschma [349] and Hekkert *et al.* [33] have argued for another method of analysis that evaluates the development of IS functions and structural components over time. The literature on ISs stresses the importance of path dependency and cumulative causation for understanding change and long-term innovative development [24], [272], [293]. Therefore, Broekel and Boschma [349] and Hekkert *et al.* [33] have argued for the benefit of such an evolutionary method as the influence of the IS functions and components have on each other could be traced to determine how systemic problems are developed or mitigated throughout the IS's development. Furthermore, insight regarding the influence of the IS's external environment on the IS's development may also be obtained. Authors such as Hekkert *et al.* [33], Suurs [23], [24] and Negro [34], [36] have therefore argued for the adoption of the Event History Analysis method (as described in §4.5.1) as an additional analysis tool of the IS framework.

Following the critique of Wieczorek and Hekkert's [27] framework, several authors utilised the method of Event History Analysis (EHA) to analyse ISs (Figure 6.2) [23], [24], [33], [34], [36]. The method grew in popularity as, unlike the generic systemic innovation policy framework, it provides insights into the underlying mechanisms that influence the development and change within a system over time [33]. In this method, the narrative (case study) provides an overview of how forces initiated as an event, how they diffused through to subsequent events, and how combinations of events led to the development or destruction of the system [337].

Unlike the generic systemic innovation policy framework, EHA does not evaluate systems' functional performance based on indicators. Instead, it uses indicators to guide the identification of IS events and studies the development of the events and the IS functions over time. Similarly, EHA does not utilise systemic instruments to improve system functions as the objective is to study the functions' development, not improve their performance. Additionally, the *component-function-based approach* is not a fundamental step in the EHA process as it is in the systemic framework but is a module that Suurs [23], [24] have utilised to summarise the drivers and blocking mechanisms of the patterns identified in the fifth EHA step (Figure 6.2).

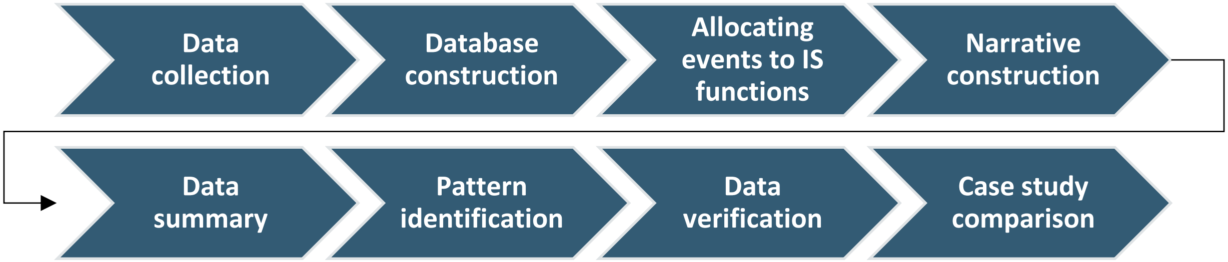


Figure 6.2: Event History Analysis steps

As the *component-function-based approach* is not incorporated into the generic EHA steps, the coding of the event data during *Step three: Allocating events to functions,* only includes identifying the related IS functions and categorising the event as constructive (+1) or destructive (-1). As mentioned in §4.5.1, if the allocation of the events, however, incorporates the actors performing the functions and events, the *component-function-based* analysis would be possible and much richer insight may be gained into a system's development or regression [27], [32], [281], [308]. Similarly, richer *context-specific* recommendations may be derived [29].

A novel framework is suggested to address the shortcomings mentioned for both the generic systemic innovation policy framework and the method of EHA. The proposed framework in this study is distinguished from those in the existing literature largely by the following characteristics:

i. The framework incorporates a *situationist* boundary-setting approach that empirically traces the IS structures and influential context systems on a case-by-case basis [326].

ii. Rather than utilising the generic indicators to evaluate the performance of the IS functions, the framework is *context-specific* and focuses particularly on the development of the IS functions over time to evaluate functional performance. Therefore, generic systemic goals and instruments are not utilised, but *context-specific* instruments are designed.

iii. It combines the component-function-based approach and the EHA method to provide insight into path dependencies, cumulative causation and *why and how* functions developed over time, as well as which events and actors caused change and development.

iv. Instead of merely presenting a case's functional development over time, the framework focuses particularly on the actors who performed the functions and each actor's systemic contribution. The framework, therefore, incorporates actor classification into the event scoring.

v. The framework incorporates the identification of systemic instruments as a module to improve an IS's performance after the system's functional development over time has been studied.

6.2. The generic innovation system paradigm

As mentioned in Chapter 1 and Chapter 2, this study aims to develop a framework for evaluating the development of ISs. Such a framework should preferably be generic and adaptable to various problem settings. To achieve this objective, it is proposed that the framework function within the IS framework paradigm and be modular in nature. Any modules incorporated into the framework may thus be exchanged, modified, or removed according to new literature findings and the objectives of the analysis in question without disrupting the correct functioning of other modules of the framework. Additional modules may also be added to substitute for existing framework modules. Furthermore, basing the framework on the widely adopted IS framework paradigm ensures that all stages necessary for extracting knowledge and insights are included in the framework, thereby preserving its generic nature.

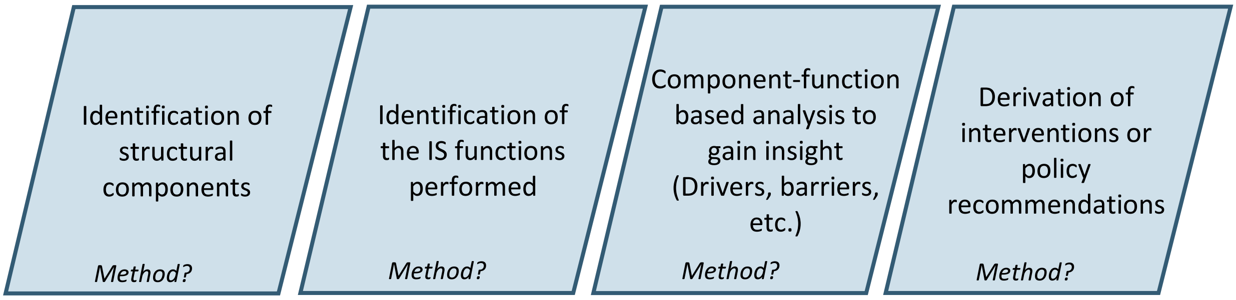


Figure 6.3: A high-level abstraction of a generic innovation system framework paradigm

Figure 6.3 presents a high-level overview of the proposed generic IS framework paradigm derived from the frameworks found in innovation system literature, particularly Wieczorek and Hekkert's [27] systemic innovation policy framework. It comprises four components. The first component identifies the focused system's structures: actors, networks, institutions, and infrastructure. Thereafter, the identification of the activities the IS structures performed, namely, the seven IS functions. Subsequently, the system's performance is analysed and evaluated using the component-based approach, the function-based approach or the component-function-based approach (as the generic systemic innovation policy framework). In this stage, insight may be derived, and drivers and blocking mechanisms or barriers of innovative development may be identified. Finally, given the development drivers and barriers identified, suggestions for improvement and future studies may be derived for IS scholars. Policy suggestions may also be developed for IS policymakers.

These steps form the foundation on which the generic systemic innovation policy framework is built. However, it has not yet fully been implemented into the analysis of the EHA method, presented in Figure 6.2. Furthermore, to incorporate the *situationist* boundary-setting and *context-specific* analysis and recommendation, the CIMO-logic structure (§4.4.1) may be implemented (which has not yet been implemented into the IS framework or the EHA method). Consequently, the proposed analysis framework will shed light on "*what works for whom, in which contexts, in what respects and how"* [10, p. 1].

The CIMO-logic structure relates to the generic innovation system paradigm, as presented in Figure 6.4. As the identification of the IS structures comprises the identification of the actors, networks, institutions, and infrastructure of a focused system, the IS support the identification of the system's starting context. Therefore, identifying the IS structures form part of the *context* definition of the focused IS. Subsequently, as the CIMO *interventions* refer to those activities performed to solve the contextual problem, identifying the IS functions corresponds to the CIMO *interventions* as they are the activities the IS actors perform. Furthermore, the CIMO *mechanisms* are the tools or processes that develop due to the manner in which the *interventions* are performed. Consequently, the CIMO *mechanisms* relate to motors of innovation that develop due to the manner in which the IS actors perform the IS functions (§5.7.2). Finally, the outcomes of the ISs achieved by the motors of innovation relate to the results delivered by the mechanisms, namely the CIMO *Outcomes*.

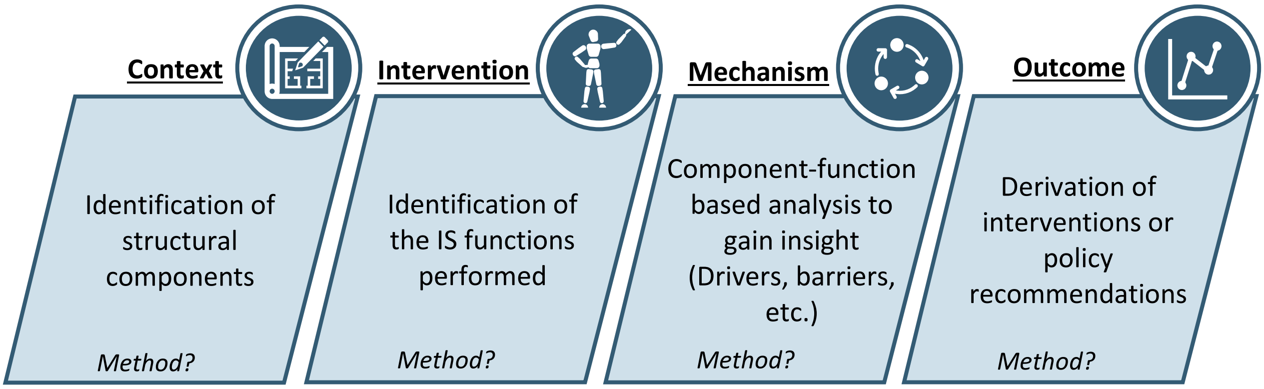


Figure 6.4: The high-level generic innovation system framework paradigm relates to the components of the CIMO-logic structure

6.3. The proposed CIMO-based EHA analytical framework

Given the generic paradigm in Figure 6.3 and the relation between the generic paradigm and the CIMO structure in Figure 6.4, the proposed *CIMO-based Event History Analysis framework* may be introduced. A high-level overview of the framework is presented in Figure 6.5. The *generic* paradigm of §6.2 has been expanded into the *CIMO-logic structure* and incorporated into the *EHA method* to analyse the development and evolution of ISs.

Furthermore, the CIMO structure and the generic innovation system paradigm are incorporated into the analysis steps of the EHA method. Therefore, the CIMO structure is embedded in the *EHA Step four: Data summary* and *Step five: Pattern identification*. Additionally, to enable the component-function-based analysis of the motors of innovation during the mechanism phase, the actors performing the events should be captured during the event identification and allocation phase of EHA. Therefore, the actor identification coding is incorporated into *EHA Step three: Allocation of the events to the IS functions*.

In the remainder of this section, the EHA method with the additional actor coding and the CIMO-based analysis are discussed in detail.

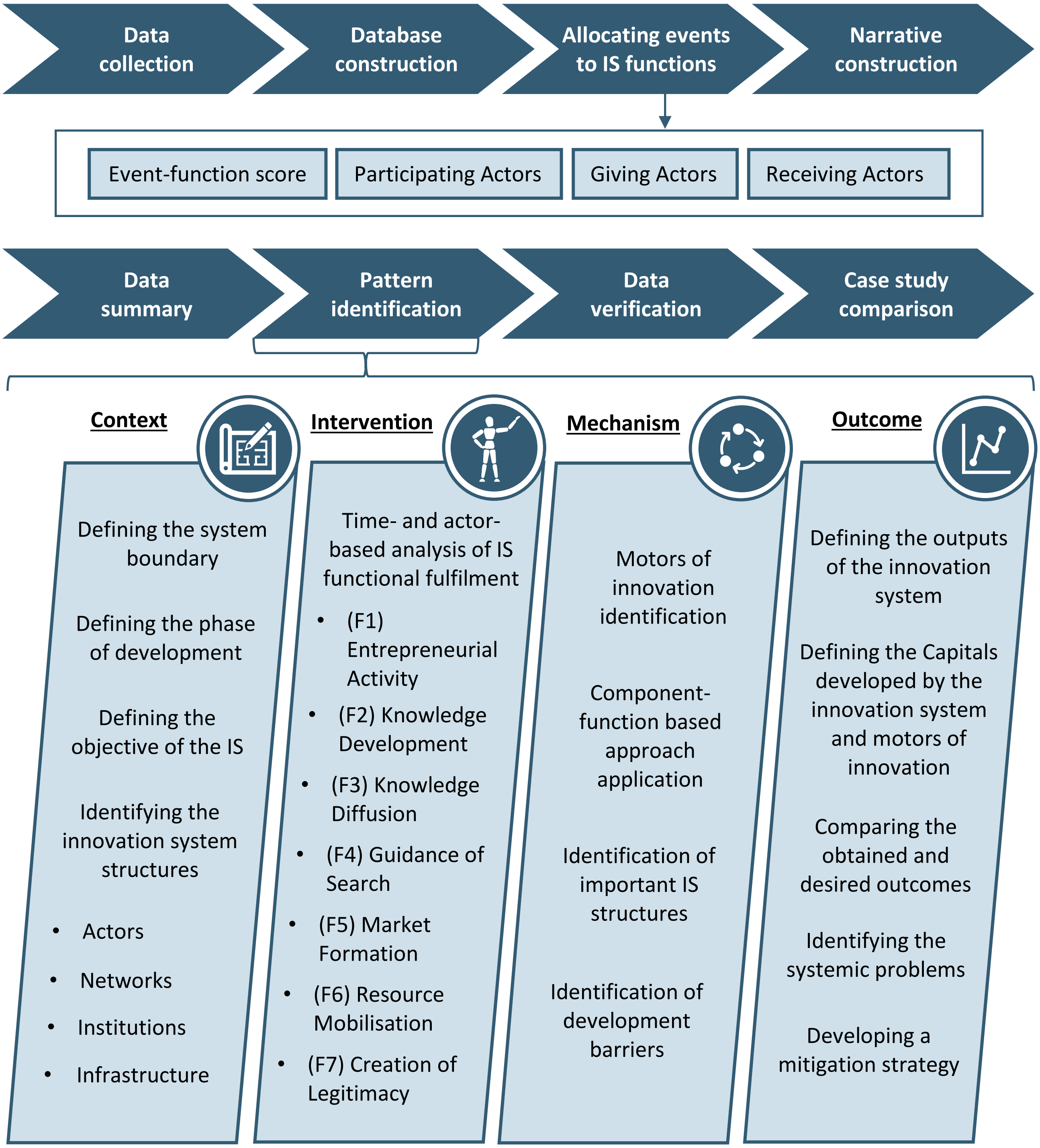


Figure 6.5: A high-level overview of the proposed CIMO-based Event History Analysis framework

6.4. CIMO-based EHA analytical framework: Event History Analysis component

This section reflects on the event history analysis (EHA) component of the CIMO-based Event History Analysis framework. Particular focus is placed on the *EHA Step 3: Allocating events to IS functions* as novel coding categorises are introduced. The CIMO-logic component incorporated into *EHA Step 6: Pattern identification* is explained in the subsequent section.

6.4.1. Data collection

To collect data on the case of the studied IS, as suggested by Negro [36] and Suurs [23], various literature sources should be utilised to gain event information on the studied IS. Therefore, professional journals, reports, national strategies, websites, and newspaper periodicals should be utilised. Research databases, such as Scopus, Google Scholar, SpringerLink, Web of Science and ScienceDirect, that allow the use of search terms are recommended. The selection criteria for the text of the literature sources should comprise event information explaining why events occurred, their effects, and their consequences. For example, a conference was held, technology was implemented, relationships were established, funding was available, and national strategies were released. Incomplete information events should be further investigated, completed, and verified by other sources.

However, if the studied IS dynamics have not yet been documented or are not well documented, key informants should be utilised as information sources. As Suurs [25] suggested, these informants should be heterogeneous and include representatives of all facets of the IS. Additionally, these actors should include both actors actively involved in the IS and actors involved from a distance who know the IS's dynamics.

6.4.2. Database construction

Once the literature on a particular IS's case events have been collected, Cresswell's [50] six-step process for qualitative data analysis may be used to identify the events and event information from data sources. As with the general EHA method, the identified events must correspond to the IS functions. Therefore, the indicators of the IS functions, as discussed in §4.4 and presented in Figure 6.6, should be used as a heuristic to guide the coding search terms and the identification and interpretation of the events. Incomplete event information should again be investigated, completed, and verified by other sources [23]. Once all the events have been identified, the second coding layer should be utilised to categorise similar events. For example, all events related to learning should be grouped. After the event categorisation, the events should be sorted chronologically and stored in a database table. The event database table provides a good overview of the event categories associated with IS's case.

6.4.3. Allocating events to IS functions

Once the database has been constructed, the event categories (from the second coding layer) should be allocated to their corresponding IS functions. As an event may have a favourable or adverse effect on a study, for example, the provision of funding in contrast to the suspension of funding provision, the effect of an event should be noted. Therefore, the events should be scored as follows:

- +1 - The events with favourable effects contribute to the fulfilment of the system functions. within the event database[23], [34], [294].
- -1 - Events with adverse effects on the IS and the IS functions should be scored with a `-1' value.
- 0 - Those events included in the database to provide context for other related events [23], [34], [294].

Entrepreneurial Activity

- Projects with commercial aims
- Technology demonstrations
- Portfolio expansions
- Entry of firms
- Manufacturing, constructing, or installing technology

Knowledge Development

- (Academic) Research studies
- Feasibility studies
- Pilot projects
- Developing prototypes
- Testing of model performance
- Adapting model
- Assessing the availability of raw materials
- Conducting impact analysis
- Market surveys
- Technology literacy of entrepreneurs
- Learning by doing and using

Creation of Legitimacy

- Lobbying activities
- Advice
- Advocacy coalitions actors

Knowledge Diffusion

- Alliances between actors
- Joint ventures
- Training activities
- Setting up branch organisations
- Awareness campaigns
- Conferences, workshops, seminars, and meetings
- Demonstrations

Guidance of Search

- Setting policy targets, standards, and research outcomes
- Designing favourable regulations and policies
- Defining expectations and communicating vision
- Promises
- Providing directions or showing interest
- Communicate research outcomes to the public

Market Formation

- Market regulations
- Regulations supporting niche markets
- Reforming regulations
- Setting tax incentives and tax exemptions
- “Obligatory use”
- Subsidies (such as the cost-sharing of investment)
- Public procurement
- Expectations

Resource Mobilisation

- Financial resources
  - Financial incentives
  - Subsidies
  - Investments
- Physical resources
  - Infrastructure development
  - Providing equipment
- Knowledge resources
  - Recruiting human resources

Figure 6.6: Innovation system functional indicators framework

In addition to the traditional `-1, 0, +1’ scoring of events generally performed by EHA and IS authors [23], [24], [33], [34], [36], [294], [299], the CIMO-based EHA framework captures the actors involved in each event. For example, suppose an enterprise performs an event (function). In that case, it should be noted in the event database to ensure that it is not mistaken for an event performed by an academic actor. Actors may be categorised as government, industry, civil society and academia in accordance with the IS innovation actors.

Furthermore, as events and functions link forward to further events and functions and form cumulative causation, it is important to track the dynamics of the actor involved in an event. Therefore, in addition to noting the actor who performed the functions relevant to an event, the dynamics of the actor should be noted. Some events and functions, such as sharing funding, feedback, or advice, comprise dynamics where one actor provides the funding, feedback or advice and another actor receives it. Due to cumulative causation, the dynamics of both the provider and receiving actors influence subsequent events, which may influence the dynamics of the system favourably or adversely. Consequently, it is important to note the dynamics of provider-receiving functions' actors and categorise them as *givers* and *receivers*.

In contrast, some events and functions, such as conducting a research study or starting a new project, do not necessarily comprise giving-receiving dynamics as an actor merely performs them. It is only once the outcome of the research, or the project is communicated to other actors that the giving-receiving dynamics are present. Therefore, to distinguish the giving-receiving dynamics from the non-giving-receiving dynamics, the actor performing non-giving-receiving functions should be noted as *performers* as their functions are being performed, not shared with other actors. Thus, in the CIMO-based EHA framework, the dynamics of an actor are defined as *performed, giver* or *receiver*.

Therefore, in addition to the traditional database allocation of events to the IS functions performed by EHA and IS authors Negro [34], [36], Suurs [23], [24], [33] and Maarsingh *et al.* [294], the relevant actors involved in each event should be captured in the database and categorised as either *performer, giver*, or *receiver*, according to the context of the event. Table 6.1 provides an example of the format of the event database.

Table 6.1: Examples of events included in Case III's database

Event #	Event date	Event description	Event category (Functional indicator)	IS function and score (+1, 0, -1)	Actors with roles (performer, giver, or receiver)
…	…	…	…	…	…

6.4.4. Construction of a narrative

Following allocating the events to IS functions, the database's chronological events should be used to narrate the IS's case. The IS functions corresponding to the events should be denoted by **[F1/EA, F2/KDev, … F7/CoL]** along with a `-1 or 1' to indicate their influence. Additionally, to ensure that valuable insights regarding each actor's contribution may be lost, the relevant actors should be included in the denotation along with a **(P)**, **(G)** or **(G)** to indicate whether functions were *performed, given, or received*. Finally, the narrative may be divided into phases to simplify the narrative analysis in the succeeding steps [294]. At the end of each phase, the key milestones should be summarised in timeline figures.

6.4.5. Data summary

During the data summary stage, all functions are plotted on function-time graphs so that their development may be studied over time to identify trends. Similarly, the number of events each actor contributed to is presented in graphs. These graphs enable the analysis of the subsequent pattern identification stage.

6.4.6. Pattern identification

For the *EHA step 6: Pattern identification*, the CIMO-based analysis component is implemented and discussed in the following section, §6.5.

6.4.7. Data verification

As only a small amount of quantitative data is used in an EHA study and the interpretation of the events and the functions' development is based on a researcher's interpretation, bias may influence an EHA study. Therefore, to address the bias, the event identification, the narrative and the pattern identification and analysis should be verified and validated using triangulation ()[23], [24], [36].

Therefore, in addition to literature sources, interviews with various key informants involved in the studied IS should also be exploited to verify the information obtained from the literature sources [36]. The interviews ensure that only meaningful and influential are included in the IS's analysis and that they are appropriately defined according to their functional fulfilment. Furthermore, the key informants may validate the coding of the narrative events [29]. Additionally, IS field experts not involved in the studied ISs should be consulted to ensure the validity of the CIMO-based EHA analysis of the studied IS.

6.4.8. Case study comparison

The preceding seven steps should be applied to each case when multi-case studies are studied. Each case will reveal dynamics, patterns, cycles, and motors of innovation specific to the case context. The conclusions derived from each case may then be compared to validate the cases' analysis once again and to derive more general, inclusive insights and explanations of how dynamics, patterns, cycles, and motors of innovation generally come about. Figure 6.7 summarises the EHA steps to be followed.

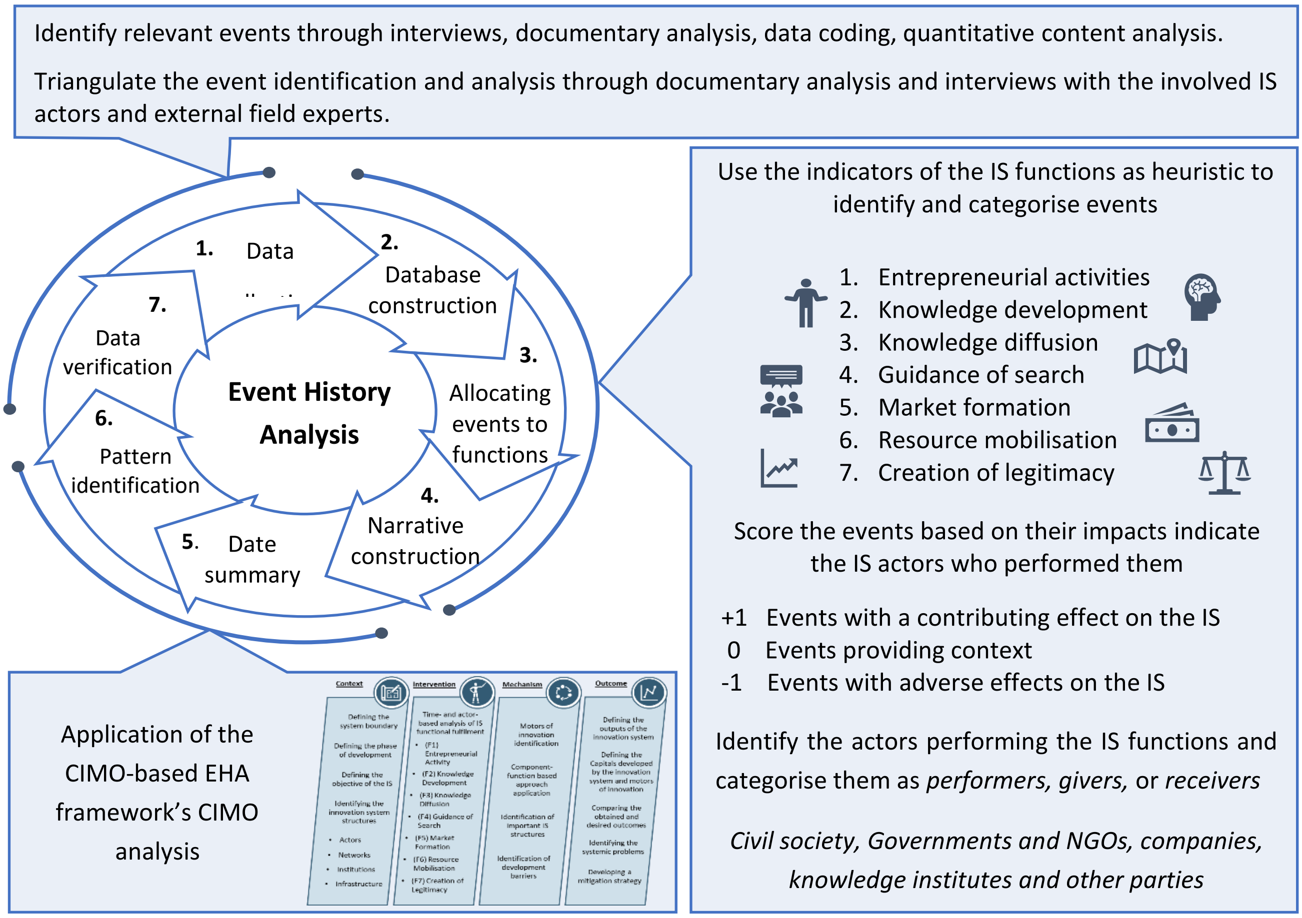


Figure 6.7: The Event History Analysis steps followed to identify the Interventions and Mechanisms of an IS

6.5. CIMO-based EHA analytical framework: Novel CIMO-based analysis component

This section details the novel CIMO-based analysis incorporated into *EHA step 6: Pattern identification* to address the critique of IS scholars on the original Event History Analysis method and the generic systemic innovation policy framework.

6.5.1. Context

As mentioned in §4.3, *Context* refers to the surrounding, external and internal environmental factors and the nature of humans that influence behavioural change [253], [254]. Therefore, before a case narrative or section of a case narrative may be analysed, it is essential that all factors – internal, external, individual, interpersonal, institutional wider infrastructural – are considered at the start of the analysis [250].

Consequently, as presented in Figure 6.5 and Figure 6.8, the *context* definition of the *CIMO-based EHA framework* includes defining the system boundary, phase of development, the IS's objective, and identifying the innovation system structures.

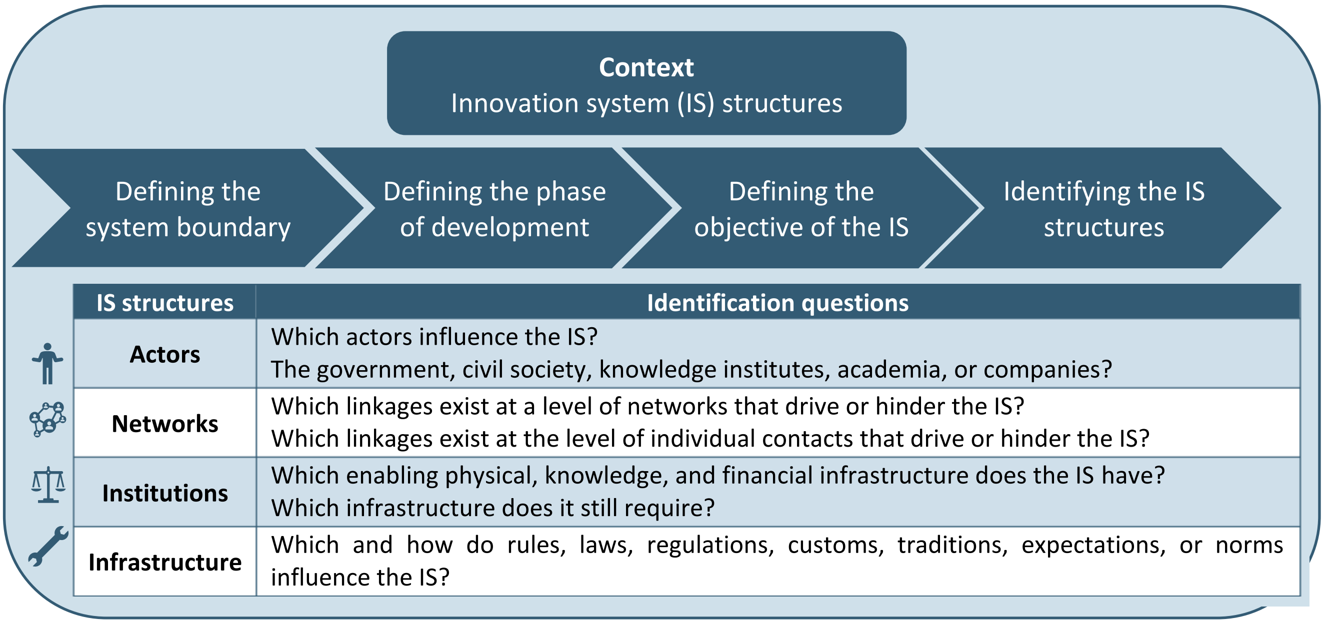


Figure 6.8: The *Context* definition steps of the CIMO-based EHA framework

1.5.1.1 Defining the system boundary

The first context step is the definition of the studied case's or case section's boundary as it defines the technology IS (TIS) in focus. Typically, IS scholars may study national (NIS), regional (RIS), sectoral (SIS), and TISs, but as the framework incorporates the IS functions developed for TISs, the generic IS framework allows for the study of TISs. Defining the system boundary may be viewed as selecting the unit of analysis. The selection should be carefully considered as it will influence the results the IS deliver. To support system analysts in defining the system boundary, from § 4.2.5, boundaries may be defined around a single product or groups of products, services or groups of services, technology or groups of technologies, sector or sub-sector, target group, and geographic region.

When a geographic boundary is selected, all actors involved in the development and diffusion of a specific innovation or whose activities are orientated towards the innovation within a geographical area are included within the system's boundary [295]. Therefore, actors present within the boundaries [29] and those influencing the system and interacting with the system's actors from beyond the system's boundary are included [282]. These external actors should be noted as exogenous influences on the system [282].

1.5.1.2 Determining the phase of development

As the boundaries of ISs may be defined around single or groups of products, services, technologies, sectors, sub-sectors or geographies, the specifications regarding the inducement of the innovation processes may differ from IS to IS. Furthermore, in IS literature, the structures and functioning of an IS depend on the development phase of the unit of analysis studied [23], [299]. Thus, if the technology is still in an early development phase, the IS has a different structure, and certain IS functions are also more relevant than those of a more mature technology [299]. Therefore, it is necessary to determine the phase of development of an IS before IS analysis to determine whether it performs well in relation to its development phase and whether it can continue towards the next development phase.

1.5.1.3 Defining the objective of the IS

In § 6.1, Van der Hilst [29] and Coenen's [326] critique of the generalised systemic goals of the systemic instruments from the systemic innovation policy framework were mentioned. These authors argued that Wieczorek and Hekkert's [27] systemic goals were generalised to suit all ISs and consequently did not consider a system's context or objectives. In CIMO literature, a process or system's primary objective is delivering outcomes and outputs that are of value to its user [253], [254]. In IS literature, the primary objective of an IS is to induce innovation processes and improve the productivity of an IS [281], [297].

As the boundary and development phases differ from IS to IS, the objectives or desired outcomes of ISs depend on the IS's boundaries and the development phase. Similar to the IS boundary's definition, the IS's objective will influence the conclusions derived from IS analysis. Subsequently, the objective of the IS or the IS's particular *job to be done*, namely the progress the IS is trying to make in a particular context, may be determined.

As outcomes depend on the outputs produced, it is suggested that secondary objectives be identified to deliver outputs that contribute to fulfilling the primary goal or outcome. These objectives may be specific to the studied IS and include the development capitals the IS aim to deliver, namely business, cultural, financial, human, intellectual, natural, political, produced, and social capital.

1.5.1.4 Identifying the IS structures

Finally, all the influential internal and external factors may be identified once the boundary and objectives have been identified. As the IS structures perform the IS function, their presence or absence and capacities are critical to the functioning of ISs [29]. They also align with the minimum requirements set by Pawson and Tilley [8] for identifying the CIMO-logic structure's context component. Therefore, the actors involved in the IS (both actively involved and distant, passive actors), the interactions they share, the institutions that influence the system and the infrastructure the IS have and requires should be identified. Wieczorek and Hekkert [27] suggest utilising the definitions of each IS structure (Table 5.2) as detection questions to identify the IS structures of ISs.

Once the studied system's boundary, phase of development, objectives and IS structures have been identified, the context phase is completed. The IS' intervention and mechanism analysis may commence.

6.5.2. Intervention and Mechanism

Once the studied case' or case section's context has been defined, the event data should be analysed to identify the dynamics, interventions and mechanisms in the case or case section. Based on the work of EHA scholars Poole *et al.* [337] and Suurs [23], the event data can be subjected to two types of pattern analyses, namely, *trend patterns* and *interaction patterns*.

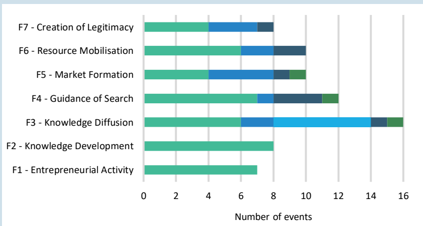
Trend patterns are associated with the fulfilment of the individual system functions and are used to identify important developments in the narrative [23], [24]. *Trend patterns* captured the *CIMO interventions.* As mentioned in §4.3, *Interventions* are purposeful activities performed to solve the (problematic) context. Therefore, it is essential to examine the nature of the intervention, how it is implemented, and by whom it was implemented [250], [253], [254].

Following the identification of the interventions, the *Interaction patterns* focus on the sequences in which functions occur [23],[36]. As *interaction patterns* capture the sequence in which events occur, they support the identification of CIMO mechanisms. *Mechanisms* can explain the cognitive processes (reasoning) actors use to choose their response to the interventions and their ability (resources) to put them into practice. Consequently, it is valuable to note how and why mechanisms were triggered and the effect each intervention had on the mechanisms [250], [253], [254]. Consequently, as presented in Figure 6.9, the *intervention* and *mechanism* definition phases include the motors of innovation, the component–function approach from the generic systemic innovation policy framework, and data visualisation to identify trend and interaction patterns.

Interventions and Mechanisms
Innovation system functions and motors of innovation

IS functions	Functional activities
F1: Entrepreneurial Activity	Projects with commercial aims, demonstrations, portfolio expansions, entry of firms
F2: Knowledge Development	Product and market research, surveys, assessing raw materials, (feasibility) studies, laboratory trials, pilot projects, prototypes, adapting model
F3: Knowledge Diffusion	Training activities, alliances between actors, joint ventures, demonstrations, workshops, conferences, awareness campaigns
F4: Guidance of Search	Favourable regulations and policies, defining expectations, communicating vision, providing directions, showing interest, communicate research outcomes
F5: Market Formation	Sharing cost of investments, market regulations, regulations supporting niche markets, tax incentives and exemptions, public procurement
F6: Resource Mobilisation	Financial incentives, subsidies and grants, investments, infrastructure developments, providing equipment, recruiting human resources
F7: Creation of Legitimacy	Lobbying activities, advice, advocacy coalitions

Innovation System actors
Civil society
The Government and NGOs
Companies
Knowledge institutes
Other parties



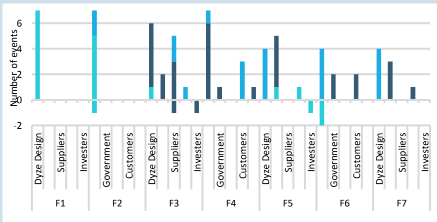


Figure 6.9: The *Intervention* and *Mechanism* definition steps of the CIMO-based EHA framework

6.5.2.1 Identification of interventions

To gain insight into the narrative's functional development (interventions) and the influence it produced within a case, the fulfilment of the case's functions should be tracked over time using quantitative content analysis to develop timeline graphs for each IS function. Quantitative content analysis uses coding to count the number of times an occurrence appears in literature, thus quantifying specific occurrences in qualitative data [47]. Therefore, at the start of the narrative, each function should be given a value of zero. Thereafter, the numerical value of the events should be added to the specific function's numerical value as the timeline of events progresses. Finally, a graph can be drawn of the functional development over time. This graph will indicate the primary (most developed) functions or interventions and secondary interventions involved in the studied case or case section. In addition to the functional development time graphs, high-level overview graphs may be developed of each participating actor to identify the functions each actor participated in.

6.5.2.2 Identification of motors of innovation (mechanisms)

Following the identification and visual representation of the functions involved in the studied case or case section, the interaction patterns present in the studies case or case sections must be identified by mapping the operations of the studied case over time. Therefore, the sequence in which the functions are performed needs to be traced throughout the development of the studied case or case section. As Maarsingh et al.'s [52] suggested, causal loop diagrams should be developed to visualise the sequence of events (Figure 6.10). If the sequence in which the functions developed repeats and cause cumulative causation, the causal loop diagram may be labelled a motor of innovation [24].

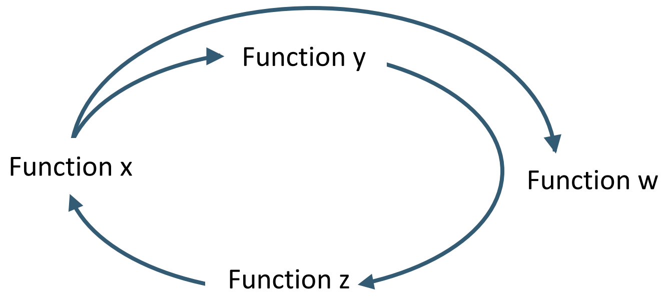


Figure 6.10: Causal loop diagrams of the IS functions

6.5.2.3 Component-function-based analysis and data visualisation

Following the identification of the function and actors involved in the studied case or case section and the motor of innovation, the analysis of each participating actor's role in the case or case section may be studied. Data visualisation should be implemented to support the actor analysis

First, pie charts should be developed to visualise the functions each actor contributed to. This visualisation will provide a summary and enable a high-level understanding of each actor's role. For example, if an actor primarily contributed to the *F2: Knowledge Development* function, while another actor primarily contributed to the *F1: Entrepreneurial Activity* function, the researcher and entrepreneurial roles may at first glance be allocated to the first and second actors, respectively.

Similar to the pie charts, stacked column charts should be developed to visualise the number of events each function was part of and the actors who performed them. This chart will present all the actors who performed, for example, the F*2: Knowledge Development* function, and indicate who contributed to (performed) the function the most. Actors who performed numerous research studies may thus be distinguished from those who only performed single research studies.

Finally, a graph should be developed to visualise the functions each actor *performed, gave,* and *received.* This graph will shed light on the actor's influence on the case in terms of their contribution. Primary actors who were the primary *performers or givers* of particular functions will be highlighted, while secondary *receiver* actors will also be indicated. Furthermore, functions that were *given* and *received* by numerous actors will also be highlighted.

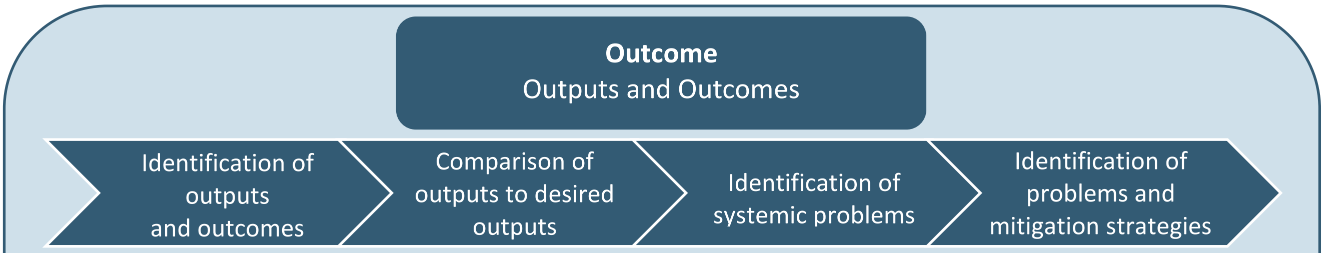
Following the visualisation of the actors' contributions, the contributions may be related to the functions of the identified motor of innovation. Insight may then be derived on the drivers and enablers of the motor of innovation and why certain events developed as they did. Additionally, insight will be gained on the primary roles that need to be filled for the motor to exist and continue, while supporting roles that may be excluded from the motor may also be identified.

Once the studied system's interventions and motors of innovation have been identified, the interventions and mechanisms phases are completed. Then, the Outcome analysis may commence.

6.5.3. Outcome

Outcomes are the various aspects of the results interventions cause. It is, therefore, valuable to view the various influences of the outputs of the mechanisms achieved [250], [253], [254]. As outcomes depend on the outputs produced, based on the suggestions of Botha *et al.* [297], IS outcomes may be broken up into system-specific outputs and development capital outcomes. Furthermore, as presented in Figure 6.5, the outcomes and outputs achieved may also be compared against the initial objectives set in the *context* definition phase. Additionally, mitigation strategies may be developed to solve the issues causing inadequacies in the obtained outcomes and outputs.

Consequently, as presented in Figure 6.11, the *outcome* definition of the *CIMO-based EHA framework* includes identifying the outputs and outcomes the IS delivered, comparing them to initial outcomes set in the *context* definition stage, identifying systemic problems causing inadequacies and finally, developing mitigation strategies to solve the inadequacies.



Capitals	Capital gains
Business	The establishment of spin-out businesses or corporations.
Cultural	Traditions and shared identity, ethnicity
Financial	Funding, grants and loans, investments, higher earnings/cost savings
Human	Jobs created, learning, skills, leadership development, faster knowledge diffusion
Intellectual	Copyrights, licences, tacit knowledge, systems, procedures, protocols, and reputation
Natural	Assets, resources, investments, and opportunities gained from the surrounding community
Political	The ability to voice needs and have influence to achieve certain aims.
Produced	Innovations and infrastructure developed
Social	Trust, networks, community capacity building

Figure 6.11: The *Outcome* definition steps of the CIMO-based EHA framework

6.5.3.1 Defining the outcomes and capital outputs delivered

Once the mechanisms (motors of innovation) and their corresponding IS structures and functions have been analysed, the outputs and outcomes may be identified. First, the outputs of the IS should be defined. These outputs may be defined by the relevant IS actors or the general IS. Thereafter, the outcomes delivered in pursuit of the objective outputs may be mapped in order of occurrence. This should be done in terms of events, the involved actors, and the development capitals, as schematically presented in Figure 6.13. Tree diagrams or CLDs may be developed to illustrate and support the identification of patterns. To support the analysis, the order in which the capital outcomes typically influence each other (from the centre outwards) is presented in Figure 6.12.

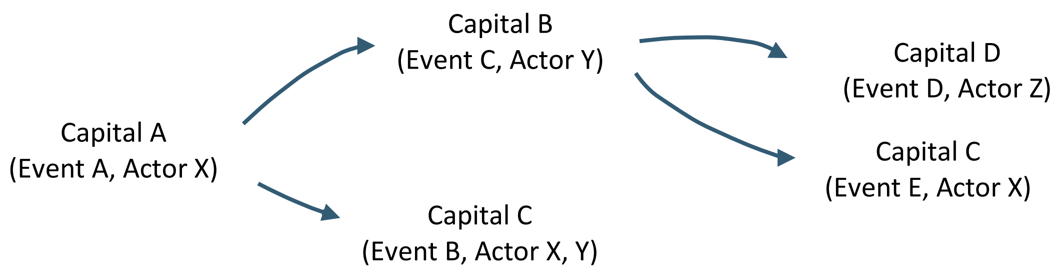


Figure 6.13: Schematic representation of development capitals mapping

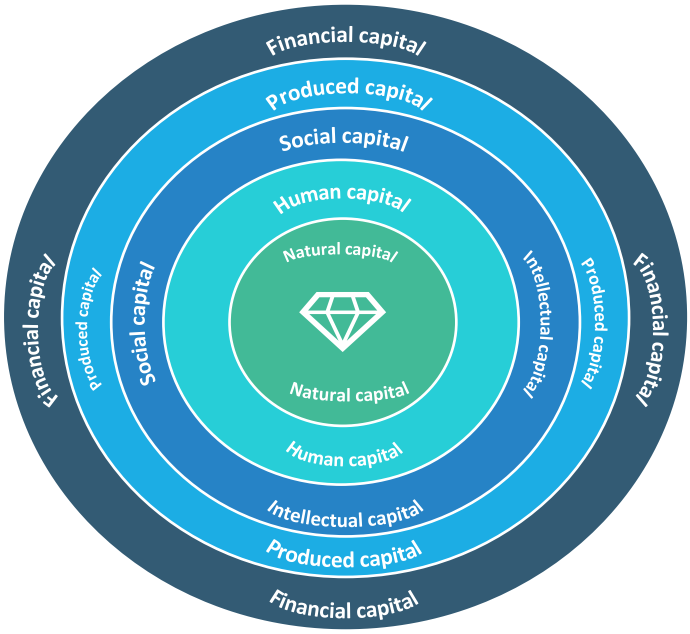


Figure 6.12: Six capitals as used by Sasol [333]

6.5.3.2 Comparing the obtained and desired outcomes

After identifying the outputs and outcomes, they may be compared to the desired outcome and outputs. Both inadequacies and unanticipated achievements should be noted as both provide valuable insight into the IS's performance.

6.5.3.3 Identifying the systemic problems

Following the comparison, the systematic identification of the IS's systemic inadequacies and unanticipated achievements may be exploited to determine why and where differences may have originated. However, as *context* and the development of events and functions over time are emphasised in the CIMO-based EHA framework, the predefined systemic goals and instruments will not be fruitful. Consequently, when systemic inadequacies and unanticipated achievements are identified, the development path of the functions and corresponding IS structures should be traced back to determine when, how and why the inadequacies or unanticipated achievements developed.

6.5.3.4 Developing a mitigation strategy

Following identifying when, how, and why the systemic inadequacies and unanticipated achievements developed, suggestions or a mitigation strategy may be derived to guide how future inadequacies may be avoided and unanticipated achievements may be achieved. To guide the development of such mitigation strategies, Wieczorek and Hekkert's [27] goals for systemic instruments (Table 6.2) may be used as a guide.

Table 6.2: Wieczorek and Hekkert's [27] goals of systemic instruments per (type of) systemic problem

IS structures	(Type of) systemic problem	Goals of systemic instrument
Actors	Presence?	Stimulate and organise participation of relevant actors
	Capabilities?	Create space for actor capability development
Interaction	Presence?	Stimulate occurrence of interactions
	Intensity?	Prevent too strong and too weak ties
Institution	Presence?	Secure presence of hard and soft institutions
	Capacity?	Prevent too weak and too stringent institutions
Infrastructure	Presence?	Stimulate physical, financial and knowledge infrastructure
	Quality?	Ensure adequate quality of infrastructure

6.6. Framework validation and evaluation: Expert reviews

Semi-structured interviews were conducted with six expert reviewers to validate and evaluate the CIMO-based EHA framework. Rabionet's interview process, presented in Figure 6.14 and detailed in §7.4, was followed. Furthermore, Cresswell's [7] six-step process for data analysis in qualitative research, detailed in §6.5, was implemented to analyse the expert review data.

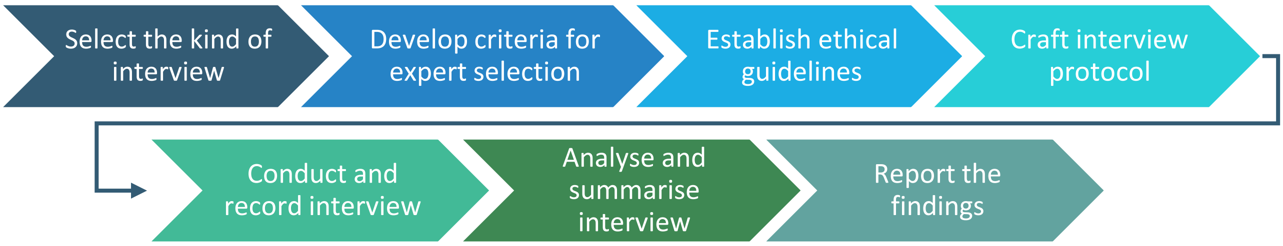


Figure 6.14: Interview process applied in this thesis [353]

6.6.1. Subject matter experts for the review

As established by Fuller, Warren and Argyle [81], the normative value of research may be tested by the extent to which relevant individuals deem the artefact and ideas behind it to be of value. The validation of the framework is therefore tested via expert analysis. In this study, the expert analysis took the form of semi-structured interviews (*process followed documented §6.2*) with experts who were asked their perspectives on the rationality and applicability of the framework steps, IS tools and functional indicators to achieve the framework's objective. Additionally, key insights into their recommendations and motivations were gained.

The information shared during the framework's validation process is presented in Figure 6.15. The expert interview process was initiated with a presentation of the project and framework objectives to minimise

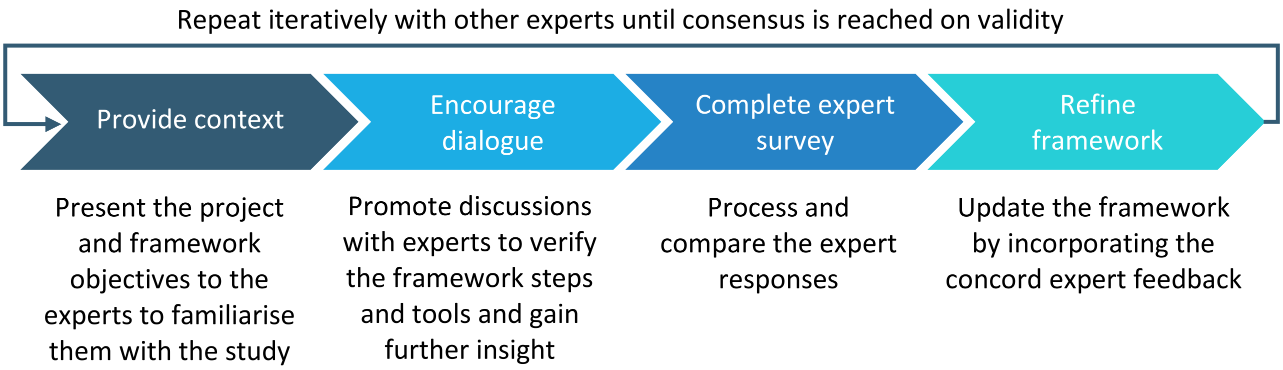


Figure 6.15: Framework validation: Expert interviews

ambiguity regarding the framework or how its steps and components were arrived at. Thereafter, a discussion was held to address aspects of concern, after which validation questions on the framework were answered. Finally, the expert responses were summarised and compared before the necessary amendments were made to the framework. The data capturing was regulated by the Stellenbosch REC's ethical guidelines.

Six expert reviewers were interviewed. The expert consisted of three innovation system researchers and three experts active in the innovation system research environments and industry. Experts with many years of experience, a thorough understanding and practical application experience of the innovation system framework were selected for consultation. They provided valuable insight into the framework structure, presentation, and IS functions' indicators. In addition, these experts provided practical insight on the utilisation of the framework by innovation scholars and policy developers and on the innovation insight that may be gathered from the industry survey. The expert reviewers and their years of experience are summarised in Table 6.3. Each expert reviewer (E#) was assigned a unique identifier to maintain their anonymity throughout the reporting process. Combining the experts' domains, fields of expertise and years of experience provided comprehensive inputs and views of the innovation system landscape.

Table 6.3: Characteristics of the framework's expert reviewers

Expert	Domain: Research or industry	Years of experience	Field of expertise
E1	Both	25+	Innovation management and sustainable development
E2	Research	12	Innovation systems and management
E3	Research	8	Innovation and industrial systems, industrial policy
E4	Both	22	Technology and innovation management
E5	Both	20	Innovation management, business development
E6	Research	23	Innovation systems and management

As the framework is not specific to the South African environment, South African and international reviewers were included to obtain diverse insights. None of the experts had any prior involvement in the project to ensure non-bias opinions and inputs as far as possible during the evaluation process. The experts were identified based on their expertise, years of experience, and ability to provide credible and accurate information. Convenience sampling [47] was used to select the experts, as their selection was based on their accessibility and willingness to participate.

Six reviewers participated in the semi-structured interviews and completed the evaluation questionnaire (Appendix B). The review experts were asked to evaluate the framework according to the five system dimension criteria of the DSR artefact evaluation framework [70], presented in Figure 6.16 (cf. Table 2.6). They include goal, environment, structure, activity, and evolution.

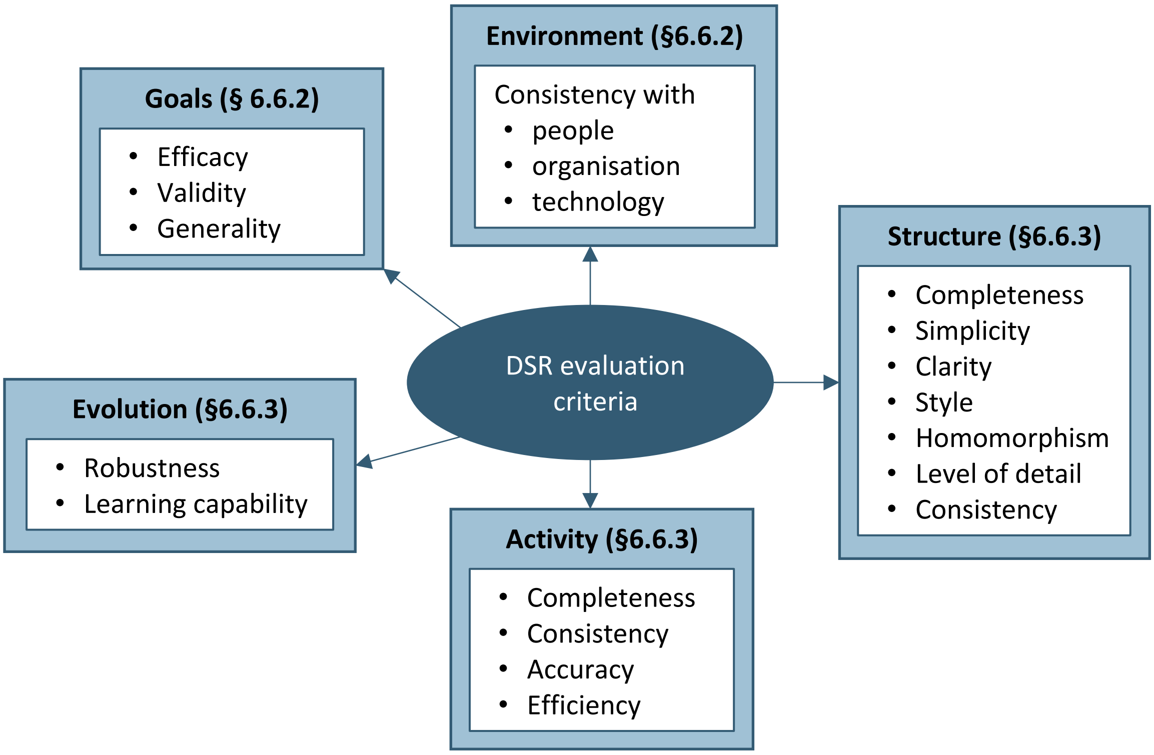


Figure 6.16: CIMO-based EHA framework evaluation criteria following the DSR artefact evaluation [70]

6.6.2. Evaluation of framework goals and environment

The framework's ability to achieve its intended goals was tested using the efficacy, validity, and generality criteria of the DSR artefact goal evaluation criteria [70]. Furthermore, the framework's environment was analysed in terms of its consistency with people, organisation and technology (DSR artefact environment evaluation criteria [70]). The primary goal of the CIMO-based EHA framework and DSR artefact sub-goals were formulated as follows.

An evaluation framework and tool that provides high-quality decision support to guide the analysis of any innovation system

a) Structure the evolutionary analysis of any innovation system.
b) Support the existing practices or frameworks for innovation system analysis.
c) Be generalisable and applicable to most innovation systems, particularly the South African AM domain.
d) Be simple to understand and apply.

To test whether the framework achieved its intended goals and is consistent with its environment, the experts were asked to rate ten statements from *Strongly Disagree* up to *Strongly Agree* based on their level of agreeance. As shown in Table 6.4, multiple evaluation criteria could be incorporated into single statements. The feedback was analysed and reported according to the percentage breakdown per statement. Table 6.4 indicates that the feedback on the overall framework was positive, as 80% of the questions received a *Strongly Agreed* or *Agreed* response, and none received a *Strongly Disagree* or *Disagree* rating. This indicates that the CIMO-based EHA framework was adequately designed to achieve its goals and be consistent with its environment with reasonable efficacy.

E2: "*In my opinion, the framework allows one to understand the reason why it was developed, how it was developed and the purpose it has to address for it to be useful and applicable in a specific context.*"

Table 6.4: Percentage breakdown of expert reviewers' ratings of agreeance.

"In my opinion, the CIMO framework…"	Strongly Disagree	Disagree	Undecided	Agree	Strongly Agree
1. Is easy to understand.	-	-	-	50%	50%
2. Is easy to use.	-	-	17%	33%	50%
3. Addresses a real-world problem or need.	-	-	-	50%	50%
4. Incorporates the concepts needed to understand the development (evolution) of (manufacturing) innovation systems.	-	-	-	50%	50%
5. Is compatible with existing analysis frameworks on innovative development research or practices.	-	-	-	33%	67%
6. Is applicable to the manufacturing context.	-	-	50%	33%	17%
7. Is generalisable – it may be applied to contexts other than manufacturing.	-	-	-	33%	67%
8. Provides an adequate level of detail for application in practice.	-	-	-	17%	83%
9. Identifies appropriate concepts and categories for its stated purpose.	-	-	-	50%	50%
10. Appropriately categorises the concepts included.	-	-	-	67%	33%

Statements 2 and 6 received 'Undecided' ratings. Following statement 2, expert reviewer 3 provided the following comment:

E3: *"At first glance, the framework looks easy to apply. However, to guide future analysis, guiding steps or canvases explaining how to perform each step of the framework are suggested, particularly for the CIMO part, as it is the main contribution. If guided canvases of questions are not desired, real-world examples of how the different components may be used in practice may be provided to guide analysts."*

Following this suggestion, the development of stepwise canvases to guide the application of the CIMO-based EHA framework was deemed warranted and developed in §6.7. In response to statement 6 regarding the framework's applicability to the manufacturing context, 50% of the reviewers provided an 'Undecided' rating. These reviewers agreed that the framework was generalisable but that none of the components was manufacturing-specific.

E1: *"The framework is generalisable because it may be applied to any innovation system. However, no framework component points to manufacturing innovation systems. A manufacturing component may be incorporated to ensure a more manufacturing-specific framework. as the framework is modular, future applications of the framework may omit the manufacturing-specific framework component."*

These reviewers' suggestions were deemed warranted. Therefore, it was decided that the manufacturing component would be identified during the application of the framework to the four 'AM for hardmetal' case studies studied in Part III.

6.6.3 Evaluation of framework structure, activity, and evolution

To analyse the structure, activities and evolution of the CIMO-based EHA framework, the interviewers' feedback was asked on each section of the framework.

6.6.3.1 EHA component of the CIMO-based EHA framework

For the EHA components, the experts were not asked their opinion regarding the steps of the EHA method as it is already an established method. Instead, the experts were asked their opinion regarding the inclusion of a) the identification of the actors performing the events and the three roles allocated to the actors (*perform, give, and receive)*, and b) the CIMO component during the pattern identification phase.

Regarding the *allocation of events to IS functions phase* and the additional identification of the actors who performed the narrative events, the expert reviewers were asked to rate the relevance and importance of the inclusion on a scale from 1 (very low importance and relevance) to 5 (highest importance and relevance). Figure 6.17 indicates that all expert reviewers deemed the inclusion highly relevant, while the inclusion is rated moderately to very important. The expert reviewers thus confirm that the inclusion of the actor identification during the *allocation of events to IS functions phase* is warranted.

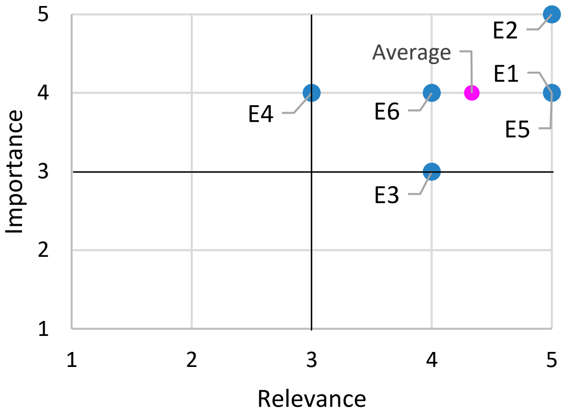


Figure 6.17: Expert reviewer's importance and relevancy ratings of the inclusion of actor identification during the allocation of events to IS functions phase

Expert reviewer 4 also argued that the actor allocations should be more specific instead of only distinguishing between government, industry, civil society and academia. For example, civil society should not include the customers and the supplier. They should be captured and analysed separately as more insight may be gained. Users of the framework should be instructed to specify the categorisations of the actors. This observation was deemed warranted and was included in the refined framework.

Regarding the scoring of the events, reviewers 4 and 6 objected to the +1, 0, and -1 scoring of the narrative events. They argued that valuable insights might be lost if all events were awarded similar scores. They argued that investments of R5 million should be awarded higher scores than those of R5 and mentioned that presentation of these values on functional time graphs would be misleading.

E6: "*The importance of different events varies greatly, and their intensity should also be considered. However, the framework simply attributes them to 1, 0, or - 1, which might have great problems and directly affect the conclusions. Consequently, the scoring of the events needs to be adjusted.*"

This project acknowledges that some events may have a more significant impact than others but will still view events as positive (+1), neutral (0) or negative (-1). In this project, it is argued that mapping the functions on a timeline through EHA is the most important, along with identifying trends and interaction patterns.

Finally, review expert 5 argued that the inclusion of the CIMO-based framework could be ascribed to both the *data summary* and *pattern identification phases* of the EHA components, as presented in Figure 6.18. They argued that although the CIMO inclusion is implied in both the *data* and *pattern identification phases*, the framework indicates the inclusion only in the *pattern identification phase*. This remark was deemed warranted and was included in the refined framework.

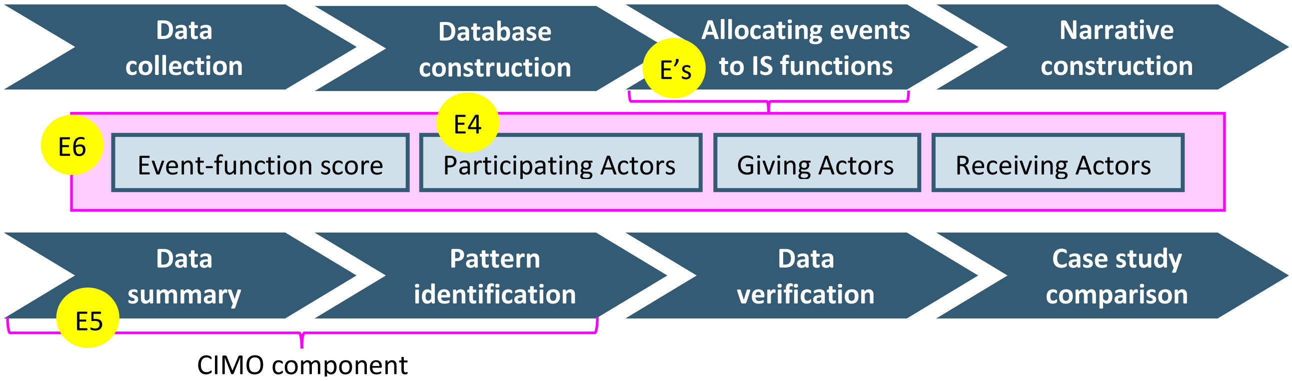


Figure 6.18: EHA component of the CIMO-based EHA framework

6.6.3.2 CIMO-structure

Following the EHA component analysis, the framework's CIMO components were analysed. First, the subcomponents of the Context definition component were analysed. The expert reviewers were asked to rate the importance and relevance of the subcomponents. As indicated in Table 6.5, all the reviewers deemed the Context definition subcomponents valid as they ranked them highly important and relevant.

Table 6.5: Context definition subcomponent expert reviewer importance and relevant ratings

Context definition subcomponents	Importance	Relevance
Defining the system boundary	4.75	5
Defining the phase of development	4.25	4.5
Defining the objective of the IS	4.75	4.75
Identifying the IS structures	4.75	4.5

In addition to the ratings, the expert reviewer mentioned the following regarding the initial understanding of a system's context. E3: "*The context of a system is often better understood when its dynamics are studied. Feedback from the intervention and mechanism stages is needed to inform the context stage. If a comprehensive overview of a system's context is not obtained at the start of the analysis, the CIMO process would have to be applied numerous times until the context and dynamics are sufficiently defined and studied. This could be very time-consuming. A loop back towards the context stage is highly recommended.*"

Next, the expert reviewers were asked to rate the importance and relevance of the Mechanism subcomponents. As indicated in Table 6.6, all the reviewers deemed the Mechanism definition subcomponents valid as they ranked them as highly important and relevant. The reviewers also supported the use of CLDs to map the motors. CLDs were said to both support the system analysts and the readers of such analysis as they visually present the development patterns over time.

Table 6.6: Mechanism definition subcomponent expert reviewer importance and relevant ratings

Mechanism definition subcomponents	Importance	Relevance
Identification of motors of innovation	4.5	4.5
Identification of important IS structures	4.1	4.3
Identification of development barriers	4.5	4.5

Finally, the expert reviewers were asked to rate the importance and relevance of the Outcome subcomponents. As indicated in Table 6.7, all the reviewers considered the Outcome definition subcomponents valid as they ranked them as highly important and relevant.

Table 6.7: Outcome definition subcomponent expert reviewer importance and relevant ratings

Outcome definition subcomponents	Importance	Relevance
Defining the IS-specific outputs	5	5
Defining the Capitals developed by the IS and motors of innovation	5	5
Comparing the obtained and desired outcomes	4.75	4.5
Identifying the systemic problems	4.75	4.75
Developing an improvement strategy to support the motor of innovation	4.5	4.5

In addition to the *Defining the Capitals developed by the IS and motors of innovation* phase, the expert reviewers rated the individual capitals. Before the commencement of the expert reviews, it was decided that the capitals that received average importance or relevance rating of 3 or lower were to be discarded from the framework. As seen in Figure 6.19, cultural capital, referring to traditions, shared identity, and ethnicity, received an importance rating of 2 and a relevance rating of 3. E2: "*In the context of manufacturing through the innovation system framework, cultural capital may be omitted as the innovation system's structural institutions capture those dynamics*."

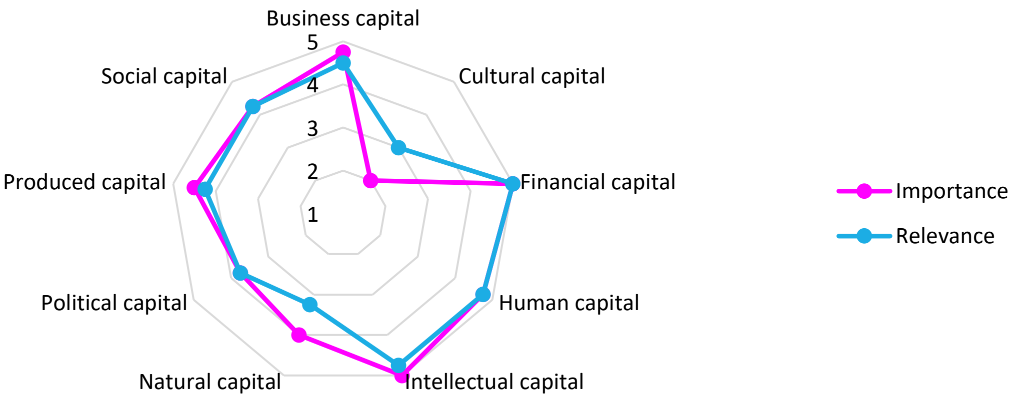


Figure 6.19: Average importance and relevance ratings of the development capitals

6.6.3.3 Feedback on the framework indicators

To validate the functional indicators that will support the identification of the EHA events and later guide the derivation of the industry survey questions, the expert reviewers were asked to rate each function's indicators according to their importance and completeness. Figure 6.20 presents the expert reviewers' average importance and completeness ratings. All the functions received 5-start importance ratings as they comprise the functions of the well-established IS framework.

> E2: *"I think the functions are all relevant, complete, and important and this is also dependent on who evaluates these because an academic will approach the importance and relevance from another angle than an industry CEO or innovation practitioner. If one has to apply these functions with your own purpose in mind, it will affect the importance and relevance of these functions. I am an academic and an innovation developer, so I have evaluated your framework from this point of view."*

However, function *F6 – resource mobilisation* did not receive an average 5-star completeness rating for its functional indicators. Expert reviewer 5 suggests that indicators pointing to digital resources be included in *F6 – resource mobilisation's* indicators to ensure that the framework incorporates a manufacturing component.

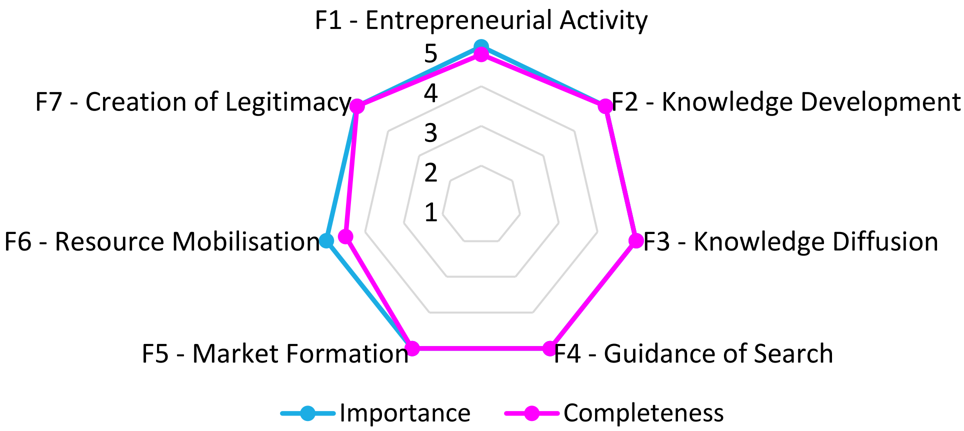


Figure 6.20: Average rating of the framework indicators

6.7 Refined CIMO-based EHA Framework

The overall feedback received from the expert reviewers was positive. The feedback identified valuable improvement points to refine the preliminary CIMO-based EHA framework. The expert reviewers allowed the first relevance cycle to inform and update the CIMO-based EHA framework as required during the second design cycle, adhering to the DSR methodology. The expert reviewers' suggested updates and revisions were incorporated into the components and subcomponents of the framework. Figure 6.22 numbers the refined subcomponents to guide the reflection of the refinements.

Refinement 1: This project acknowledges that some events may have a more significant impact than others but will still view events as positive (+1), neutral (0) or negative (-1). This project argues that mapping the functions *on a timeline* through EHA is the most important. Through the CIMO-based analysis, the effect of each event and the contributions of the actors will be traced over time. The CIMO-based analysis thus ensures that the impacts of more profound events are captured to their full extent and that less significant events are noted.

Refinement 2: the framework is adjusted to include the CIMO-based component in both Steps 5 and 6 of the EHA method. As functional-time and actor contribution graphs are developed during the CIMO-based analysis, the CIMO component sufficiently fulfils the EHA method's *data summary and pattern identification* phases.

Refinement 3: To fulfil the expert reviewers' request for a digital resource, the *F6 – resource mobilisation* function's list of indicators was updated with the inclusion of the digital resources.

Refinement 4: Based on the expert reviewers' suggestions for implementation canvases or stepwise guides for applying the CIMO component of the CIMO-based EHA framework, an application canvas was developed for each CIMO structure. Figure 6.21, Figure 6.24, and Figure 6.25 present these canvases.

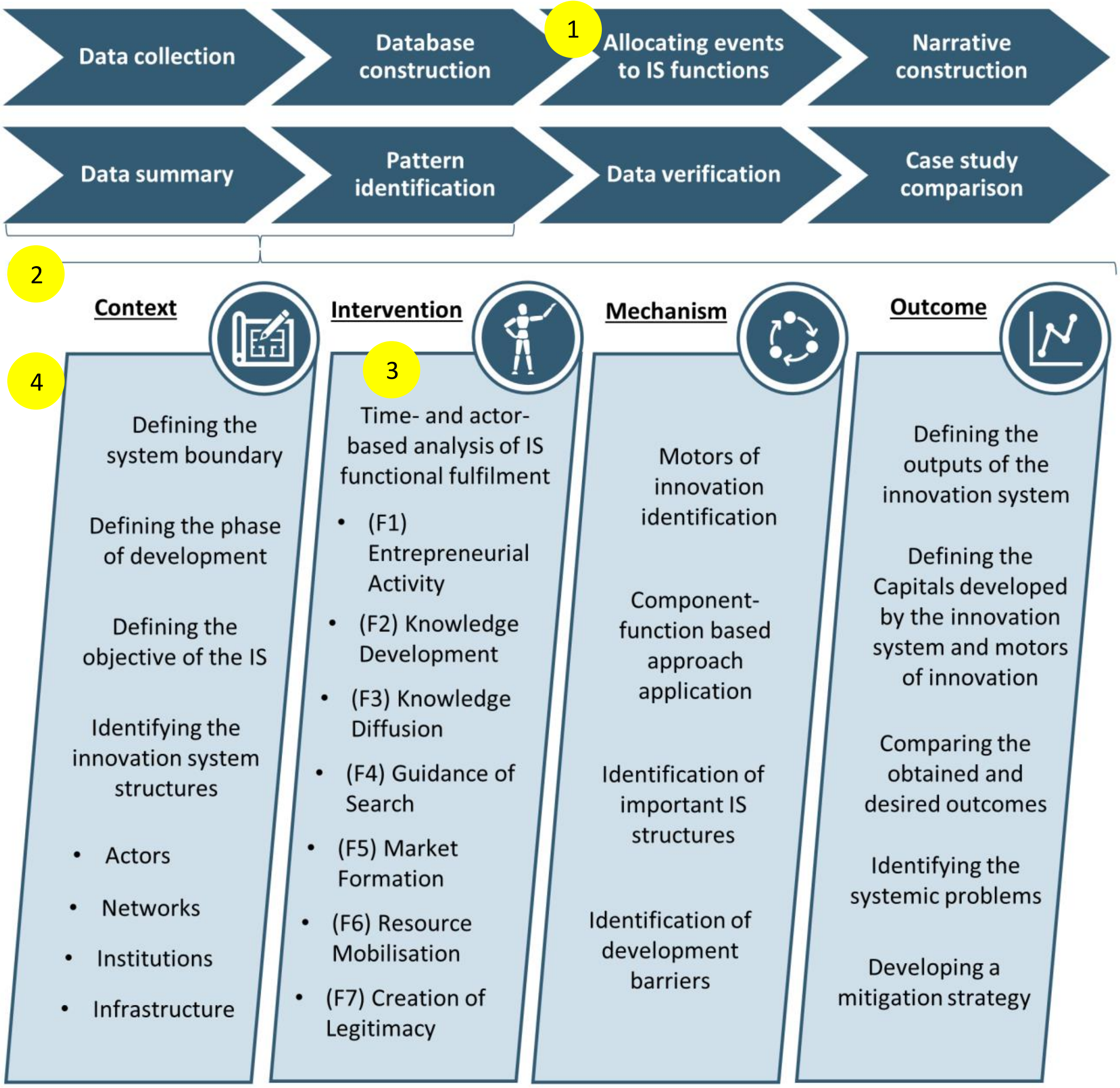


Figure 6.22: Refined CIMO-based EHA framework

Context
Innovation system (IS) structures

Defining the system boundary

3. What is the unit of analysis?

Product Service Technology Group Community Company

4. Which period of the system is being studied? (For example, years or months x and y)

Phase of development

2. In which development phase is the studied IS?

Idea generation Research and Development Production Commercialisation Market expansion

Defining the system objective

3. What is the primary aim of the IS?
4. What are the secondary objectives of the system? Use the development capitals as a guide

Capital	Description
Business	The establishment of spin-out businesses or corporations
Financial	The financial resources available for investment support, businesses and entrepreneurship, development and accumulate wealth for future company development.
Human	The skills, knowledge, and capabilities people utilise to enhance other capitals and acquire more skills, knowledge, and capabilities.
Intellectual	Intellectual property, such as patents, copyrights, and licences. `Organisational capital' such as tacit knowledge, systems, procedures, protocols, a brand and reputation
Natural	The assets, resources, and ecosystem services of the natural world.
Political	The ability to voice needs and have influence to achieve certain aims.
Produced	The physical assets produced by applying human capital to natural capital and can provide a flow of goods or services.
Social	Connections within communities, networks, and the sense of trust, mutual understanding, shared values and socially held knowledge.

Identifying the IS structures

IS structures	Identification questions
Actors	Which actors influence the IS? Who are actively involved (enactors) and who are only involved at a distance (selectors)?
Networks	Which linkages exist at a level of networks that drive or hinder the IS? Which linkages exist at the level of individual contacts that drive or hinder the IS?
Institutions	Which and how do rules, laws, regulations, customs, traditions, expectations, or norms influence the IS?
Infrastructure	Which enabling physical, knowledge, and financial infrastructure does the IS have? Which infrastructure does it still require?

Figure 6.23: The preliminary CIMO-based EHA framework: Context definition

Interventions and Mechanisms
Innovation system functions and motors of innovation

Identification of interventions	To identify the functions present with a case or case section, develop timeline graphs for each IS function. 1. At the start of the narrative, award each function a value of zero. 2. Read though the narrative. 3. Add the numerical value of the events to the specific function's numerical value as the timeline of events progress. 4. Develop a graph of the cumulative value of the IS functions over time. 5. Additionally, develop a graph of each participating actor to identify the functions each actor participated in.
Identification of motors of innovation (mechanisms)	1. Map the sequence in which the functions are performed throughout the studied case or case section. 2. Develop a causal loop diagram to visualise the sequence of events. 3. If the sequence in which the functions developed repeats and cause cumulative causation, label the casual loop diagram a motor of innovation [24].
Component-function based analysis and data visualisation	1. To analyse of each participating actor’s role in the case or case section, the following graphs should be developed: i. Pie charts to visualise the functions each actor contributed to. This visualisation provides a summary and enable a high-level understanding of each actor’s role. ii. Stacked column chats to visualise the number of events each function was part of and the actors who performed them. This chart visualises the functions in terms of the actors who were involved in them. iii. A stacked column chart to visualise the functions each actor *performed, gave,* and *received.* This graph sheds light on the actor’s influence on the case in terms of their contribution. 2. Following the visualisation of each actors’ contributions, relate the contributions to the functions of the identified motor of innovation. The drivers and barriers of the motor of innovation should be identified.

Figure 6.24: The preliminary CIMO-based EHA framework: Interventions and Mechanisms definition

Outcome
Outputs and Outcomes

Identification of outputs and outcomes

1. Which outputs were delivered?
2. Which capital outcomes were achieved in the IS? In which sequence were they achieved?

Capital	Description
Business	The establishment of spin-out businesses or corporations
Financial	The financial resources available for investment support, businesses and entrepreneurship, development and accumulate wealth for future company development.
Human	The skills, knowledge, and capabilities people utilise to enhance other capitals and acquire more skills, knowledge, and capabilities.
Intellectual	Intellectual property, such as patents, copyrights, and licences. `Organisational capital' such as tacit knowledge, systems, procedures, protocols, a brand and reputation
Natural	The assets, resources, and ecosystem services of the natural world.
Political	The ability to voice needs and have influence to achieve certain aims.
Produced	The physical assets produced by applying human capital to natural capital and can provide a flow of goods or services.
Social	Connections within communities, networks, and the sense of trust, mutual understanding, shared values and socially held knowledge.

Comparison of outputs to desired outputs

1. List the obtained outputs against the desired outputs
2. List the desired fulfilment of the capitals against the obtained fulfilment of the capitals
3. Identify the differences and inadequacies

Identification of problems and mitigation strategies

1. Trace the functional dynamics of the inadequacies
2. Determine the IS structure associated with the unfulfilled functions
3. Determine the systemic problems associated with the unfulfilled functions
    i. Actors: Presence/ capabilities?
    ii. Interactions: Presence/Quality
    iii. Institutions: Presence/Capacity?
    iv. Infrastructure: Presence/Quality?
4. Using the IS functional indicators, develop a strategy to mitigate the inadequate functions

IS structures	(Type of) systemic problem	Goals of systemic instrument
Actors	Presence?	Stimulate and organise participation of relevant actors
	Capabilities?	Create space for actor capability development
Interaction	Presence?	Stimulate occurrence of interactions
	Intensity?	Prevent too strong and too weak ties
Institution	Presence?	Secure presence of hard and soft institutions
	Capacity?	Prevent too weak and too stringent institutions
Infrastructure	Presence?	Stimulate physical, financial and knowledge infrastructure
	Quality?	Ensure adequate quality of infrastructure

Figure 6.25: The preliminary CIMO-based EHA framework: Outcome definition

6.8 Reflection on expert reviews conducted

The expert reviews proved to be very valuable. As the reviewers comprised experts from the research and industry domains, the review allowed for the theory-based findings to be analysed and refined with inputs that would not have been known based on literature alone. The DSR evaluation goal, environment, structure, activity, and evolution criteria were used to assess the CIMO-based EHA framework's usefulness, completeness, and generalisability.

The expert reviews comprised semi-structured interviews with a framework presentation and questionnaire. The combined qualitative and quantitative responses elucidated clear framework improvements. The semi-structured interview type proved to be valuable as the structured questions ensured comparable findings and therefore eased the analyses thereof. The Likert-scale ratings proved to be beneficial as they supplemented the interview comments. The semi-structured interview and Cresswell's [7] six-step data analysis process contributed to the consistency and reproducibility of the qualitative analyses.

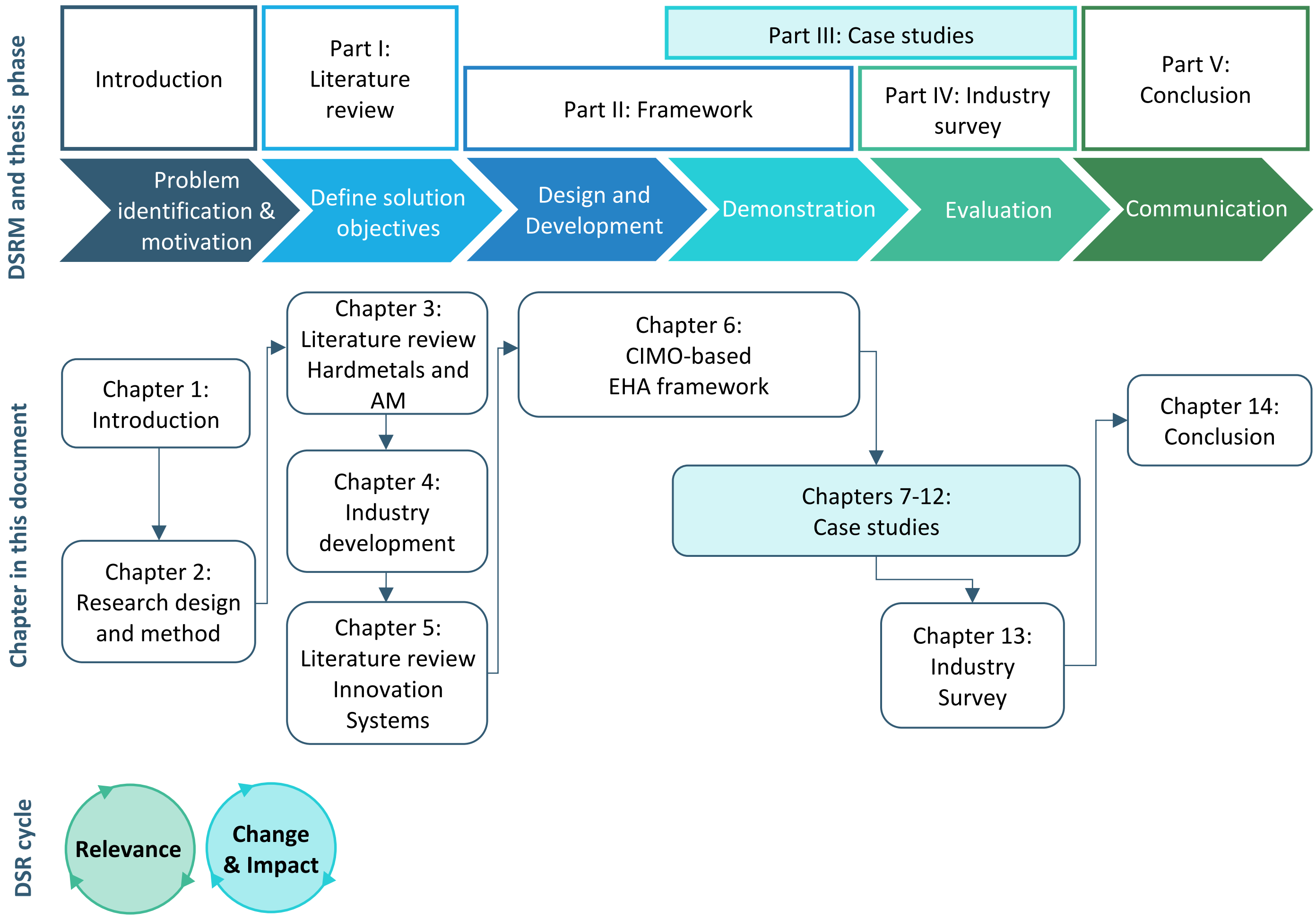
6.9 Chapter 6: Conclusion

In this chapter, the framework proposed in this study, namely the CIMO-based framework, was introduced. The chapter started with a reflection on similar existing frameworks from the literature and highlighted the shortcomings of these frameworks. They include a lack of an actor-specific focus, context-specific interventions, guidelines for analysts on designing and implementing new interventions and focus on cumulative causation of long-term innovative development. Additionally, the systemic goals and instruments derived were too general. Thereafter, a generic paradigm for innovation system analysis was proposed, within which a CIMO-based EHA framework was developed. Finally, the CIMO-based EHA framework was detailed. First, a high-level overview of the proposed framework was given before a detailed description of the framework steps, namely context, intervention, mechanism, and outcome, was presented. The chapter concluded with expert review feedback on the framework. The overall feedback received from the expert reviewers was positive, and valuable improvement points to refine the preliminary CIMO-based EHA framework were identified. The expert reviewers allowed the first relevance cycle to inform and update the CIMO-based EHA framework as required during the second design cycle, adhering to the DSR methodology. This chapter satisfies objective VI, as mentioned in §1.4.

In the following chapter, the study will move on to the third phase, the Case study phase. To validate the framework, the succeeding four chapters will apply the CIMO-based analytical frame to four 'additive manufacturing for hardmetal' case studies. For the sake of comprehension, each case will focus on a different unit of analysis. The first case applies the technology innovation system (TIS) perspective on an industry level and studies the South African additive manufacturing industry.

Part III

Case studies



Chapter 7

Methods used for case study analysis

Part III demonstrates the application of the proposed framework developed in Part II and evaluates the framework according to the evaluation criteria listed in Table 2.6. The chapter describes the interview, event history analysis and data analysis methods used in this thesis during the framework's application to Cases I to IV.

Chapter 7 contribution:

- Describe the application of the CIMO-based framework on the four case studies.

Chapter 7 objectives:

- Detail the case study selection process (§7.1 and §7.2).
- Detail the application of the Event History Analysis component of the CIMO-based EHA framework in the four case studies (§7.3).
- Detail the interview process followed (§7.4).
- Detail the data analysis methods followed (§7.5).

This chapter starts with an introduction to case studies. Thereafter, the case study selection criteria are discussed. The application of the event history analysis method in this thesis is discussed. Finally, the chapter concludes with a discussion of the interview process followed to obtain the case information and the data analysis techniques used to extract the relevant case data.

7.1. Introduction to case studies

Case studies are useful to researchers investigating the `how' and `what' of a social phenomenon [77], [350]. This study used case studies to demonstrate and evaluate the proposed framework. Case study research investigates a complex phenomenon within its natural context by using various data sources [76]. Various data sources enable a researcher to take on different lenses for an in-depth understanding of the phenomenon.

Tellis [350] proposed a four-step process for conducting case studies listed in Figure 7.1. Step one requires researchers to design a case study protocol. It typically includes an overview of the context of the case, the procedures required to conduct it, the case questions and the case report [78]. To prevent cases from becoming too long and compromising their ability to meet their goals, Tellis [350] and Yin [70] urge researchers to reduce and simplify the case objectives. Thereafter, the case data should be collected, and interviews should be conducted with the relevant parties to develop the case. Once documented, the cases may be subjected to data analysis techniques, after which subsequent conclusions and recommendations may be derived.

Figure 7.1: Guidelines for the case study process [1]

According to Yin [77], each case study yield insights particular to the case of study. Yin [77], [78], therefore, suggests that the insight gained from typically three to five multiple case studies combined is necessary to yield more general insights into a study field. However, a limitation of using case studies is that it is time-consuming [23]. This limitation implies that the generalisation of the case studies cannot be made using statistical techniques. Therefore, Suurs [23] and Abell [79] suggest that generalisation should be made by comparing and arguing from the content of the cases and relating these results to theory. In addition, Suurs [23] highlights that the criteria for the case selections must be carefully considered to render an argumentative generalisation feasible. Furthermore, studied cases should cover a long enough period to include a variety of activities. The different cases should also cover as much variety as possible to enable various insights to be obtained [23].

7.2. Case study selection

As mentioned in Chapter 1, the focus of this study is to develop a framework to study the evolution of innovation systems (IS). Furthermore, to illustrate the method and theory associated with the framework, the South African additive manufacturing (AM) industry was selected as the application industry with hardmetal as material.

Therefore, following Suurs [23] and Yin's [77], [78] guidance, inclusion criteria for the cases were developed (Table 7.1). As AM and hardmetals were selected as application focus areas, the first inclusion criteria were that cases had to be relevant to AM technology and hardmetals. Secondly, to gain examples from 'best practice' countries or industries, cases from geographical areas other than South African had to be studied. Furthermore, to enable the study of the development of core capabilities in actors and the capacities to perform the IS functions, the cases had to include a variety of actors. Furthermore, to ensure that the cases included various activities as Suurs [5] recommended, the cases had to differ in level and cover a minimum of a one-year period. Finally, the cases had to be relevant to the introduction and growth phases of an industry development life cycle as they enabled the study of how IS actors and dynamics evolved during those phases. It also ensured that the case studies overlap in terms of industry development.

Table 7.1: Case study inclusion criteria

Focus	Inclusion criteria	Motivation
Application industry	• The cases should be relevant to AM technology and hardmetals.	This study's application industry and material are the South African hardmetal industry and AM technology.
	• The cases should be based in different geographical areas	As the South African AM industry is gradually implementing AM as an additional manufacturing technology for hardmetals, case studies from international industries were used as best-case examples.
Framework application (ISs and EHA)	• Cases should include different types of actors.	The focus of this study is to evaluate the development of core capabilities in actors and the capacities to perform the innovation systems functions in the hardmetal industry. Therefore, a variety of actors should be studied throughout the cases.
	• The cases should be relevant to the introduction and growth phases of the industry development life cycle.	It enables the researcher to study how the innovation system actors were introduced and evolved during the first two phases of industry development. It also ensures that the case overlaps in terms of industry development, as recommended by Suurs [23].
	• The case should differ in TIS level, for example, project level, organisational level and industry level.	Although all the cases applied a technology innovation system (TIS) perspective, Suurs [23] recommended that the cases cover as much variety as possible and include various activities.
	• The cases must cover a minimum of a one-year period	The cases should cover a long enough period to include a variety of activities [23].

Given the inclusion criteria listed in Table 7.1, a cube or three-dimensional framework could be drawn to schematically represent the solution space of case studies relevant to the development of the AM industry and hardmetals. As AM-hardmetal cases from different geographical areas, maturity levels, and actors should be included, the three dimensions of the framework could be defined as Actors, Maturity level and Geography, as presented in Figure 7.2. The dimension included academic actors such as university research groups, research organisations, governmental departments, and industry partners such as start-up companies, SMEs, and large enterprises. The maturity level dimension included the research and development phase of the industry life cycle as well as the growth and maturity phases, as mentioned in §4.1. The geographical dimension comprised the global continental regions such as Africa and the Middle East, Europe, Central Asia, and the Americas.

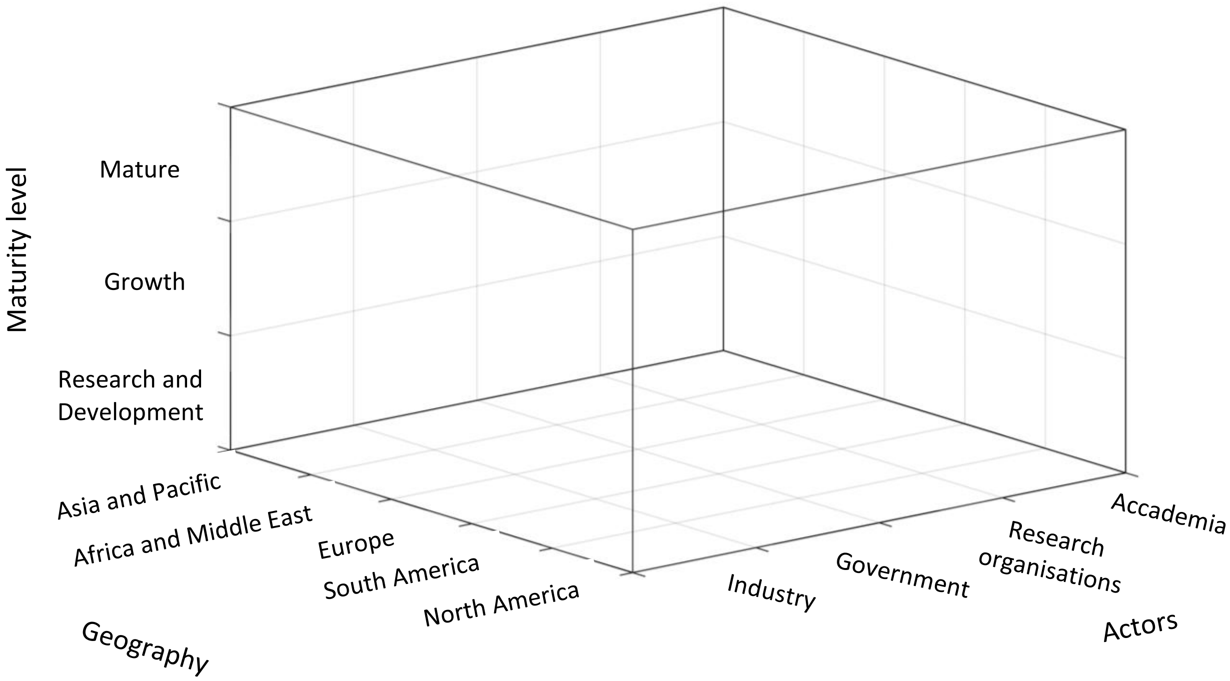


Figure 7.2: Case study cube

Each segment of Figure 7.2's framework can be filled by a specific AM-hardmetal case characterised by the relevant segment's location on the three-dimensional axes of the framework. Some case studies may stretch over more than one segment, and segments may be filled only halfway, depending on the case's dimensions. Due to the limited time associated with a master's degree study, only four cases could be studied. Therefore, only a few framework segments were filled in this study. As future studies are conducted, and more segments are filled, the framework will become richer until an augmented version of the framework is obtained. The following sections give an overview of the four cases that were studied.

Case I: The South African additive manufacturing industry

For the first case, an industry boundary was selected. The framework was applied to analyse the case of the South African AM industry from 1991 to 2020. This case was selected for two primary reasons. First, as the study is focused on the evolution of ISs with application to the South African industry, studying the introduction of AM into the South African manufacturing industry is important. Valuable insight may be gained into the actors and dynamics responsible for the development within the industry and determine why and how they were effective. Secondly, Part IV documents an industry survey conducted on South African AM enterprises. This case, therefore, provides theoretical insights into the industry, while the survey will provide practical insight.

Case II: The Additive Manufacturing of Machining Tools out of WC-Co

For the second case, a project perspective was applied, and a case on a research group from one of Europe's largest application-oriented research organisations, Fraunhofer, was studied. In this case, government-funded research is conducted by a research organisation, a university and twenty industry partners to improve an AM technique to manufacture hardmetal machining tools. The case aims to shed light on the first case's industry dynamics and effectiveness from a research collaboration perspective. Furthermore, as the case involves academic and industry actors, insight is gained on the 'Valley of Death' metaphor discussed in Section 4.1.

Case III: Dyze Design's Hardmetal Nozzle

The third case applied a company-level perspective. The case studies the development dynamics of a multi-award-winning Canadian start-up company that grew rapidly due to the commercialisation of its hardmetal 3D printer nozzle. This case demonstrates the channels the start-up used to raise awareness and capital for their brand and products. This case, similar to the second case, overlaps with the first case and gives insights into the necessities of governmental support programmes and initiatives.

Case IV: Varel's high-precision nozzles

The fourth case also applied a company-level perspective. This case studied the R&D activities of the world-leading AM-hardmetal product developers and multinational engineering company, Sandvik. The case provides insights into the dynamic involved in implementing new technology in large companies, their R&D objectives, and the resources they are willing and able to invest. Finally, the case sheds light on the procedures established companies follow to evaluate, develop and commercialise their R&D findings.

7.3. Application of Event History Analysis in this thesis

As presented in Figure 7.3, the EHA method comprises eight steps. Seven of the method's steps were applied in each case study. The final step, case study comparison, was completed in a case comparison chapter at the end of the case studies. The application of each of the eight steps is discussed in this section.

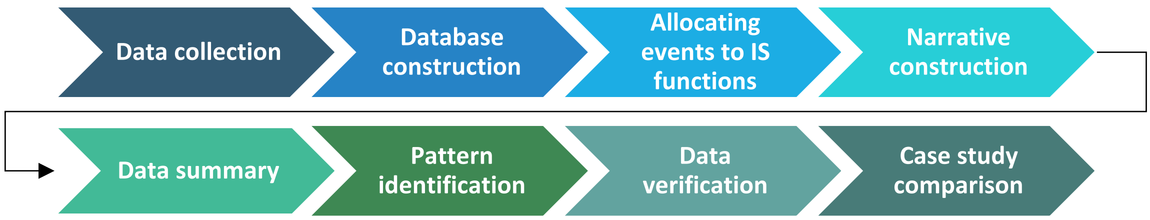


Figure 7.3: Steps of the Event history analysis method

7.3.1. Data collection

A comprehensive literature study of each case was conducted to find all the information relevant to the studied cases. Various literature sources, including professional journals, periodicals, reports, national strategies, and websites, were collected for each case study. The selection criteria were that the text had to cover topics related to each specific case. For example, the selection criteria for the first case included that the text had to be relevant to the development, diffusion or implementation of AM technologies in South Africa. Research databases, such as Scopus and SpringerLink, were used as they allowed the use of search terms and delivered various academic literature. Google was also a powerful literature source, directing the author to non-academic sources, such as industry websites, national strategies, and monthly newsletters.

7.3.2. Database construction

The literature collected for each case study was read through, and the reported events were identified. Event information refers to explanations of why events occurred, the events' effect, and the events' consequences were stored. Incomplete information events were further investigated, completed, and verified by other sources. [23]. Once all the events had been identified, they were sorted chronologically and stored in a database table.

Cresswell's [50] six-step process for qualitative data analysis was used to identify the events and event information from each data source. The event identification process was inductive. As the identified events had to correspond to the IS functions, the definitions indicators of the functions, presented in Table 7.2, were used as a heuristic to guide the coding search terms and the identification and interpretation of the events. Once all the events were identified, a second layer of coding was used to categorise similar events, for example, all events related to learning were grouped. After the event categorisation, a database of the events in chronological order was constructed.

Table 7.2: Indicators of the fulfilment of the IS functions [23], [299], [301], [302], [304]

Function	Event categories
(F1) Entrepreneurial Activity	Projects with commercial aims, demonstrations, portfolio expansions, entry of firms, manufacturing, constructing, technology installation
(F2) Knowledge Development	Academic research and studies, market surveys, feasibility studies, pilot projects, developing promotional materials and or prototypes, testing of model performance, adapting model, assessing the availability of raw materials for technological production, conducting impact analysis, testing the technology literacy of entrepreneurs, learning-by-doing and -using
(F3) Knowledge Diffusion	Training activities, alliances between actors, joint ventures, awareness campaigns, conferences, workshops, seminars, setting up branch organisations, demonstrations
(F4) Guidance of Search	Setting policy targets, standards, research outcomes, designing favourable regulations and policies, defining expectations, promises, communicating vision, providing direction or showing interest, and communicating research outcomes to the public
(F5) Market Formation	Subsidies (i.e., sharing cost of investment), market regulations, regulations supporting niche markets, setting tax incentives and tax exemptions, "obligatory use", public procurement, reforming regulations, expectation
(F6) Resource Mobilisation	Financial incentives, subsidies, grants, investments, infrastructure developments, equipment provision, recruiting of human resources (including consultants and technical staff)
(F7) Creation of Legitimacy	Lobbying activities, advice, advocacy coalitions

7.3.3. Allocating events to innovation system functions

The databases constructed for each case study provided a good overview of the event categories associated with the case. The event categories were allocated to the relevant IS functions. As each event category had different effects on the fulfilment of the IS functions, each event's effect was also identified. The categories contributing to the fulfilment of the system functions were allocated a `+1' value, while the categories with adverse effects on the system functions were allocated `-1' values. A value of `0' was also awarded to those events included to provide context for other related events.

In additional to the traditional `-1, 0, +1’ scoring of events generally performed by EHA and IS authors [23], [24], [33], [34], [36], [294], [299], the CIMO-based EHA framework captures the actors involved in each event. Furthermore, the actor's action is categorised as *performer, giver, or receiver*. For example, when an actor executes a task, such as starting a research study or commercial project, their action is categories as *performed*. However, when a function is performed by an actor and received by another, the performing actor is labelled *giver,* while the receiving actor is labelled *receiver*. Figure 7.4 illustrates this concept by distinguishing between a person who reads on their own (performer) and a lecturer (giver) who teaches students (receiver) their knowledge through speaking.

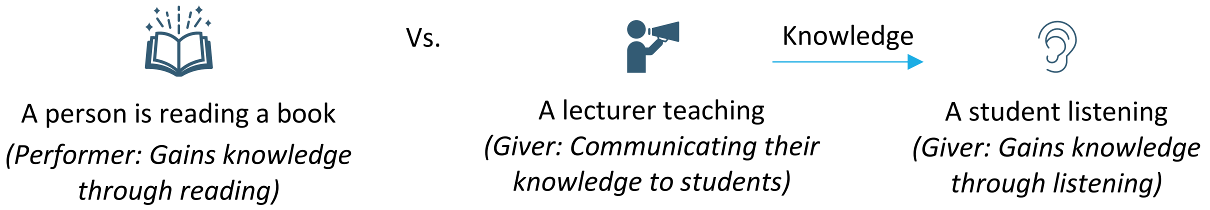


Figure 7.4: Categorisation of event actors as *performers, givers* and *receivers* based on the action that is performed

Therefore, in addition to the traditional database allocation of events to the IS functions performed by EHA and IS authors Negro [34], [36], Suurs [23], [24], [33] and Maarsingh et al. [294], the relevant actors involved in each event were captured in the database and categorised as performer, giver, or receiver, according to the context of the event. Table 7.3 provides an example of Case III's updated database where the traditional event categorisation and the additional actor categorisations are listed.

Table 7.3: Examples of events included in Case III's database

Event ID	Year	Description	Event category	IS function	Actors
1	07/2015	Dyze Design is founded.	Entry of firms	F1+	DD F1 (Performer)
5	08/2015	Dyze Design won the Montréal Foundation Inc innovation competition hosted by the government.	Advocacy	F7+	Gov (Giver: F7) DD (Receiver: F7)
7	11/2015	Dyze Design received training from a government-supported organisation.	Learning and Training activities	F3+ F2+	Gov (Giver: F3) DD (Receiver: F2)

Along with the constructed event database presented in Table 7.3, an Excel database of the events was captured from the event database to enable data analysis of the events, functions, and related actors in the subsequent EHA steps. An example of the Excel database constructed for each case is presented in Table 7.4, Table 7.5, and Table 7.6.

Table 7.4: Extract the data coding tool developed for each case

Events			IS Functions							Participating Actors				Actors performing the IS functions							
														F1				F2			
Date	ID	Ref	F1	F2	F3	F4	F5	F6	F7	DD	Gov	CSoc	Aca	DD	Gov	CSoc	Aca	DD	Gov	CSoc	Aca

In Table 7.5, the information relating event's date, ID and literature sources reference is captured first. Thereafter, the functions related to the event are captured. Furthermore, in Table 7.6, the involved actors are captured first. Thereafter, the actors are categorised as `givers' or `receivers' at their corresponding functions. The capturing of Table 7.5,'s events 1 and 7 in the Excel database is presented in Table 7.5 and Table 7.6.

Table 7.5: Data coding tool Part I: Event details and relevant functions

Event information			Functions performed						
Date	Event ID	Reference	F1	F2	F3	F4	F5	F6	F7
07/2015	1	[351]	+1						
11/2015	7	[352]		+1	+1				

Table 7.6: Data coding tool Part II: Actors details, the functions performed and the `Giver' and `Receiver' categorisation

Participating Actors				Actors performing the IS functions											
				F1				F2				F3			
Comp	Gov	Aca	Soc	Comp	Gov	Aca	Soc	Comp	Gov	Aca	Soc	Comp	Gov	Aca	Soc
✓					P										
✓	✓							R					G		

Performer	P
Giver	(+-) G
Receiver	(+ -) R

7.3.4. Construction of a narrative

Following the coded events database, the chronological events were used to narrate each case. To simplify the narrative analysis in the succeeding steps, the narrative was divided into phases. At the end of each phase, the key milestones were summarised in timeline figures, and a reflection was given on the period's structural components and their drivers, barriers, and impacts. The IS functions each event corresponds with are also indicated in the narrative phases. The events contributing to the development of the system functions were denoted by **[F1/EA, F2/KDev, … F7/CoL]**, while the adverse events were denoted as **[-F1/EA, -F2/KDev, … -F7/CoL]**. To ensure that valuable insights regarding each actor's contribution may be lost, the actors involved in each event were denoted to ensure that their contributions and IS functions were captured. For example, the events associated with the government, civil society, and academia were denoted as **[Gov]**, **[CSoc]** and **[Aca],** respectively.

7.3.5. Data summary

To gain insight into the functional development of the narrative and the influence it produced within a case, the fulfilment of the case functions was tracked over time. To track these fulfilments, timeline graphs for each IS function was developed. At the start of the narrative, each function was given a value of zero. Thereafter, the numerical value of the events was added to the specific function's numerical value as the timeline of events progressed. Finally, a graph could be drawn of the functional development over time. Quantitative content analysis, as discussed in Section 7.5, was implemented to develop the time-based functional development graphs. Additionally, radar graphs indicating each actor's functional contributions were also developed to present an overview of their contributions.

7.3.6. Pattern identification

Once the narrative was developed, and the event data was analysed, the CIMO *context*, *interventions, mechanisms, and outcomes* of each case' phases could be determined through the data analysis. Based on the ideas of Poole *et al.* [337] and Suurs [23], the event data can be subjected to two types of pattern analyses: trend and interaction.

Trend patterns are associated with the fulfilment of the individual system functions and are used to identify significant developments in the narrative [23], [24]. *Trend patterns* captured the *CIMO interventions.* These patterns were identified through plots of time graphs of the events and functions over time. Changes in the graph's slope were indicative of changes or turning points that occurred during the case development. Furthermore, give-and-receive functional interaction maps were developed to identify how these functions performed in terms of giving and receiving.

Following the identification of the interventions, the functions present during the narrative phase, the *Interaction patterns* offered possible explanations for the identified trend patterns as they focus on the sequences in which functions occur [23],[36]. As *interaction patterns* capture the sequence in which events occur, they support the identification of CIMO mechanisms, namely motors of innovation. To support the identification of the interaction patterns and motors of innovation, Maarsingh *et al.*'s [52] causal loop diagrams were developed.

Following the identification of the CIMO mechanisms and motors of innovation, further data analysis was performed to capture the IS structures associated with the mechanisms. Finally, these mechanisms' case-specific outcomes and development capitals were captured (CIMO outcomes).

7.3.7. Data verification or triangulation

As only a small amount of quantitative data was used in the narratives, the interpretation of the events and the functions' development was based on the researchers' interpretation. Although the analysis was conducted as objectively as possible to minimise bias [23], [24], [36], the event identification, narrative and pattern recognition were verified using triangulation.

Semi-structured interviews were conducted with the field experts to verify and validate the events constructed in the narratives and ensure that only meaningful events directly influencing the development of the IS studied in each case are included. They also validated the event drivers, barriers and impacts documented and highlighted in the narratives. The affiliation of the interviewees and the number of interviews differed for each case studied. As the cases focus on historical development, field experts from different phases and `fields' (academia, industry, government) of each case were identified and interviewed to obtain a comprehensive overview of each case. The interview process was guided by Rabionet's [353] six-step interview guideline, as discussed in Section 7.4. The interviews were recorded and transcribed, after which coding strategies, as discussed in Section 7.5, were implemented. Following the coding and subsequent analysis of the interview data, the narratives were adapted and modified based on the findings.

By conducting the semi-structured interviews with field experts, the interpretation of the events and the case study analysis was based on the researcher's knowledge and opinion, public opinion obtained from the articles and reports, and the judgment of multiple field experts.

7.3.8. Case study comparison

The preceding seven steps were applied to each of the four case studies. Each case study revealed particular patterns, cycles, and motors of innovation accompanied by IS structures. As the four case studies overlapped in terms of industry development and application theme, the conclusions derived from each case study could be compared and again validated. This led to the derivation of more general, inclusive insights and explanations of how motors of innovation generally come about.

7.4. Semi-structured interviews

Interviews are a standard and powerful method to obtain information and build an understanding [50]. It is a conversation that involves an interviewer, who coordinates the conversation by asking questions, and an interviewee, who responds to the questions and provides information [80]. They can take on different designs based on the information that is required. These designs can be grouped into three categories: structured, semi-structured, and unstructured interviews [80].

Structured interviews aim to gather specific information on a particular topic [354]. The interview questions are predetermined and structured so the interviewees' responses can readily be coded and categorised [80], [354]. An advantage of these interviews is that the interviewer has complete control of the theme and format of the conversation, which allows the interviewer to obtain the required information [80]. Disadvantages of structured interviews include limited exploration, the possibility of misinterpretation of the predetermined questions and the possibility that an interviewer's cues could influence bias [354].

Unstructured interviews are open-ended, informal, spontaneous, and exploratory [80], [354]. There are no specific guidelines, restrictions, or predetermined questions [354]. Unstructured interviews are beneficial when little information is available or known on a topic [80]. Disadvantages of unstructured interviews include possible bias and the possibility of inappropriate questions when the interviewer is inexperienced. Additionally, as the conversation is unstructured and open-ended, information may be difficult to analyse [354].

Semi-structured interviews are more open-ended than structured interviews and allow new ideas to be explored based on interviewees' responses to predetermined themes, topics and questions [80], [354]. These interviews balance the inclusion of required topics and the possibility for new themes, topics or perspectives to be included. They allow interviewers to prepare and generate supplementary questions ahead of time and provide interviewees with the opportunity to clarify questions, which reduces the misinterpretation of the predetermined questions [80]. These interviews are useful when there is a need for in-depth information to be collected systematically, and interviewees are not available for several follow-up interviews [80]. These interviews are generally recorded and transcribed, after which coding strategies are implemented. A disadvantage of semi-structured interviews is that inexperienced interviewers may inadequately prompt the interviewee to collect relevant data [80], [354].

Cresswell [50] pre-scribed the development of an interview protocol for successful research interviews. An interview protocol includes the interview information, standard instructions that should be followed throughout the interview, and the predetermined questions [50]. In addition, Kajornboon [354] and Rabionet [353] suggest that interviews be conducted with complete transparency on possible ethical implications. Although Cresswell's [50] interview protocol is open-ended, it allows for reliable and comparable data. Rabionet [353] developed a seven-step process or interview guideline, presented in Table 7.7.

A primary element of both case studies and semi-structured interviews is data analysis. If the data from these methods are analysed correctly, great insights will be gained into the innovation systems and their events. Conversely, if the analysis is done incorrectly, the researcher will miss out on the richness of the data.

Table 7.7: Interview process applied in this thesis [353]

Step	Description	This Thesis
1. Select the kind of interview	Choose between structured, semi-structured and unstructured interviews	Semi-structured interviews were selected as the predetermined questions were developed on the required case information. It also allowed for new information, concepts, and potential improvements.
2. Develop criteria for expert selection	Determine the selection criteria for experts based on the purpose of the interview.	Two types of experts were consulted. First, experts involved in the cases were interviewed to obtain case-specific information. Thereafter, IS experts were consulted to validate the framework's application to the case following the relevance cycle's evaluation criteria listed in Table 2.6.
3. Establish ethical guidelines	Investigate possible consequences, risks, safety, confidentiality, and permission issues regarding the interview.	Stellenbosch REC ethical clearance was obtained. Consent was obtained from all experts before the interviews. Experts remained anonymous during the reporting process.
4. Craft interview protocol	Gather information to create the context for the expert. Develop questions and supplementary questions.	An interview protocol was set up and provided to all relevant parties before the interviews commenced to provide the interview context. Experts were also provided with the questions and supplementary questions before the interview upon their request.
5. Conduct and record the interview	Conduct and record the interviews, and make handwritten notes.	Interviews followed the developed protocol. Interviews were conducted using Microsoft Teams, and consent was obtained for recording the interviews. Microsoft Teams transcribed all interview recordings.
6. Analyse and summarise the interview	Manage, organise, and analyse the data	Data analysis followed the qualitative data analysis approach explained in Section 7.5.
7. Report the findings	Present the results of the interview data	Any adjustments made to the case study or framework upon the conclusion of the interview and data analysis were shared with the experts for verification and validation.

7.5. Data analysis

Following the qualitative data collection methods mentioned in the previous section, a data analysis approach is necessary. Cresswell [50] identified a six-step process for qualitative data analysis. Cresswell [50] describes the six steps as, although being resented linearly in Figure 7.5, to be interrelated and not necessarily to be executed in the presented order.

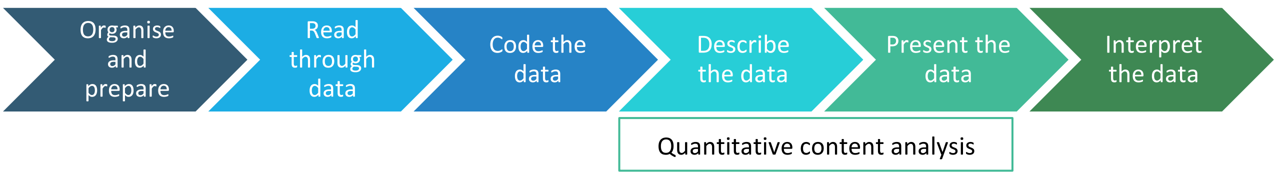


Figure 7.5: Six-step process for data analysis in qualitative research [50]

The first step, organising and preparing data, involves transcribing and arranging data in a usable format. Then, in step two, reading through the data provides a general overview of the themes and concepts included in the data and an idea of the insights that may be gained.

Step three involves coding the data to analyse the data in detail. Data coding refers to the process where data is organised into categories and allocated different code labels specific to their category. Coding types may include setting and context codes, perspectives applied in research, process codes, activity codes, strategy codes and relationship codes [50]. Once a coding layer has been applied, additional layers of analysis may be developed until no additional themes or connections between themes are discovered. The coding process can iteratively be applied at each layer [50], [75].

Miles, Huberman and Saldana [355] describe data coding as a mechanism that condenses vast amounts of qualitative data as it selects, focuses, simplifies, abstracts and transforms data. They describe data coding also as a mechanism used to consider the meaning of the data. Coding is, therefore, an important part of data analysis in qualitative research and should not in itself be considered an analysis method [355].

Coding was used in the case studies to identify relevant concepts, theories and EHA event information from the various data sources. Primary coding levels were used to categorise the event information according to their types and relevant functions. In contrast, secondary coding levels were used to categorise the influence (positive or negative) and actors related to the events.

During the fourth step, meaning is given to the coded data. The data description is summarised by the setting, theme and categories that emerge within the data. The emergent themes may also be used for additional analysis layers to identify more complex theme connections.

Quantitative content analysis was used during the fifth step to present the data. Quantitative content analysis is a content analysis technique that quantifies qualitative data [50]. It is a useful technique that uses coding to count the number of times an occurrence appears in literature, thus quantifying specific occurrences in qualitative data [47]. Quantitative data analysis was used in Part III to obtain descriptive statistics of each case's event data.

During the sixth and final step, the data is interpreted. During this step, the researcher aims to answer the question "What were the lessons learnt?" from the information source, and additional questions are formulated for further research.

7.6. Chapter 7: Conclusion

This chapter discussed the interview, event history analysis and data analysis methods used in this thesis during the framework's application to Case I to Case IV. The chapter started with an introduction to case studies. Thereafter, the case study selection criteria were discussed. Then, the application of the event history analysis method in this thesis was discussed. Finally, the chapter concluded with a discussion of the interview process followed to obtain the case information and the data analysis techniques used to extract the relevant case data. The following chapter studies the first of four case studies.

Chapter 8

Case I: The South African additive manufacturing industry

This chapter presents the first case in a series of four case studies. An industry perspective is used to study a case where new technology is introduced into a country. The method of event history analysis will be used to analyse the case of the South African additive manufacturing industry from 1991 to 2020. The additive manufacturing industry is studied as additive manufacturing is the focus technology of this study. The primary actors in this case study are the South African governmental departments and research organisations that diffuse the technology to academia and industry. The governmental departments released national policies and strategies in the case to guide and align the additive manufacturing research conducted within South Africa. This case's position in the framework is indicated in Figure 8.1. This chapter contributes to objectives IV and V, as mentioned in §1.4.

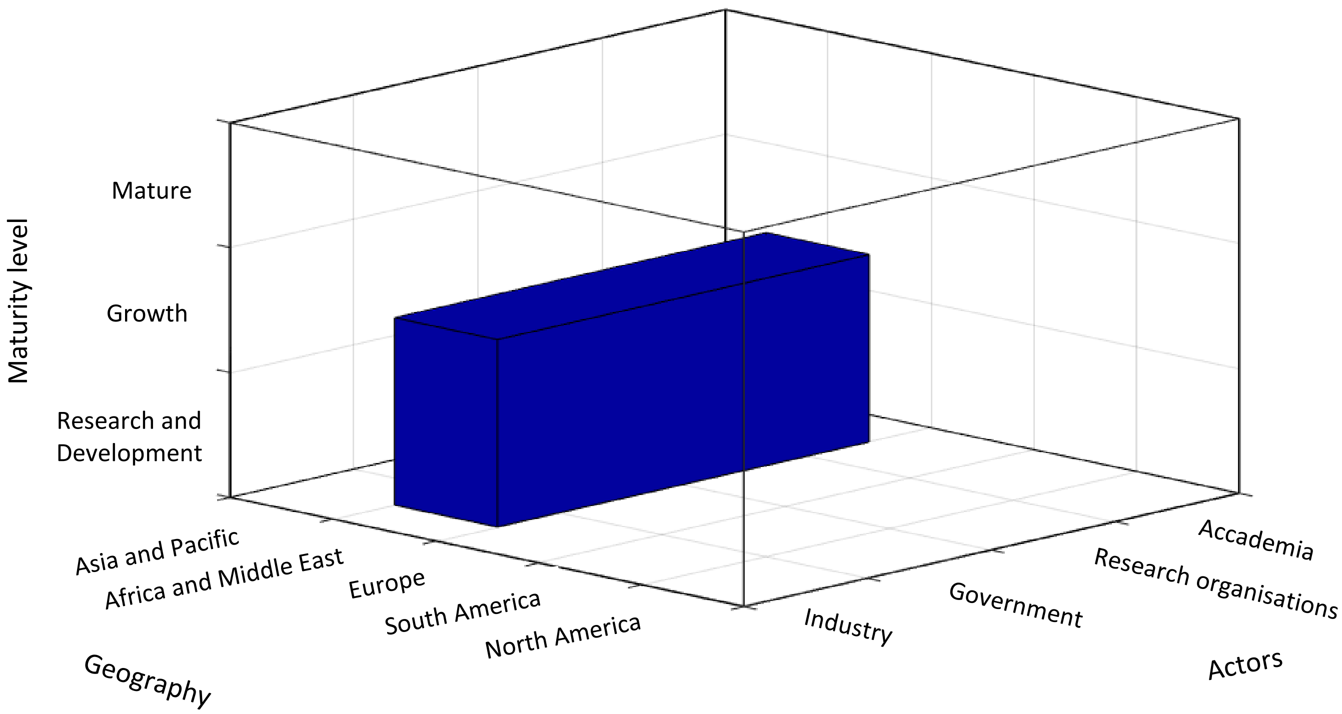


Figure 8.1: First case in case study framework

The chapter starts with an introduction to the South African-focused case and the chapter's objectives. Thereafter the case study is presented as a narrative. Thereafter follows the application of the CIMO-based EHA framework's four steps of the CIMO. First, the *context* of the case is introduced. Thereafter, the narrated is analysed to identify the *interventions and mechanisms* present in the case. The chapter then concludes with the identification of the case *outcomes and outputs* delivered by these *mechanisms.*

Chapter 8 contribution:

- This case expands the current literature on the South African AM industry by compiling the industry events over the past 31 years.
- Through the application of the CIMO-based EHA framework, the underlying dynamics and mechanisms that supported and hindered the industry's growth is explored. It identifies the industry's innovation actors and how they influenced each other.
- The paper derived from this chapter is also among the first to analyse the development of the South African AM industry and the first to analyse the industry through the innovation system framework

Chapter 8 objectives:

- Provide the background of the South African AM industry (§8.1).
- Define the research design of the case study (§8.2).
- Narrate the case study (§8.3).
- Identify the context and motors of innovation that led to development (§8.4.1 and 8.4.2).
- Identify the underlying structural drivers and barriers of the motors of innovation (§8.4.1.1 and 8.4.2.1).
- Identify the influence these IS structures and motors of innovation have on the outcomes and outputs of the case (§8.4.2.2 and 9.4.2).

8.1. Introduction

Although additive manufacturing (AM), or rapid prototyping[1] as it was called until 2006, was developed in 1983, South Africa's AM activities only started in 1991. The imposition of sanctions against South Africa until the late 1980s caused South Africa to miss the technology's initial uptake and thus start from a lagging position behind other industrialised countries [135], [356], [357]. During that period, most research and development activities focused on the mining and defence industries. Thus, when the sanctions were lifted, the South African government introduced strategies to stimulate the manufacturing industry, several of which directly impacted the AM industry [358]. Through a collaborative approach, the government has encouraged cooperation amongst higher education institutions and between industry and higher education institutions to efficiently utilise the country's limited economic resources [358].

The following sections will look at the progressive development of the South African AM industry, a national innovation system, to the end of 2020. By analysing the industry's evolution through the innovation system (IS) perspective and the CIMO-based EHA framework, motors of innovation and underlying structural drivers and barriers may be identified, which will explain the successful adoption of AM technology in the country. Additionally, it will answer §1.3's case study research questions.

1. What were the motors of innovation that led to development within the case?
2. What were the underlying structural drivers and barriers that explained the emergence of the various motors of innovation?
3. How did the various motors of innovation influence the IS structures?

[1] Although additive manufacturing systems were referred to as rapid prototyping systems until 2006, for the sake of simplicity, this case will only refer to additive manufacturing (AM) systems.

8.2. Case approach

This case presents an industry-level technology innovation system (TIS) as the evolution of the South African AM industry is studied. The primary focus of the case is also mainly placed on the development of new actors within the industry and capacity development. The method used to analyse the TIS dynamics and evolution of this case is the CIMO-based EHA framework (§7.3). The identification of the events was guided by the typical activities associated with each IS function. Cresswell's [50] six-step process for qualitative data analysis, as described in §7.5, was used to extract the events and event information from various data sources. As listed in Appendix A, the data sources used include professional journals, reports, national strategies, online databases such as SpringerLink, Scopus and Google Scholar, conference proceedings, and websites like those of the CSIR and RAPDASA. Events related to the development, diffusion, or implementation of AM technology in South Africa were included, for example, a conference, technology implemented, relationships established, funding made available, and national strategies released. Incomplete information events were further investigated, completed, and verified by other sources. The events included in this case study's final database were confirmed by at least three data sources.

During the construction of the event database, it was found that the case actors could be categorised into seven groups: knowledge institutes, academia, government, RAPDASA, companies, members of civil society, and the external international market. Figure 8.2 presents a summary of each actor. Furthermore, it was found that the evolution of the South African AM industry could be broken up into two stages: a development stage and a growth stage (Table 8.1). Furthermore, the development stage could be broken up into two periods: the industry initiation and growth periods. The three periods are based on the growth trends identified by authors such as Du Preez [124], [357], [359] and Campbell [356], [358], [360], [361].

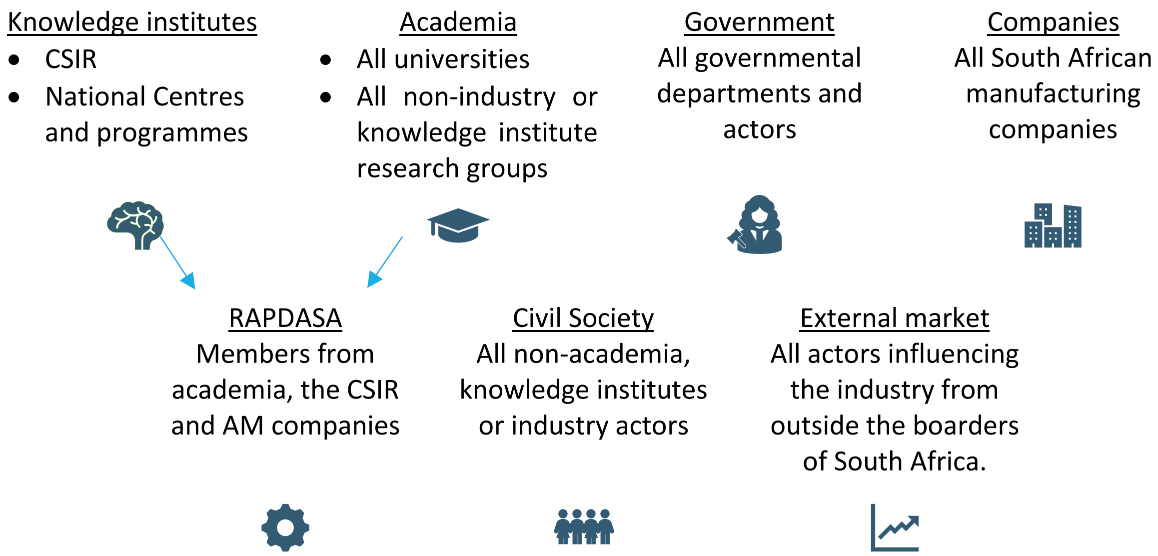


Figure 8.2: The participating actors of the South African AM industry case

The database events were used as the storyline of the narrative. After the narrative was constructed, it was analysed to answer the research questions. Semi-structured interviews were conducted with several field experts to validate the constructed narrative and the analysis thereof. As the case study focuses on the evolution of the South African AM industry, field experts from each narrative period were consulted. In addition, field experts from different organisations – academic institutions, research organisations, industry, and government - that were actively involved in the development of the industry were consulted.

Table 8.1: The three periods in the evolution of the South African AM industry

Stage	Period	Year	Description
Development	Industry initiation	1991 - 2002	Ten AM systems were imported into the country. The government recognised the importance of AM to ensure global manufacturing competitiveness and consequently initialised support programmes. Research studies for various AM application fields started, and an international AM conference was launched.
	Growth	2003 - 2010	One hundred ninety new AM systems were imported into the country. New materials and AM technology became available. From 2006, AM was no longer viewed only as a prototyping technology. Several national strategies were also released to support the manufacturing industry.
Growth	Accelerated growth	2010 - 2020	The number of AM systems in the country grew to more than 6000. The government developed a South African AM strategy, and more research programmes were launched. Several commercial AM organisations were also established.

8.3. The event history of the South African additive manufacturing industry

This section outlines the evolution of the South African AM industry as a chronological narrative. The narrative is divided into two stages of three periods, as mentioned in Table 8.1. The narrative events corresponding to the IS functions are denoted by [F1/EA, F2/KDev, … F7/CoL] along with a `-1 or 1' to indicate their influence. Furthermore, events related to the knowledge institutes, companies, RAPDASA, academia, members from civil society, governmental departments and the external international market are indicated as [KI], [Comp], [Rap], [Aca], [CSoc], [Gov] and [Ex], respectively. At the end of each period, a timeline figure summarises the period's main events. Readers may skip the period descriptions to Figure 8.3, Figure 8.4 and Figure 8.5.

8.3.1. Development stage: Industry initiation period (1991-2002)

Until the late 1980s, through published international case studies and vendor literature, South African researchers learned about the benefits the AM offered **[Ex (G), KI (R), Aca F2/KDev]** and quickly identified application areas relevant to the local context where research opportunities existed **[KI (P), Aca F4/GoS]** [358], [362]. Then, in 1991 and 1994, the first three AM systems were implemented in South Africa by the South African 3D Systems (Pty) Ltd agent and the CSIR[2] **[KI (P), Comp (P) F1/EA]** [135].

In the mid-1990s, the introduction rate of new product models into the global market led to the realisation of the enabling power AM offered **[Ex (G) F4/GoS, F5/MF, F7/CoL]**. In South Africa, it led to the realisation that competitive product development was required to support the local manufacturing industry **[Gov (R) F4/GoS]** [357]. This realisation was fundamental to establishing the CSIR's Product Development Centre in 1995 **[KI (P) F1/EA]** [357]. Through the Centre, the CSIR intended to demonstrate good, fast and effective product development technologies that were not well known in the country **[KI (G), CSoc (R) F3/KDif]**.

In 1996, three AM systems were implemented at the Product Development Centre **[KI (P) F1/EA, F7/CoL]** [358], [362]. In addition, a partnership between the CSIR and 3D Systems (Pty) Ltd was formed **[KI (G), Comp (R), F3/KDif]** to promote the Centre as an AM service centre for the local manufacturing industry and as a development centre for the CSIR and local universities **[KI (G), Comp (R), Aca (R) F4/GoS]**.

[2] The Council for Scientific and Industrial Research (CSIR) is South Africa's central and premier scientific research and development organisation that was established by an act of parliament in 1945.

In the same year, the Central University of Technology (CUT) purchased two AM systems, becoming the first South African university to own AM systems **[Aca (P) F1/EA, F7/CoL]** [135], [358]. However, purchasing these systems was extremely challenging as some researchers did not understand their application in global or local manufacturing **[Aca (G, R) -F4/GoS]**, and single installations had to be imported directly from international manufacturers **[Comp (G), Aca (R) -F1/EA]** [362]. Therefore, strategic support and funding from private partners and the university finally led to the acquisitions of the two machines [362] **[Aca (G) F6/RM]**.

In 1997, CUT and the CSIR established the Centre for Rapid Prototyping and Manufacturing (CRPM) to conduct extensive research on AM technologies and expand its application fields within the local manufacturing industry [363], [364] **[KI (G, P), Aca (R, P) F3/KDif, F1/EA]**. The CRPM purchased an AM system **[Aca (P) F1/EA]** with support from the National Research Foundation[3] (NRF) **[Gov (G), Aca (R) F6/RM]** [365]. In the same year, a similar centre, known as the Global Competitive Centre (GCC), was established by the Department of Industrial Engineering of Stellenbosch University (SU) **[Aca (P) F1/EA]** [366].

By the end of 1997, the Product Development Centre obtained a new form known as the Time Compression Technologies Centre (TCTC), focussing on reducing time to market through AM technologies **[KI (P) F1/EA]** [135]. This Centre operated as a physical centre and a virtual network of partners, with the CRPM and GCC as the leading academic and knowledge institutions and Rapid Design Technologies (Pty) Ltd as the leading industry partner **[KI (G), Aca (R), Comp (R) F3/KDif]** [357].

In May 1998, the Global Alliance of Rapid Prototyping Associations (GARPA) was formed to enable and encourage knowledge sharing across international borders [367]. Through the support of the TCTC, South Africa became a founding but interim member of GARPA **[KI (R) F3/KDif]** with the challenge to form a national association to obtain full membership **[Ex (G) F4/GoS]** [135]. Gaining full membership was essential to South Africa, as GARPA offered a platform that allowed South Africa to exhibit its research to the world while accessing world-class knowledge [357].

In 1998, the Department of Science and Innovation (DSI)[4] conducted a National Research and Technology Foresight Project. The project emphasised integrated product development and production system design to speed up production time **[Gov (G) F4/GoS]**. The project also listed RP, virtual prototyping, computer-aided design, computer-aided manufacturing and tooling among the key technologies that would support this aim **[Gov (G) F4/GoS, F7/CoL]** [368]. The report thus indicated that AM technologies were firmly established within the South African government's strategy for future industrial development [357], [358].

In response to the Foresight Project's key findings, the South African government provided funding for AM research and more AM systems **[Gov (G), Aca (R), KI (R) F6/RM]** [124], [135]. Additionally, government initiatives such as the Technology and Human Resources for Industry Programme (THRIP) were established **[Gov (G) F5/MF]**. The THRIP initiative, a cost-sharing programme established to encourage research collaborations focused on the technological needs of industry parties, provided 50% funding to industry-academia research projects, given that industry partners also provided 50% **[Gov (G), Aca (R), KI (R), Comp (R) F5/MF]** [369]. Several institutions, including CUT, SU and the CSIR, utilised this programme for industry-related AM research **[Gov (G), Aca (R), KI (R), Comp (G) F6/RM]** [124], [362].

[3] The South African National Research Foundation is an autonomous statutory body that acts as the intermediary agency between the South African government's policies and strategies and the South African research institutions.
[4] The DSI were formerly known as the Department of Science and Technology (before 2020) and the Department of Arts, Culture, Science and Technology (before 2003).

In 1999, the DSI and CSIR established the National CAD/CAM Training Centre **[KI (P) F1/EA, Gov (G), KI (R) F6/RM, F7/CoL]** [357]. In the same year, the DSI also launched the Technology Stations Programme to demonstrate knowledge and technology diffusion from universities to SMMEs to improve SMMEs' competitiveness **[Gov (P) F1/EA]** [370]. At least six of them focused on AM and topics related to product development technologies [362]. As a result, the stations effectively became AM demonstration centres, enabling potential buyers to access and test AM technology before making financial commitments **[Gov (G), Comp (R) F2/KDev, F5/MF]** [135].

Later in 1999, a small group of members from the CSIR, GCC and the CRPM conceptualised the Rapid Product Development Association of South Africa (RAPDASA) **[KI (G), Aca (R) F3/KDif]** in fulfilment of the challenge set by GARPA [357]. The non-profit organisation was established to represent the South African AM and wider rapid product development community **[Rap (P) F1/EA]** [357]. However, due to a lack of AM awareness in South Africa (which was reasonable given the short period AM technology was available in South Africa) **[CSoc (G) -F7/CoL]**, industry partners still had a very conservative perspective regarding AM **[Comp (G) -F4/GoS]**, academic partners were sceptical about AM **[Aca (G) -F4/GoS]**, and globally AM was only seen as prototyping technologies **[Ex (G) -F4/GoS]**. Therefore, RAPDASA's objectives were to demonstrate AM technology to South Africans to convince them of the importance of developing AM technology to maintain international competitiveness and to include industry partners in the research community **[Rap (G, R) F4/GoS]** [136]. RAPDASA, therefore, hosted an annual international conference and its members contributed to the annual Wohler's Report, which strengthened RAPDASA's position in the international arena **[Ex (G), Rap (R) F7/CoL]** [135]. The first annual international RAPDASA conference was hosted in 2000 **[Rap (P) F3/KDif]** [357].

In 2000, growing awareness of the need for AM and competitive product development to support the South African manufacturing industry **[Gov (P) F4/GoS, F7/CoL]** led to the conversion of the National CAD/CAM Training Centre into the National Product Development Centre **[KI (P) F1/EA]**. The Centre was actively supported by the DSI **[Gov (G), KI (R) F6/RM]**, and within the first year, a series of CSIR short courses and research studies were hosted at the Centre **[KI (G, P), Aca (R, P) F2/KDev, F3/KDif]** [357].

Between 2000 and 2005, the National Product Development Centre built South Africa's international standing as a manufacturing competitor of distinctive products [357]. The Centre acted as the knowledge hub of the national AM network **[KI (P) F2/KDev, F3/KDif]**. Du Preez [136] ascribed the Centre's success to the network of partners as they enabled human and financial resources to be leveraged towards a common goal **[Aca (R), KI (G), Comp (R) F3/KDif, F5/MF]**.

In November 2001, RAPDASA hosted the annual GARPA meeting coinciding with the annual RAPDASA conference **[Rap (P) F3/KDif]** [371]. Although this was only the second annual conference, fourteen international delegates attended the conference **[Ex (G), Rap (R) F7/CoL]**. According to du Preez and de Beer [357], the possibility of getting access to current global knowledge became a reality.

In August 2002, the DSI released the National Research and Development Strategy (Figure 8.3) **[Gov (P) F4/GoS, F7/CoL]** [4], [6]. Along with the strategy, R125 million were allocated to technology and innovation for the advanced manufacturing and logistic industries **[Gov (G), Aca (R), KI (R) F6/RM]** [4].

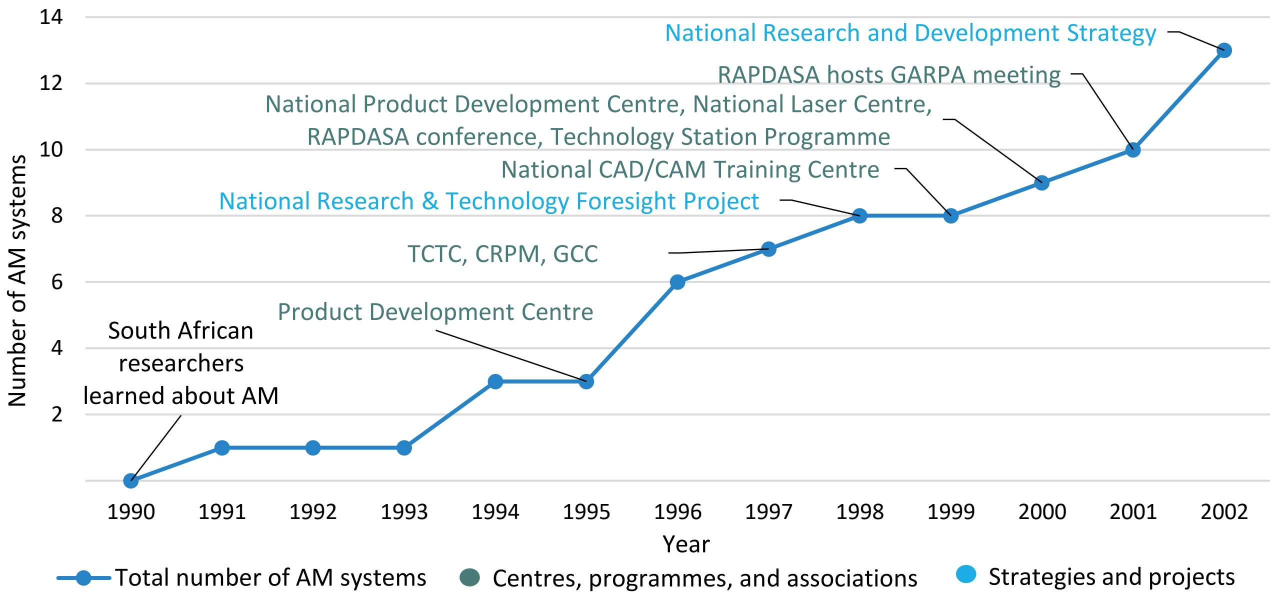


Figure 8.3: The number of AM systems implemented during the industry initiation stage along with the key events that occurred during each year

8.3.2. Development stage: Growth period (2003 - 2010)

In 2003, the National Integrated Manufacturing Strategy [5] and National Advanced Manufacturing Technology Strategy for South Africa [6] were released by the DSI **[Gov (P) F4/GoS, F7/CoL]** [368]. These strategies aimed to stimulate advanced manufacturing, product development and AM in South Africa **[Gov (P) F4/GoS]**. The strategies allocated R650 million to support projects, centres and networks of innovation for the following three years **[Gov (G), Aca (R), KI (R) F6/RM]** [24].

In the same year, the CSIR launched the Rental Pool Programme through DSI funding **[KI (P) F1/EA, KI (R), Gov (G) F6/RM]** [372]. It is an equipment support programme that supports laser and laser-based application research projects and strongly encourages collaboration between universities and science councils [373]. In its first year, it supported seven projects **[Aca (P) F2/KDev, KI (G), Gov (G), Aca (R) F6/RM]** [372].

In 2004, RAPDASA again hosted their annual conference coinciding with the annual GARPA meeting **[Rap (P) F3/KDif]** [371]. More than a hundred South Africans attended the conference **[Rap (G), KI (R), Aca (R), Comp (R), Gov (R) F3/KDif]** [357]. Progressively more private companies were implementing AM systems, and industry leaders became active members of the RAPDASA management committee **[Comp (G), Rap (R) F7/CoL]** [357]. The conference attendees identified several weaknesses and potential threats within the South African AM industry **[Aca (G, R), KI (G, R) -F4/GoS]** [358]. They included a) a limited range of AM systems and material combinations were available in the country **[Gov (G) -F5/MF]**, b) several prominent South African industries were still not implementing AM technologies **[Comp (G) -F1/EA]**, c) there was a lack of fundamental research in academia which made peer-reviewed publications challenging **[KI (G) -F2/KDev, -F3/KDif]**, and d) the tooling industry had growing international competition **[Ex (G) -F5/MF]** [358], [360].

By December 2004, 29 AM systems were implemented in South Africa by universities and private companies **[Aca (P), Comp (P) F1/EA, F7/CoL]** [357], which stimulated further research opportunities **[Aca (P), Comp (P) F2/KDev]** [357], [358], [360]. The continuous growth was ascribed to the stabilised Rand exchange rate **[Gov (G) F5/MF]** and decreased machine price fluctuations **[Ex (G) F5/MF]** [358].

By 2005, the Technology Stations Programme was well established **[Gov (P) F1/EA]**. However, as the programme had a similar focus to the CSIR's National Product Development Centre, the DSI closed the

National Product Development Centre **[Gov (P) -F1/EA]** and redirected its funding to the technology stations **[Gov (G) F6/RM]**.

In 2006, the CRPM implemented the Direct Metal Laser Sintering system **[Aca F1/EA]** [362]. This technology made it possible to manufacture metal moulds for injection moulding, which could be reused for thousands of cycles. Furthermore, rapid prototyping technology enabled metal moulds to revolutionise the global AM industry, as rapid manufacturing was possible in contrast to rapid prototyping. During this period, AM technologies were no longer globally viewed as rapid prototyping technologies but as additive manufacturing technologies **[Ex (P) F4/GoS]**.

In 2007, as part of the National Advanced Manufacturing Technology Strategy, the South African government invested in FabLabs to promote the use of AM in the manufacturing industry and academia **[Gov (P) F1/EA]** [360]. As a result, the government set aside R16 million to establish ten FabLabs (Fabrication Laboratories) across South Africa [374] **[Gov (G) F6/RM]**. Based on MIT's successful FabLabs initiative, the laboratories aimed to provide vast access to modern invention technologies and programmable equipment to support a wide range of AM projects [360]. By the end of 2007, six FabLabs were established across the country **[Gov (P) F1/EA]** [374].

At the end of 2007, 112 AM systems were implemented in South Africa **[Aca (P), Comp (P) F1/EA F7/CoL]** (Figure 8.4), of which one was the first titanium AM system in the country **[Aca F1/EA]**. The purchase of this system was motivated by international companies, such as Boeing, showing great interest in South Africa's titanium-bearing reserves **[Ex (G), Aca (R) F5/MF]** [359], [362], [375].

In 2008, 136 AM systems were implemented in South Africa **[Aca (P), Comp (P) F1/EA F7/CoL]**. Lower cost systems, improved part quality, and ease of use materials became available globally **[Ex (G) F5/MF]** [360]. Designers were starting to combine rapid tooling with AM technologies as the advantages of geometric freedom in small batch production were realised **[Aca (P), Comp (P) F2/KDev]** [358]. Universities, with SU and CUT taking the lead, research focused on new materials, improving machine accuracy and novel industrial applications **[Aca (P), F2/KDev]** [360], [376].

Shortly thereafter, Aerosud Innovation Centre, an international aeronautical engineering company that manufactures Boeing and Airbus components, partnered with the CSIR to manufacture titanium aerospace parts **[KI (G), Comp (R) KI F3/KDif]** [377]. Together they conceptualised an R&D project named `Aeroswift' to

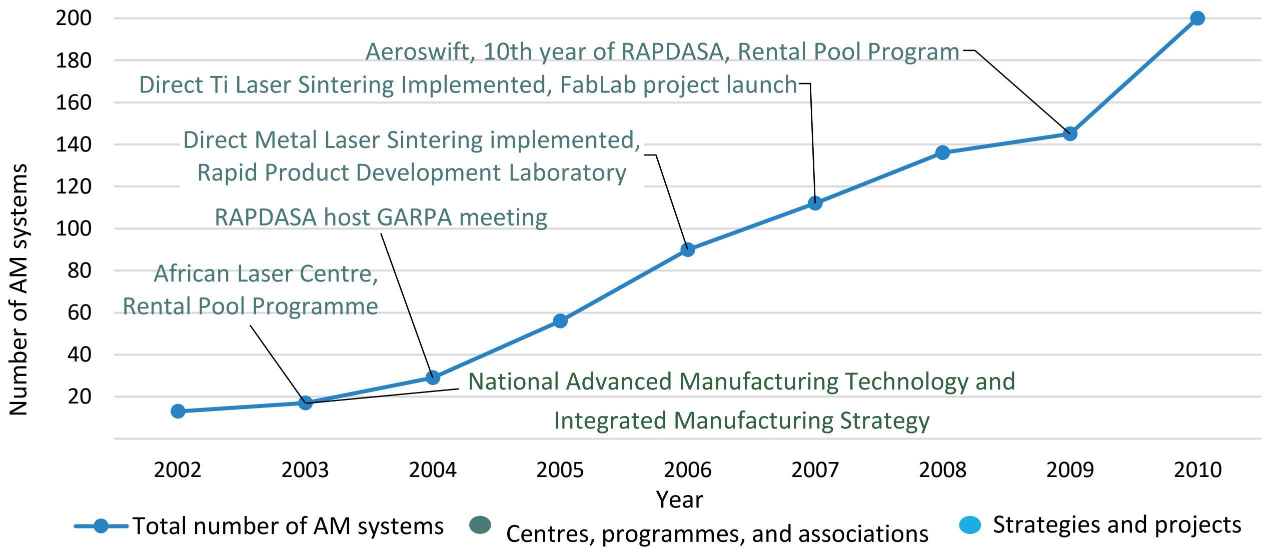


Figure 8.4: The number of AM systems implemented during the Growth stage along with the key events that occurred during each year

advance South Africa's laser technology (Figure 8.4) **[Comp (P), KI (P) F1/EA]**. In the same year, the CSIR's Rental Pool Programme had grown to support 32 programmes per year **[KI (G), Gov (G), Aca (R) F6/RM]** [372].

8.3.3. Growth stage: Accelerated growth period (2011 -2020)

In 2011, the Aeroswift project officially launched **[Comp (P), KI (P) F1/EA]** through funding provided by the DSI and the CSIR **[Gov (G), KI (G) F6/RM]** [377]. As part of the project, Aerosud and the CSIR developed an advanced 3D printer for metal components, the world's largest 3D printer with a build volume of 2000 x 600 x 600mm **[Comp (P), KI (P) F2/KDev, F7/CoL]** [377].

In the same year, the Idea2Product laboratory was established at VUT **[Aca (P) F1/EA]** [378] to introduce AM principals to impoverished Gauteng communities through open-sourced technology transfer models **[Aca (G), CSoc (R) F3/KDev]** [361]. The laboratory provided free support to any product developer from concept inception to the final prototype [378]. Additionally, free CAD training and access to 20 personal 3D printers (printers sold for less than $5 000) were provided [379].

At the end of 2012, industry and public ownership of personal 3D printers had far outgrown the academic ownership of high-end systems **[Comp (G), CSoc (G) F1/EA, F7/CoL]**. De Beer [360], [362] ascribes this trend to a wide variety of industries that were adopting AM as an outcome of the South African national strategies to include SMMEs into the national innovation network and as the prices of 3D printers continued to decrease **[Gov (G), Comp (R) F5/MF]**. Consequently, the government's support programmes, through which technology was transferred from universities to industry, were succeeding.

In November 2012, at the annual RAPDASA conference **[Rap (P) F3/KDif]**, researchers identified the need for a South African AM roadmap **[Aca (G), Gov (R) F4/GoS].** Globally, an AM movement was developing **[Ex (G) F7/CoL],** and the wide variety of research studies made collaborations between research groups difficult as the research differed in application areas **[Aca (G, R) -F3/KDif]** [124]. Therefore, the DSI authorised a group of researchers to develop an AM roadmap **[Gov (G), Aca (R) F4/GoS, F7/CoL, Aca (P) F2/KDev]** [380]. For several months, these researchers extensively researched the application areas that would offer the South Africa AM industry competitiveness in the global AM market **[F2/KDev]**.

In 2014, the South AM Technology Roadmap was presented at the annual RAPDASA conference **[Rap (P) F3/KDif]** [124]. The roadmap aimed to enable South African companies to become global industry leaders by guiding the identification of market, research and technology development opportunities and investment decisions **[Aca (G), Comp (R) F4/GoS]**. The Roadmap prioritised research focus areas included qualified AM parts for the medical and aerospace industries, improving the efficiency of traditional manufacturing sectors, new AM materials and technologies, and SMME development [124] **[Aca (G, R) F4/GoS]**.

Furthermore, Stellenbosch University also established an Idea2Product laboratory **[Aca (P) F1/EA]** [381]. The laboratory provided on-demand 3D printing, 3D scanning and 3D-printing training courses to academic and societal actors [382] and consulted consultation services to product developers and private 3D printer owners **[Aca (G), CSoc (R) F2/KDev]**.

At the end of 2014, in response to the Roadmap, four South African universities, the CSIR, and Aerosud developed a research and development programme known as the Collaborative Programme in Additive Manufacturing (CPAM) **[Aca (G, P), KI (G, P), Comp (R) F3/KDif, F2/KDev]** [383]. According to du Preez [380], the collaboration was possible due to the network of actors formed at the National Product Development Centre, where the key CPAM actors learned to collaborate. They learned that through collaboration, more resources and opportunities became available **[KI (G), Aca (R) F3/KDif, F4/GoS]**. The programme received R 30.7-million from the DSI **[Gov (G), Aca (R), KI (R) F6/RM]** [384]. In addition to the DSI funding, the South African government invested approximately R 358 million, between 2014 and 2016, in AM technology research and development projects **[Gov (G), Aca (R), KI (R) F6/RM]** [384].

In December 2015, there were 3500 AM machines in South Africa (Figure 8.5) **[CSoc (P), Comp (P), Aca (P) F1/EA, F7/CoL]**. In March 2016, a discussion forum for Science, Engineering, Technology for Socio-Economic Growth in South Africa was held **[Gov (P) F3/KDif]** [385]. It was noted that not all the universities conducting AM research owned AM systems and that only a limited number of South African companies were acting as AM service bureaus **[Gov (P) F4/GoS, Aca (P) -F6/RM, Comp (G) -F5/MF]** [385]. In addition, the Rand's weak exchange rate against the Dollar and Euro made AM systems less affordable **[Gov (G), Aca (R), Comp (R), CSoc (R) -F5/MF]**.

In April 2016, the DSI released the AM Strategy for South Africa **[Gov (G), Aca(R), KI (R), Comp (R) F4/GoS, Gov (G) F7/CoL]**. The strategy identified aerospace and military, medical and dental, tooling, casting, and automotive industries as the prioritised industries for 2014 to 2023 **[Gov (G), Aca(R), KI (R), Comp (R) F4/GoS]** [118]. The CPAM programme became the strategy's implementation programme **[Aca (P), KI (P) F2/KDev]** [386]. Later that year, the CRPM became the first African AM centre to receive ISO 13485 certification for 3D printing of medical devices (Figure 8.5) **[Aca (P) F2/KDev, F7/CoL]** [363], [364]. It proved to the South African manufacturing industry that AM technology could deliver certified products and that it was worth implementing **[Aca (G), Comp (R) F4/GoS, F7/CoL]**.

In 2017 and 2018, the Rental Pool Programme supported nearly 300 research projects through equipment sharing **[KI (G), Gov (G), Aca (R) F2/KDev, F6/RM]** [372]. There were also 6000 AM systems installed in South Africa **[KI (G), Aca (G), CSoc (G), Comp (G) F1/EA, F7/CoL]** [365]. After 2018, the number of AM systems in the country became uncountable as the implementation of the systems, particularly the personal 3D printer systems, grew at a high rate **[CSoc (P) F1/EA, (P) F7/CoL]**. The technology was well known globally **[Ex (G) F7/CoL]**, and lower-cost machines became available **[Ex (G), CSoc (R) F5/MF]**.

2019 marked the twentieth year of the annual RAPDASA conference **[Rap (P) F3/KDif]**. RAPDASA grew impressively as more than 300 delegates from academia, industry, and the government attended the conference **[Rap (G), KI (R), Aca (R), Comp (R), Gov (R) F3/KDif]**. RAPDASA was recognised as the showcase of

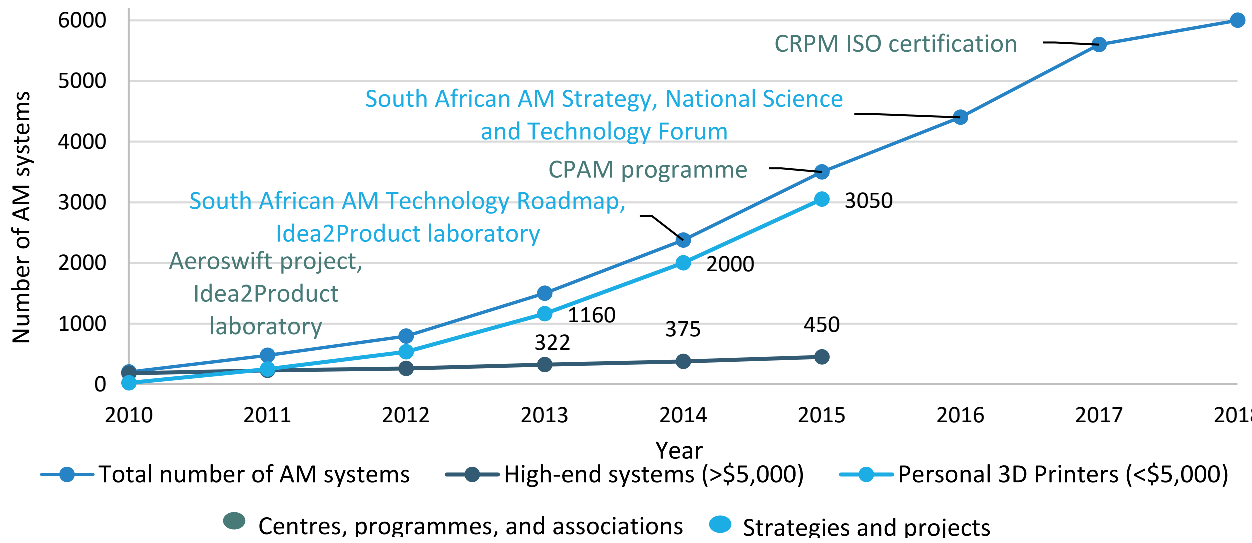


Figure 8.5: The number of AM systems implemented [124] during the Accelerated growth stage along with the key events that occurred during each year

South African AM due to its continued involvement within the industry and playing a central role in developing the fourth industrial revolution in South Africa **[Rap (P) F2/KDev]** [387]. Globally, RAPDASA was the oldest running AM association and had become a leading initiative known for its unmatchable contributions and involvement. The achievement was ascribed to strong networks of actors collaborating across the country and the government's support for the industry [136]. Figure 8.6 summarises the total number of RAPDASA conference attendees from its inception in 2000.

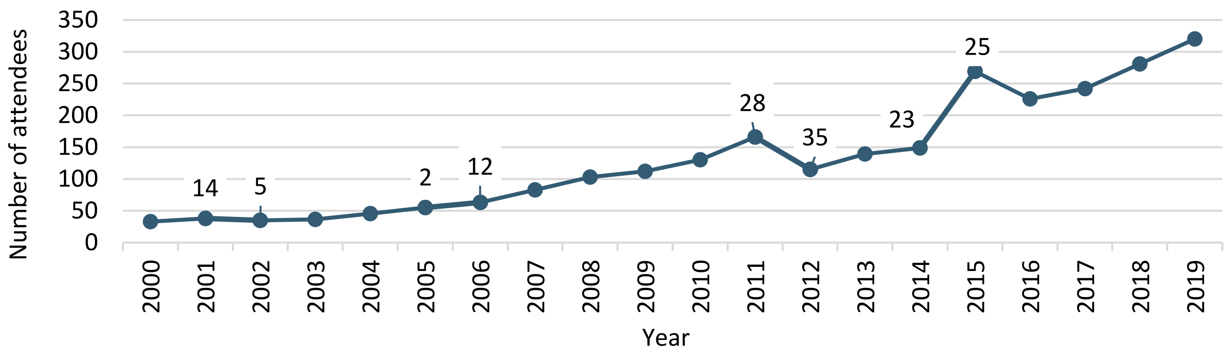


Figure 8.6: Total number of RAPDASA conference attendees from 2000 to 2020 (data found on the number of international conference attendees are indicated)

8.4. Data analysis

In this section, the CIMO component of the CIMO-based EHA framework is applied to analyse the narrative and its actor dynamics. The development of the innovation system (IS) functions and the drivers, barriers and impacts of each period will be used to identify the patterns, virtuous and vicious causation cycles and motors of innovation of each stage. Thereafter an overview is given of how the various motors of innovations influenced each other and how the motors, in turn, influence the sectoral IS structures of the South African AM sector. Finally, the research questions formulated for this case study are answered in this section.

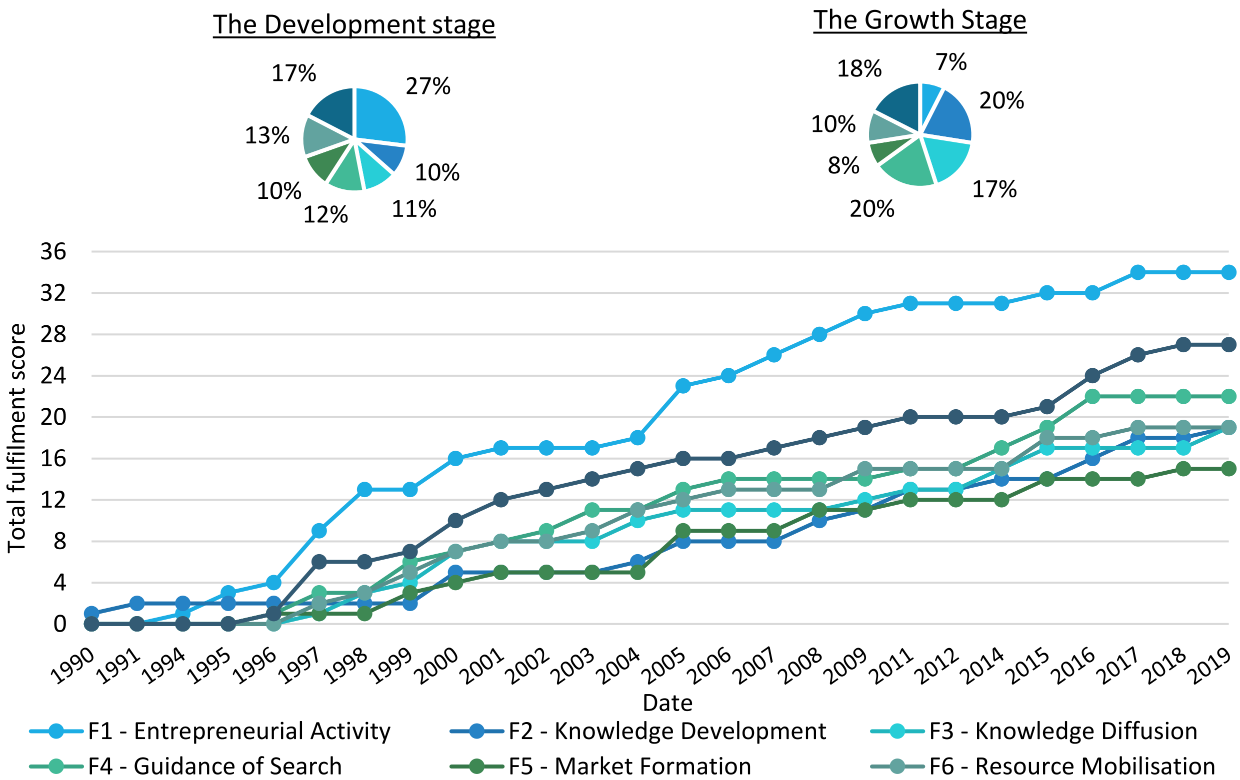


Figure 8.7: The function-fulfilment time graph of the South African additive manufacturing industry case

To get an overview of the development of the IS functions throughout the two stages and the functions participating case actors contributed, Figure 8.7 was developed. Figure 8.7's function-fulfilment time graph presents the fulfilment of each IS function over time, while the pie charts indicate the percentage each function contributed to the narrative stages.

Figure 8.7 indicates that all the functions were present during the narrative and that **[F1/WA]** and **[F7/CoL]** were the dominant functions of the narrative. The dominance of these functions was expected as, throughout the case, emphasis was placed on the continued implementation of AM systems by various actors and the growing advocacy and legitimacy various actors contributed towards the technology adoption within the South African industry. Furthermore, the **[F4/GoS, F6/RM, F3/KDif]** functions, indicating collaboration and communication between actors and the mobilisation of resources, were significant contributors to the case. Finally, Figure 8.7 indicate that functions **[F2/KDev, F5/MF]** were developed slightly less than the other functions. However, further investigation into these functions' impacts is studied in the subsequent subsections of when the CIMO analysis component of the CIMO-based EHA method is applied to the development and growth stages.

8.4.1. CIMO analysis of the Development stage

Before the Development stage can be subjected to the interaction patterns and trend analysis, the context of the stage is summarised in Table 8.2 to shed light on the circumstances that formed the initial setting for the Development stage.

Table 8.2: Defining the context of Case I's Development stage

Defining the system boundary	The South African AM industry from 1991 to 2010.
Defining the phase of development	The industry's initiation and initial growth period.
Defining the system objective	<u>Primary objectives:</u> • To introduce the South African manufacturing industry to AM technologies. • To stimulate AM research in South African research groups and companies and acquire AM systems. <u>Capital objectives:</u> • Business capital: To establish research centres focussing specifically on AM • Financial capital: To fund AM-focused research studies and centres. • Human: Introduce and teach South Africans AM-related skills, such as designing on CAD. • Political: To convince the South African government of the importance of AM to South Africa's manufacturing competitiveness. • Social capital: Stimulate AM networks by connecting AM researchers (from academia and industry).
Identifying the IS structures	<u>Actors:</u> • Knowledge institutes, academic research groups, governmental funding departments <u>Networks:</u> • Several collaborations are formed between the research organisations, university research groups and governmental funding departments. The RAPDASA conference also connected industry partners with researchers. <u>Institutions:</u> • Globally, AM is very new and seen as a prototyping technology <u>Infrastructure:</u> • The governmental departments provide financial support for research and technology acquisition.

8.4.1.1 Interventions and mechanisms

Given this context, the functions of the Development stage and the interaction patterns may be explored. During the Development stage, it is evident that research studies led to the growing awareness of the abilities and benefits of AM technology. The increasing awareness, in turn, led to the collaboration between actors, which made funding opportunities more attainable for the acquisition of AM systems. For example, after the CUT successfully conducted AM research on their two AM systems **[F2/KDev, F4/GoS, F7/CoL]**, they collaborated with the CSIR **[F3/KDif]** to establish the CRPM **[F1/EA]** with support from the NRF **[F6/RM]**. Another example is the collaboration between the CSIR and 3D Systems (Pty) Ltd. After the CSIR purchased an AM system from 3D Systems (Pty) Ltd **[F6/RM, F1/EA]**, the two actors collaborated **[F3/KDif]** to conduct further AM research **[F2/KDev]** to promote the Product Development Centre to the manufacturing industry and academic research institutions **[F4/GoS, F7/CoL]**. Furthermore, positive research outcomes **[F2/KDev, F4/GoS, F7/CoL]** from studies conducted by, amongst others, the CRPM and Stellenbosch University led to more research collaborations **[F3/KDif]**, such as the National Product Development Centre's network of actors, more funding opportunities **[F6/RM]** and AM system implementations **[F1/EA]**.

A pattern and virtuous causation cycle thus exist in the Development stage as positive research outcomes led to the development of actor alliances, which enabled funding opportunities for the implementation of more AM systems and further research projects. Given the central role of *Knowledge Diffusion*, *Entrepreneurial Activity*, *Guidance of Search*, *Creation of Legitimacy*, *Resource Mobilisation* and *Knowledge Development* within the causation cycle, the cycle could be referred to as a *technology push* cycle. Furthermore, as the *technology push* cycle led to the establishment of several national projects to stimulate the South African AM sector and the implementation of new technology at academic, governmental research and industry levels, it seems fit to label the cycle as a motor of innovation, therefore referring to it as the *Technology Push motor*, as schematically represented in Figure 8.8. A reflection of the Development stage's structural components and their drivers, barriers and impacts are presented in Table 8.3.

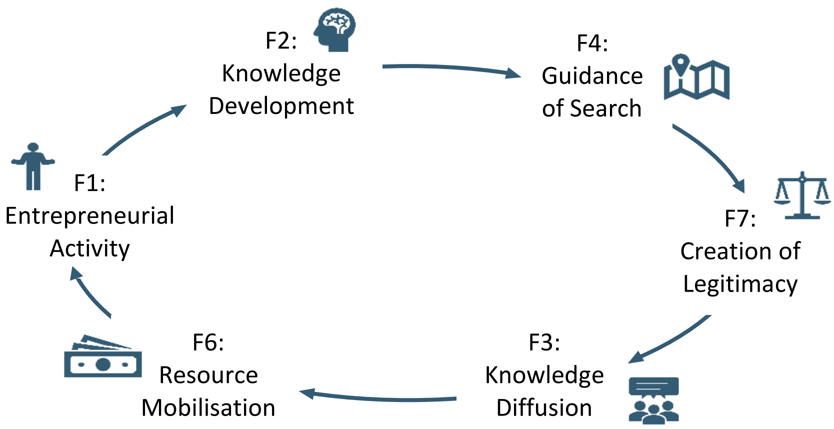


Figure 8.8: Technology Push motor

Table 8.3: The structural components and their drivers, barriers and impacts on the Development stage

	Actors	Interactions	Institutions	Infrastructure
Drivers	• The CSIR implementing new technology and launching AM programmes is the primary enactor. • A small group of South African researchers are enactors. • RAPDASA, creating awareness of the technology, is an enactor. • DSI is the primary selector as they drive research, development, and implementation through funding.	• The National Product Development Centre connecting research and industry actors. • Increased implementation of AM systems at research institutions fuelled collaboration with industry. • The complementary variety of AM systems enabled university-CSIR collaborations. • The Rental Pool Programme connecting researchers with governmental research organisations.	• Government's realisation that competitive product development was required to support the progression of South African manufacturing. • More private companies started developing trust in RP's capabilities and implementing AM systems.	• CSIR and CUT funding AM system acquisitions. • DSI funding for Centres and Networks of Innovation. • The funding provided by THRIP and private partners. • Rand exchange rate stabilising decreasing machine price fluctuations.
Barriers	• There was only a small group of researchers in this early stage. • Academics and industry players were still sceptical about RP. • Only a handful of industry players realised the importance and benefits of the technology.	• A wide range of research application areas was identified. • A limited range of AM systems and material combinations is available in the country. • The size of the bold volume of commercial machines was limited.	• The technology is seen only as a prototyping technology. • Industry's very conservative perspective about manufacturing technologies. • Several large industries were still not implementing AM technologies due to the technology's unproven capabilities and commercial cases.	• A lack of fundamental research made peer-reviewed publications challenging. • Only one South African agent importing AM systems. • It was challenging to obtain funding to purchase AM systems.
Impacts	• An early-stage network of research and industry actors is formed. • National Product Development Centre stimulating research collaborations (until 2005).	• Collaborations between researchers and industry actors are stimulated. • Increased awareness of AM technology.	• The government believes in AM's abilities, legitimise it, encourage further research, and funds the implementation of AM systems.	• Government funds AM research and the implementation of AM systems. • The implementation of more AM systems is possible.

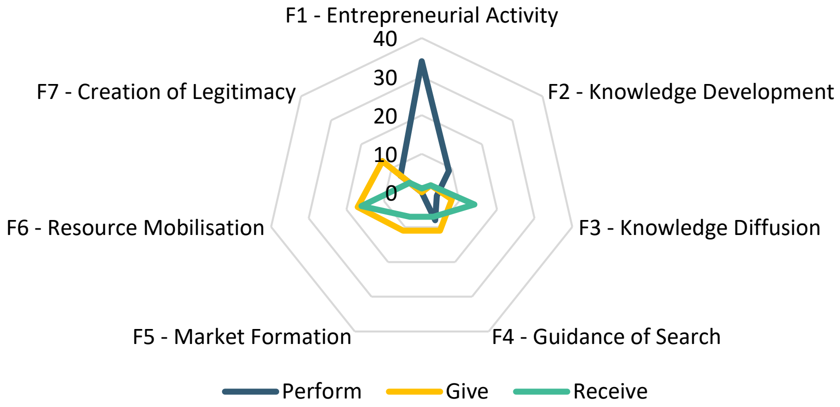


Figure 8.10: Performed-Give-and-Receive functional interaction map of the Technology Push motor

To determine the functional contribution of each of the *Technology Push motor*'s actors and the functions *performed, given* and *received* by each actor, Figure 8.10, Figure 8.9, Figure 8.12 and Figure 8.12 were developed. Figure 8.10 indicates that most of the functions were *performed* by actors rather than shared (*given* and *received*). As previously mentioned, the case focused on the number of systems implemented in the country. As these systems implementations were primarily *performed* by single actors rather than shared (*given* and *received*) between actors, the functions *performed* by the actors were in the majority.

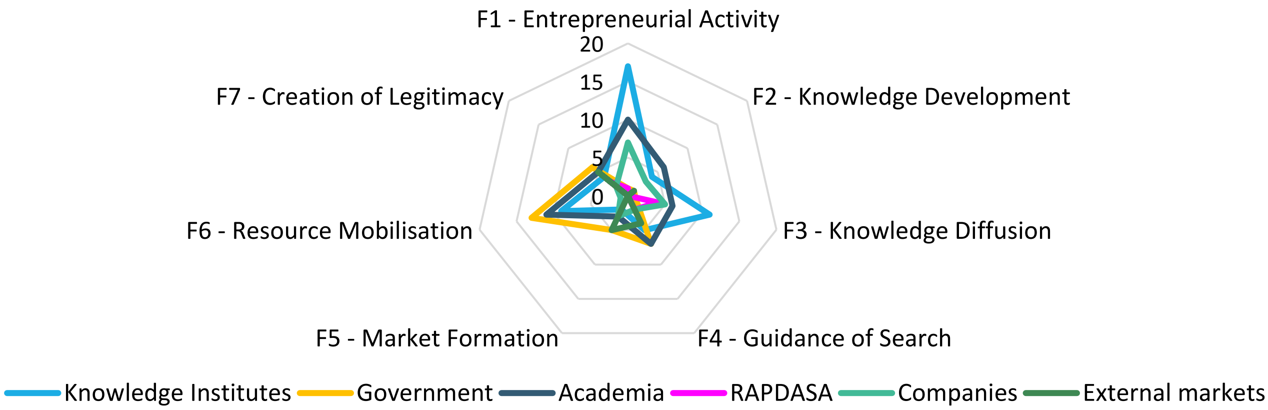


Figure 8.9: The functional contributions of the Technology Push motor's participating actors

Knowledge institutions were primary contributors to the Technology Push motor, particularly functions **[F1/EA, F3/KDif]** and **[F6/RM]**. The primary knowledge institute of the case was the CSIR. They largely contributed to function **[F1/EA]** by implementing AM systems and establishing AM-focused centres, programmes, and networks where academia and industry could test and learn of the AM technologies **[F3/KDif]**. Through these centres, programmes, and networks, they also mobilised resources **[F6/RM]** to companies such as Aerosud to manufacture the Aeroswift AM system and academia through, for example, the Rental Pool Programme.

The knowledge institute actors were thus collaboration catalysts. Collaboration catalysts, such as the CSIR, are important enactors of the *Technology Push motor* as they stimulate and encourage collaboration between different actors. They promote partnerships between academic groups, academia-research organisation relationships, academia-industry relationships, research organisation-industry relationships, and academia-research organisation-industry relationships. They understand that research collaboration leads to mutual benefits between parties as more substantial funding and resources may be obtained. A hypothesis that can be derived is that emerging (manufacturing) technologies require collaboration between

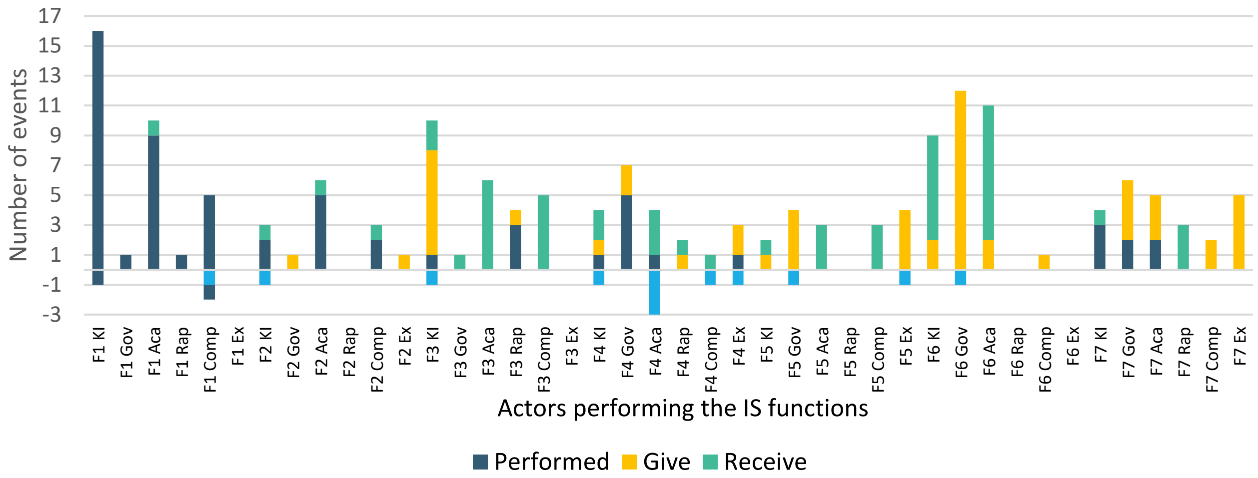


Figure 8.12: The functional Performed-Give-and-Receive map of the Technology Push motor's actors

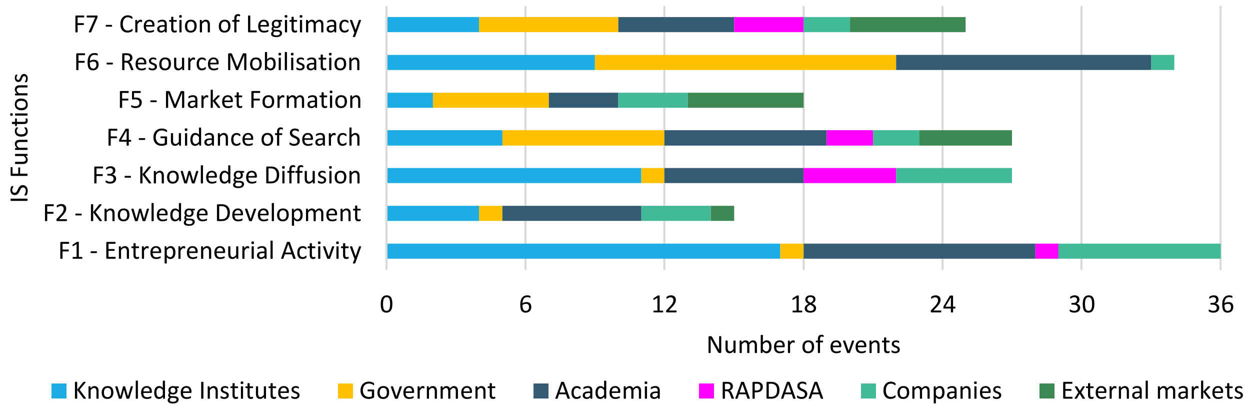


Figure 8.12: The number of events associated with the Technology Push motor's functions and the actors who performed them

different actor groups to increase the extent of the research, the speed at which the technology is diffused and adopted and obtain more substantial resources.

Following the knowledge institutes, *academia* was the primary implementer of the AM systems **[F1/EA]**. They were also, as expected, the leading researchers of the case **[F2/KDev]**. They were some of the first to investigate and implement AM technology in the country. They proved AM's abilities, benefits, and application fields and identified research focus areas. They were also primary *givers* and *receivers* of the **[F3/KDif, F4/GoS]** functions, indicating the feedback they shared and received on their research outcomes and their interest in the technology with knowledge institutes, academics, and companies they collaborated with through research programmes (such as CPAM) and the TCTC's virtual network of partners. The researchers also acted as service centres to demonstrate the technology to industry partners. They were also part of the group of actors who established the RAPDASA association and were the actors who asked for and developed the AM technology roadmap, which later became the National AM strategy. The researchers were thus instrumental to the *Technology Push motor.* A hypothesis that can be derived is that emerging (manufacturing) technologies require research groups to conduct extensive research to introduce the technology to society and industry and demonstrate its abilities, benefits, and applications. Researchers also need to act as service centres to industry partners to demonstrate AM's abilities, benefits, and possible applications.

The *Governmental* actors are the *Technology Push motor's* selectors, primarily contributing to functions **[F4/GoS, F5/MF, F6/RM, F7CoL]**. Through their national strategies, particularly the national AM strategy, the governmental actors contributed guidance and legitimacy to the South African AM industry **[F4/KDev, F7CoL]**. Through these strategies, they shared their advocacy for AM and communicated their suggested research focus areas. Additionally, they provided (*gave)* numerous market opportunities to companies to stimulate industry's adoption of AM. Through programmes such as THRIP, FabLabs and the Technology Stations programme, the government demonstrated AM technology to companies, gave them opportunities to test it, and taught them AM-related skills.

Finally, and most importantly, the governmental actors provided resources **[F6/RM]** to research projects and AM programmes. The importance of funding for research is motivated by several authors [388]–[390] as the amount of funding and resources dedicated to technology directly influences the (level of) development, quality, and commercialisation of the technology. Within the *Technology Push* motor, funding from governmental departments such as the DSI enabled the acquisition and obtainment of the first 200 AM systems in South Africa, AM research, demonstration and training activities and inspired collaboration between actors (such as the THRIP programme). A hypothesis that can be derived is that emerging (manufacturing) technologies require governmental support through advocacy, guidance, and funding to stimulate technology awareness, research studies, collaborations between actors and technology implementation. Furthermore, funding is essential to the *Technology Push motors* of emerging technologies as it enables and stimulates the research and development of the technology and the required recourses, impacts the quality of the development of the emerging technology, and enables the commercialisation of the technology.

RAPDASA is the AM non-profit organisation the *academic* and *knowledge institute* actors developed to represent the South African AM and wider rapid product development community. RAPDASA contributed to functions **[F4/GoS, F7/CoL]** and particularly to **[F3/KDif]**. Similar to the CSIR, RAPDASA was also a collaboration catalyst as they brought members from academia, knowledge institutes and industry together through their annual conference **[F3/KDif]**. The conference presented academic actors with the opportunity to share their research outcomes with researchers from other academic institutions and the attending industry partners **[F4/GoS]**. It was at the RAPDASA conference that academia requested the AM technology roadmap, and the Roadmap was first presented **[F4/GoS]**. In addition to the Roadmap, RAPDASA also gained international legitimacy for the South African AM industry **[F7/CoL]** through their contributions to the Wohler's Report and international actors attending the South African conference (Figure 8.6).

The *Companies* actor of the *Technology Push motor* represented all the manufacturing enterprises and industry parties of the South African AM industry. *Companies* contributed to all seven IS functions. Their primary contributions are to the **[F1/EA]** and **[F3/KDif]** functions through the AM systems they implemented (*performed)* and the collaborations (such as commercial projects) they *received* from the knowledge institutes and academics. Within these collaborations, they also developed and *received* some knowledge **[F2/KDev]**, provided some market opportunities **[F5/MF]** and advocated for AM technology **[F7/CoL]**.

The *external market* represented all the actors influencing the South African AM industry from outside the borders of South Africa. As in the years of the Development and Growth stages, AM systems were primarily imported from the United States or Europe, and the external market primarily comprised of American and European actors. In the Development stage and the *Technology Push motor*, the external market contributed to the **[F5/MF, F4/GoS, F7/CoL]** functions. Figure 8.12 indicates that, as expected, the external market contributed (gave) both positive and negative **[F5/MF, F4/GoS]** functions. This reflects the market opportunities **[F5/MF]** the external markets provided in terms of the AM system imports (both expensive and less expensive systems) and the feedback and interest they provided in the acceptance of the AM technologies **[F4/GoS]**, both as prototyping and manufacturing technologies. Finally, the external market contributed to the **[F7/CoL]** function. This reflects their continuous advocacy for the technology through the global AM movement and the benefits of the technology that was communicated.

8.4.1.2 Outcomes

Given the sequence in which the knowledge institutes, companies, RAPDASA, academia, members of civil society, governmental departments and the external international market performed the functional interventions, they developed the *Technology Push motor* mechanism. The *Technology Push motor* enabled the South African knowledge institutes and researchers who first learned of AM technology and wanted to implement it in South Africa to introduce AM to the South African manufacturing industry. The *Technology Push motor* led to the implementation of 200 AM systems, and at least twelve AM-focused Centres (such as the CRPM, GCC, and TCTC) and programmes (such as FabLabs and the Technology Stations programme) were established.

Furthermore, the following capitals were developed:

- Business capital: The TCTC, CRPM, GCC, National CAD/CAM Training Centre, National Product Development Centre, National Laser Centre, Technology Station Programme and Rapid Product Development Laboratory were established to demonstrate AM technologies and teach AM-related skills to academia and companies.
- Financial capital: The South African governmental departments contributed at least R800 million between 1991 and 2010 to the South African manufacturing industry's advanced manufacturing technologies, which amongst others, included the funding for the AM centres mentioned above, the implementation of AM systems and AM research.
- Human: Several training opportunities and courses were available to companies and academia to teach them AM-related skills. For example, short courses were hosted by the CSIR at the National CAD/CAM Training Centre. Furthermore, the DSI launched the Technology Stations Programme to demonstrate knowledge and technology diffusion from universities to SMMEs.
- Political: The South African Government was convinced of the importance of AM to South Africa's manufacturing competitiveness as they included AM in their National Research and Technology Foresight Project, the National Research and Development Strategy, the National Integrated Manufacturing Strategy, and the National Advanced Manufacturing Technology Strategy for South Africa.
- Social capital: An AM network of academic, knowledge institute and industry actors were established from the TCTC. Furthermore, RAPDASA, a non-profit organisation, was established to represent the South African AM and wider rapid product development community.

Finally, the Development stage's CIMO interventions, mechanisms, and outcomes are summarised in Table 8.4. This table is valuable for future decision-making as it provides insight into which activities (IS functions) were performed, by whom they were performed, the sequence in which they were performed, and the obtained outcome. Therefore, desired outcomes can be recreated with more ease in future endeavours as the mechanism and involved actors are known, while undesired mechanisms and outcomes may be mitigated.

Table 8.4: The CIMO interventions, mechanisms and outcomes of the Development stage, along with the participating actors

<table>
<tr><th colspan="7">Intervention</th><th rowspan="3">Mechanism (Motor of innovation)</th><th rowspan="3">Outcome: Objectives achieved</th></tr>
<tr><th rowspan="2">IS functions</th><th colspan="6">Actors involved</th></tr>
<tr><th>Knowledge Institutes</th><th>Companies</th><th>RAPDASA</th><th>Academia</th><th>Government</th><th>External Market</th></tr>
<tr><td>[F1] Entrepreneurial Activity</td><td>AM implementers</td><td></td><td></td><td>AM implementers</td><td></td><td></td><td rowspan="7">Technology Push motor

F1 -> F2 -> F4 -> F7 -> F3 -> F6 -> F1</td><td rowspan="7"><u>Primary objectives achieved</u>

• 200 AM systems were implemented in South Africa
• At least twelve AM-focused Centres and programmes were established

<u>Capital outcomes achieved</u>

• Business:
At least eight AM-focused Centres were established.

• Financial capital
Millions of Rands were allocated to AM systems, centres, programmes and research.

• Human capital
Through the centres and programmes, AM-related skills were taught.

• Political capital
AM technology was included in three national strategies.

• Social capital
An AM network and an AM organisation were established.</td></tr>
<tr><td>[F2] Knowledge Development</td><td>Researchers</td><td></td><td></td><td>Researchers</td><td></td><td></td></tr>
<tr><td>[F3] Knowledge Diffusion</td><td>Collaboration catalysts</td><td>Collaborator</td><td>Collaboration catalysts</td><td></td><td>Collaboration catalysts</td><td></td></tr>
<tr><td>[F4] Guidance of Search</td><td>Collaboration catalysts</td><td></td><td>Collaboration catalysts</td><td></td><td></td><td></td></tr>
<tr><td>[F5] Market Formation</td><td></td><td></td><td></td><td></td><td>Advocate</td><td>Advocate</td></tr>
<tr><td>[F6] Resource Mobilisation</td><td>Funder</td><td></td><td></td><td></td><td>Funder</td><td></td></tr>
<tr><td>[F7] Creation of Legitimacy</td><td>Advocate</td><td></td><td></td><td></td><td>Advocate</td><td>Advocate</td></tr>
</table>

8.4.2. CIMO analysis of the Growth stage

Before the Growth stage can be subjected to the interaction patterns and trend analysis, the context of the stage is summarised in Table 8.6 to shed light on the circumstances that formed the initial setting for the Growth stage, given the advanced made in the Development stage.

Table 8.5: Defining the context of Case I

Defining the system boundary	The South African AM industry from 2011-2020.	
Defining the phase of development	the technology has already been introduced into the country. Now, the accelerated growth period of the industry is studied.	
Defining the system objective	Primary objectives: • Increase the number of AM systems implemented in the system. • Stimulate industry's adoption of AM technology. Capital objectives: • Financial capital: To fund AM-focused research studies and centres. • Human: Teach South Africans AM-related skills, such as designing on CAD. • Political: To develop a national plan to guide the industry's development. • Social capital: Maintain and grow established AM networks.	
Identifying the IS structures	Actors: • Knowledge institutes, academic research groups, governmental funding departments, companies, members of society and the RAPDASA organisation	
	Networks: • Several collaborations exist between knowledge institutes, academic research organisations, and governmental funding departments. The RAPDASA conference also connected industry partners with researchers.	
	Institutions: • Several national strategies relevant to manufacturing and AM industries encouraged AM research and allocated research funding to AM projects and programmes.	
	Infrastructure: • Financial support provided by the governmental departments for research and technology acquisition • 200 AM systems have been implemented, and resources sharing programmes that enabled research groups to borrow AM-related equipment and systems have been established. • AM-related skills have been taught.	

8.4.2.1 Interventions and mechanisms

In the Growth stage, the fulfilment of the IS functions was similar to the Development stage. The *Knowledge Diffusion* **[F3/KDif]**, *Entrepreneurial Activity* **[F1/EA]**, *Guidance of Search* **[F4/GoS]**, *Creation of Legitimacy* **[F7/CoL]**, *Knowledge Development* **[F2/KDev]** and *Resource Mobilisation* **[F6/RM]** functions were developed the most. In this stage, positive research outcomes **[F2/KDev, F4/GoS, F7/CoL]** from studies conducted by various groups continued to lead to more research collaborations **[F3/KDif]**, such as the CPAM programme, more funding opportunities **[F6/RM]** and the implementation of more AM system **[F1/EA]**.

The Growth stage differs from the Development stage as *Knowledge Development* **[F2/KDev]**, *Knowledge Diffusion* **[F3/KDif],** *Guidance of Search* **[F4/GoS]**, and *Creation of Legitimacy* **[F7/CoL]** were the dominating functions. The dominance of these three functions is indicated in Figure 8.13.

This stage was initiated when RAPDASA identified the need for a South African AM roadmap **[F4/GoS]**. In response to the request, the DSI authorised **[F4/GoS]** a core team of AM experts **[F3/KDif]** to develop the Roadmap. The team did extensive research **[F2/KDev]** and developed a roadmap that identified market,

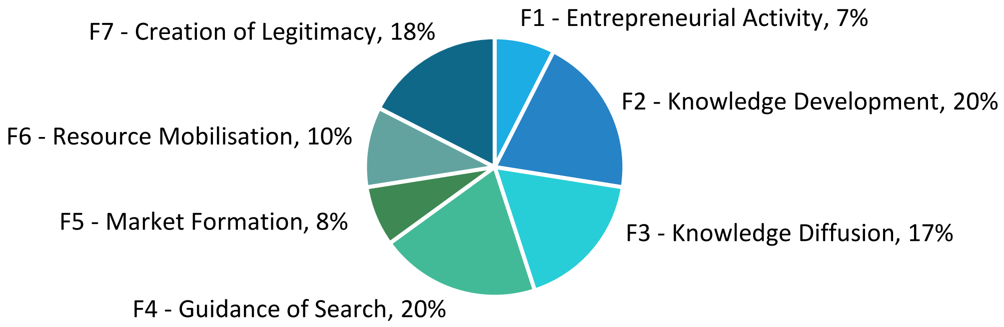


Figure 8.13: Functional fulfilment percentages of the Growth stage

research and technology development opportunities and guided development programmes and investment decisions **[F4/GoS]**. Prioritised focus areas were also presented **[F4/GoS]**. The CPAM programme stimulated further research collaboration **[F2/KDev, F3/KDif]**. It was then decided that the developed Roadmap should be refined into a national AM strategy **[F4/GoS, F7/CoL]**. Once again, the DSI authorised AM experts **[F3/KDif]** to refine **[F2/KDev]** the Roadmap into a national strategy and the Additive Manufacturing Strategy for South Africa was released soon after **[F4/GoS]**. The strategy once again identified prioritised focus areas and defined programmes to guide South African investment in AM technologies **[F4/GoS]**. Additionally, throughout the Growth Stage, the number of AM systems in the country continued to increase rapidly as less expensive systems became available, and industry and public ownership of personal 3D printers had far outgrown the academic ownership of high-end systems **[F1/EA, F7/CoL]**.

Thus, it is postulated that the Technology Push motor continued during the Growth stage as the sequence of functions continued. However, an additional pattern and virtuous causation cycle developed as guidance from AM experts [F4/GoS] and advocacy from governmental actors [F7/CoL] led to collaborative projects [F3/KDif] and research [F2/KDev] for the identified focus areas. Given the central role of Knowledge Development, Knowledge Diffusion, Guidance of Search and Creation of Legitimacy, the cycle could be considered a `guidance' loop. Furthermore, as the `guidance' loop led to the development and implementation of the South African Additive Manufacturing Roadmap and Strategy, the cycle could be considered an additional loop to be incorporated into the Technology Push motor (Figure 8.14). A reflection of the Growth stage's structural components and their drivers, barriers and impacts are presented in Table 8.6.

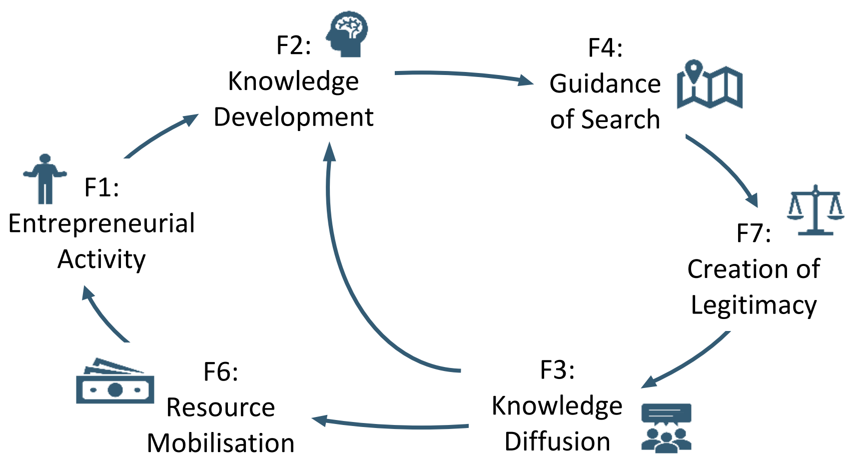


Figure 8.14: Technology Push motor with additional 'guidance' loop

Table 8.6: The structural components and their drivers, barriers and impacts on the Growth stage

	Actors	Interactions	Institutions	Infrastructure
Drivers	• The CSIR, CRPM and South African universities conducting AM research are enactors. • RAPDASA connecting academics and industry partners through the international conference is an enactor. • Aerosud Innovation Centre is an enactor. • Government departments, such as the DSI and DTI, are the primary selectors.	• The CPAM programme connected research and industry actors. • Wide range of application areas identified for research opportunities aided in awareness creation. • Government programmes connecting academic and governmental research organisations.	• Global trust in AM's abilities grew, and a movement to implement AM was established. • The South African AM Technology Roadmap and strategy confirmed governmental trust in AM technology. • National initiatives such as the National Laser Centre confirmed governmental trust in AM technology.	• South African government departments, particularly the DSI and NRF, provided funding.
Barriers	• There was still a limited number of companies in industry acting as service bureaus.	• A wide range of AM research application areas made collaboration projects challenging.	• The South African AM strategy only identified a handful of national application focus areas.	• The initial wide range of AM research application areas made • The Rand's weak exchange rate against the Dollar and Euro made AM systems less affordable for research and small businesses.
Impacts	• Guidance is given regarding AM research focus areas. • Prove that AM technology can deliver certified products and that it was worth implementing.	• Research collaborations between researchers and industry actors are stimulated. • Increased awareness of AM technology.	• Government legitimise AM technology and encourage further AM research and system implementations. • Guidance is given regarding the focus areas of AM research.	• The acquisition and implementation of AM systems were possible. • More research programmes are possible.

According to the South African AM field experts interviewed, the increased awareness of AM technology and the increasing research conducted on various AM application areas prompted academic researchers to emphasise the need for a technology roadmap to guide AM research and governmental resources at the RAPDASA conference. Therefore, these AM experts deemed the trigger between the *Technology Push motor* and the *Technology Push motor with the additional 'guidance' loop* as the increased awareness of the technology and broad range of research conducted Figure 8.15.

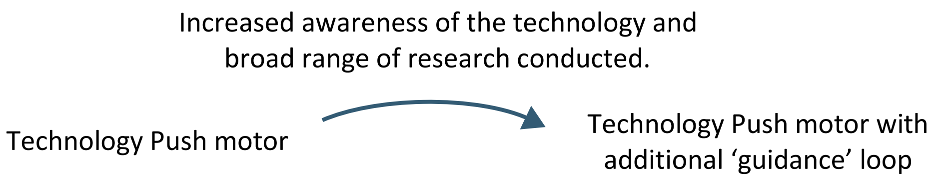


Figure 8.15: Link between the *Technology Push motor* and the new Technology Push motor

To determine the functional contribution of each of the new *Technology Push motor*'s actors and the functions *performed, given* and *received* by each actor, Figure 8.16, Figure 8.18and Figure 8.18 were developed. Figure 8.16 indicates that, in contrast with the Development stage's performed-give-and-received graph (Figure 8.10), the ratio between the functions *performed* by single actors and those shared (*given* and *received*) is severely reduced. Figure 8.16 thus indicates more interaction between actors in the *Growth stage.*

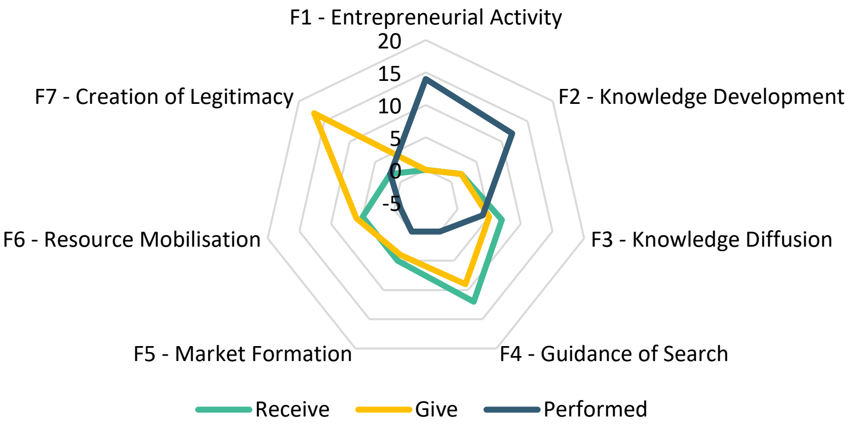


Figure 8.16: Performed-Give-and-Receive functional interaction map of the new Technology Push motor

According to the AM field experts interviewed, a primary goal of the South African government and the handful of researchers who first encouraged the implementation of AM in South Africa was to stimulate industry's adoption of AM technology. Therefore, during the Growth stage, emphasis was placed on industry support, particularly in the AM national strategy. This is illustrated in Figure 8.18 and Figure 8.18 through the *company* actors contributing to functions **[F4/GoS, F5/MF]**. Figure 8.18 indicated guidance and market opportunities industry *received* through the South African AM roadmap and national AM strategy, which aimed to enable South African companies to become global industry leaders by guiding the identification of market, research and technology development opportunities and investment decisions. Furthermore, throughout the Growth stage, the increasing awareness of AM technology and the number of AM systems implemented, particularly by non-academic actors, is continuously indicated. Figure 8.18 and Figure 8.18 indicate this by the *companies'* significant contributions to the **[F1/EA, F7/CoL]** functions. A new commercial project, Aeroswift, was also launched.

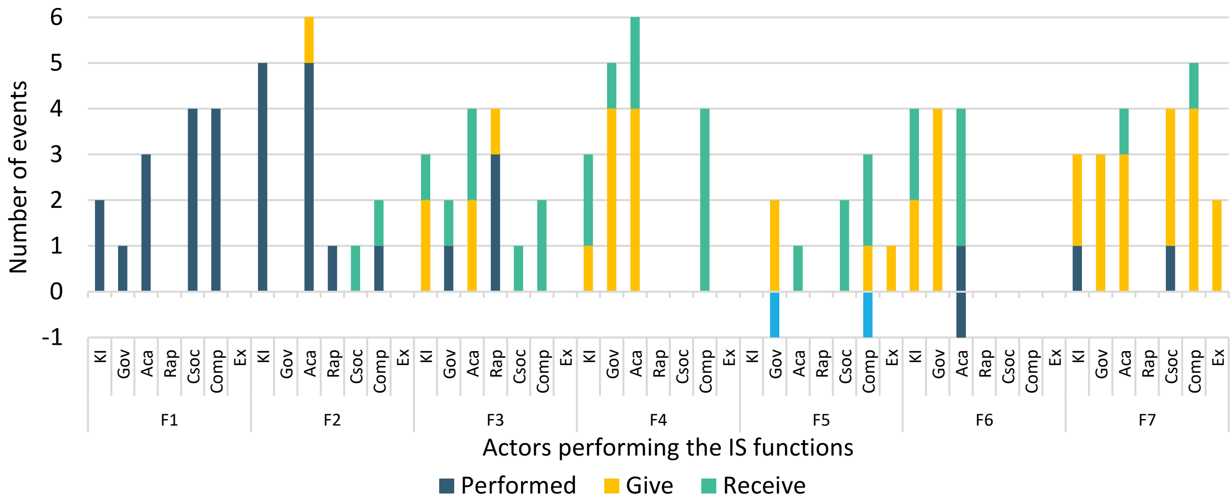


Figure 8.18: The functional Performed- Give-and-Receive map of the new Technology Push motor's actors

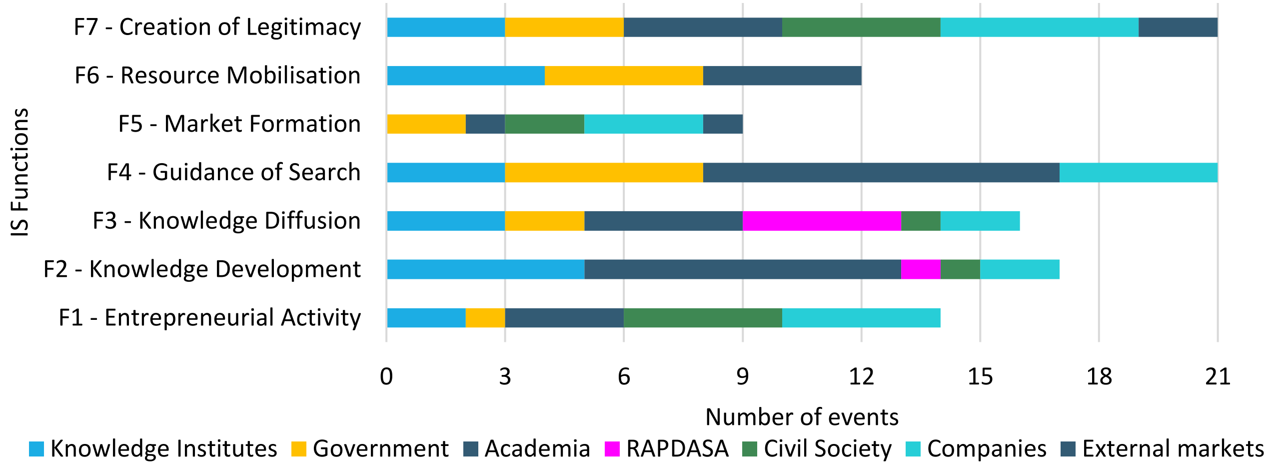


Figure 8.18: The number of events associated with the Technology Push motor's functions and the actors who performed them

Figure 8.18 and Figure 8.18 indicate that the *knowledge institutes* were once again primary actors of the *Technology Push motor*. They once again advocated for the technology's adoption in South Africa **[F7/CoL]** and launched programmes with commercial aims (the Aeroswift and CPAM projects) **[F1/EA]**. They also supported **[F6/RM]** and collaborated **[F3/KDif]** on these projects to conduct AM research and develop the Aeroswift system, the largest AM system in the world **[F2/KDev]**. Finally, similar to the companies, academia and society, they also received guidance from the AM roadmap and national AM strategy **[F4/GoS]**. RAPDASA once again contributed to the knowledge diffusion **[F3/KDif]** as they continued to host their annual conference to bring together South African researchers and industry partners. It was at these conferences that the AM roadmap was requested and presented.

Figure 8.18 and Figure 8.18 indicate that *civil society* contributed to the **[F1/EA, F5/MF, F7/CoL]** functions during the Growth stage. This indicates their growing awareness and advocacy towards AM technology as they also implemented personal 3D printers on a large scale.

Figure 8.18 indicates that the external market contributed to functions **[F5/MF, F7/CoL]**. In the Growth stage, the external market advocated **[F7/CoL]** for AM technology as globally, an AM movement was starting as the technology was well known. Furthermore, they contributed to favourable market conditions as lower-cost AM systems became available, particularly personal 3D printers (< $5000), enabling more companies and individuals to implement the technology.

Similar to the Development stage, the *Governmental actors* are the Technology Push motor's selectors as they primarily contribute to functions [F3/KDif, F4/GoS, F5/MF, F6/RM **F7CoL]**. Through the South African Roadmap and the national AM strategy, the governmental actors again contributed guidance and legitimacy to the South African AM industry **[F4/KDev, F7CoL]**. Through these strategies, they shared their advocacy for AM and communicated their suggested research focus areas. Additionally, they provided (*gave)* market opportunities **[F5/MF]** to companies to stimulate industry's adoption of AM. However, they also contributed to unfavourable market regulations as South Africa's weak exchange rate also made AM system imports difficult. Finally, the governmental actors again contributed to function **[F6/RM]** by allocating at least R385 million to AM systems and AM research projects and programmes. It thus enabled multiple AM research studies to be conducted and the Aeroswift system, the largest AM system in the world, to be developed.

Academia was a primary contributor in the Growth stage and contributed to all seven IS functions. They implemented AM systems **[F1/EA]**, collaborated on research projects **[F3/KDif]** and received research funding from governmental departments **[F6/RM]**. However, their primary contribution was to functions [F2/KDev, F4/GoS].

Due to the increasing number of AM research studies conducted **[F2/KDev]** due to the Technology Push motor, research on various application areas was delivered. However, the wide variety of research studies made collaborations between research groups difficult due to the different application areas. Therefore, the researchers asked for an AM technology roadmap to guide AM research and development **[F4/GoS]**. Upon request of the DSI **[F4/GoS]**, a group of researchers then developed the AM roadmap that later became the South African AM Strategy **[F2/KDev, F4/GoS]**. Once these strategies were presented, the researchers conducted in-depth research for the specified areas **[F2/KDev, F4/GoS]**. For example, as the medical industry was identified as a focus area, in-depth research was conducted to manufacture medical implants using AM technology. These studies led to the CRPM receiving ISO 13485 certification to design and manufacture titanium 3D printed patient-specific implants.

As most of these studies were supported through governmental initiatives, governmental resources were applied to various AM application areas. Therefore, these researchers who investigated the economic impacts of the AM application areas and identified the areas that would keep South Africa a competitor in the global AM market acted as *technology mentors*. These AM *technology mentors* then directed governmental resources to specific application areas to guide South African AM research in those fields.

According to the field experts interviewed, *technology mentors* are essential to an industry's development. The field experts highlighted the importance of guiding research and essentially guiding governmental resources. A metaphor of a *watering can and a garden* can describe the importance of guided resources. When a watering can is used to water a garden, the amount of water each plant receive is limited. Therefore, knowledge regarding each plant's water requirements is necessary. Similarly, knowledge regarding the commercial validity and economic impact of the various AM application fields is required to prioritise governmental resources for those with the highest commercial validity and economic impact. As the governmental resources are then mainly applied to specified priority application areas, research in those fields is stimulated. As a result, the inventions have a higher chance of being developed and commercialised, leading to economic growth and global competitiveness the government intended for the research funding.

8.4.2.2 Outcomes

Given the sequence in which the knowledge institutes, companies, RAPDASA, academia, members of civil society, governmental departments and the external international market performed the functional interventions, they continued the *Technology Push motor* mechanism and added a 'guidance' loop. In the Growth stage, the *Technology Push motor* with the additional `guidance' loop led to a significant increase in the number of AM systems implemented– from 200 to more than 6000 systems. Furthermore, as the Technology Push motor and the additional `guidance' loop promoted awareness of the technology, industry's adoption of the technology also increased when lower-cost systems became available.

Furthermore, the following capitals were developed:

- Financial capital: The South African governmental departments again allocated at least R385 million to AM systems and AM research projects and programmes, which enabled multiple AM research studies and the Aeroswift system, the largest AM system in the world, to be developed.
- Human: The Idea2Prodcut laboratories were established at VUT and Stellenbosch University. The laboratories offered CAD and 3D printing training and consultation opportunities to academic and societal actors to teach them AM-related skills.
- Political: The South African Government released the national AM strategy and indicated the aerospace and military, medical and dental, tooling, casting, and automotive industries as the priorities for 2014 to 2023.
- Social capital: The AM network of academic, knowledge institute and industry actors continued, and a collaborative research programme (CPAM) developed from it. Furthermore, RAPDASA continued to represent the South African AM and wider rapid product development community. They continued their annual conference and gained more industry participation. More than 300 delegates attended the 2019 conference.

Finally, the Growth stage's CIMO interventions, mechanisms, and outcomes are summarised in Table 8.7. This table is valuable for future decision-making as it provides insight into which activities (IS functions) were performed, by whom they were performed, the sequence in which they were performed, and the obtained outcome. Therefore, desired outcomes can be recreated with more ease in future endeavours as the mechanism and involved actors are known, while undesired mechanisms and outcomes may be mitigated.

Table 8.7: The CIMO interventions, mechanisms and outcomes of the Development motor along with the involved actors

<table>
<tr><th colspan="8">Intervention</th><th rowspan="3">Mechanism (Motor of innovation)</th><th rowspan="3">Outcome: Objectives achieved</th></tr>
<tr><th rowspan="2">IS functions</th><th colspan="7">Actors involved</th></tr>
<tr><th>Knowledge Institutes</th><th>Companies</th><th>RAPDASA</th><th>Academia</th><th>Government</th><th>External Market</th><th>Society</th></tr>
<tr><td>[F1] Entrepreneurial Activity</td><td>AM implementers</td><td>Technology adopters</td><td></td><td>AM implementers</td><td></td><td></td><td>Technology adopters</td><td rowspan="7">Technology Push motor

F1 -> F2 -> F4 -> F7 -> F3 -> F6 -> F1</td><td rowspan="7"><u>Primary objectives achieved</u>
• More than 6000 AM systems were implemented in South Africa.
• Industry's adoption of the technology increased

<u>Capital outcomes achieved</u>
• Financial capital
Millions of Rands were allocated to AM systems, centres, programmes, and research.
• Human capital
Through the centres and programmes, AM-related skills were taught, and consultations were offered to product developers.
• Political capital
A national AM strategy was released.
• Social capital
The AM network and RAPDASA continued to grow.</td></tr>
<tr><td>[F2] Knowledge Development</td><td>Researchers</td><td></td><td></td><td>Researchers, Technology mentors</td><td></td><td></td><td></td></tr>
<tr><td>[F3] Knowledge Diffusion</td><td>Collaboration catalysts</td><td>Collaborator</td><td>Collaboration catalysts</td><td></td><td>Collaboration catalysts</td><td></td><td></td></tr>
<tr><td>[F4] Guidance of Search</td><td>Collaboration catalysts</td><td></td><td>Collaboration catalysts</td><td>Technology mentors</td><td></td><td></td><td></td></tr>
<tr><td>[F5] Market Formation</td><td></td><td></td><td></td><td></td><td>Advocate</td><td>Advocate</td><td></td></tr>
<tr><td>[F6] Resource Mobilisation</td><td>Funder</td><td></td><td></td><td></td><td>Funder</td><td></td><td></td></tr>
<tr><td>[F7] Creation of Legitimacy</td><td>Advocate</td><td></td><td>Advocate</td><td>Advocate</td><td>Advocate</td><td>Advocate</td><td>Advocate</td></tr>
</table>

8.5. Chapter 8 summary

This chapter presented the first case in a series of four case studies. An industry perspective was used to study a case where new technology was introduced into a country. The CIMO-based EHA framework was used to analyse the case of the South African additive manufacturing industry from 1991 to 2020. The AM industry was studied as AM is the focus technology of this study. This case expands the current literature on the South African AM industry by compiling the industry events over the past 31 years. Through the application of the CIMO-based EHA framework, the underlying dynamics and mechanisms that supported and hindered the industry's growth were explored. Additionally, it identified the industry's innovation actors and how they influenced each other. The paper derived from this chapter is also among the first to analyse the development of the South African AM industry and the first to analyse the industry through the innovation system framework. This chapter contributes to objectives IV and V, as mentioned in §1.4.

Chapter 9

Case II: The Additive Manufacturing of Machining Tools out of WC-Co

The previous chapter studied the development of the South African additive manufacturing industry NIS to gain insight into the dynamics involved in introducing a manufacturing technology into a country. This chapter studies the dynamics of a research and development (R&D) project titled `*Additive Manufacturing of Machining Tools out of WC-Co – AM of WC-Co'* (AM of WC-Co). The event history analysis method is used to analyse the case of an R&D project from 2019 to 2021. This project was selected as it is a government-supported academic-industry research collaboration project. It will thus shed light on the industry dynamics studied in the previous chapter from a research collaboration perspective. The actors involved in this case are the Fraunhofer Institute for Laser Technology ILT, the Institute for Materials Applications in Mechanical Engineering IWM, the Laboratory for Machine Tools and Production Engineering WZL, both at RWTH Aachen University, and the German Federation of Industrial Cooperative Research Associations "Otto von Guericke" (AiF). This case study's position in the framework is indicated in Figure 9.1 in dark blue, while the previous case study is shown in light blue. This chapter contributes to objectives IV and V, as mentioned in §1.4.

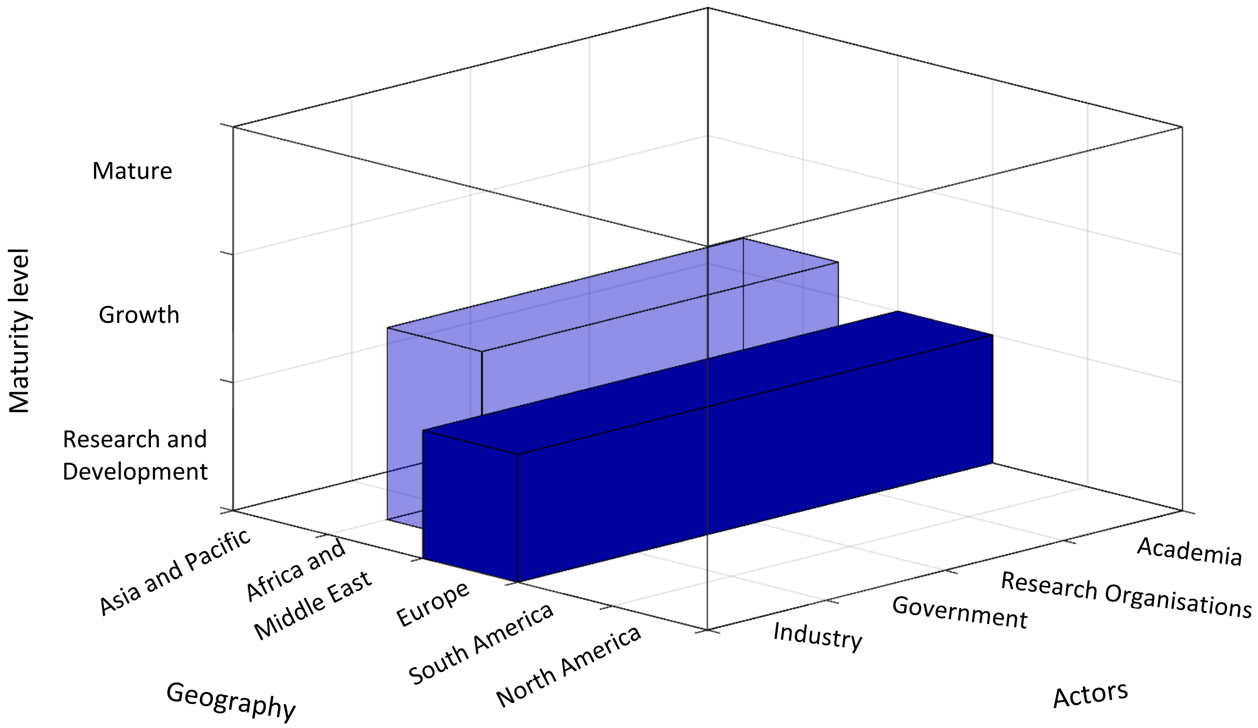


Figure 9.1: Second case in case study framework

The chapter starts with an introduction to the case approach and the research groups. Thereafter the case study is presented as a narrative. Thereafter follows the application of the CIMO-based EHA framework's four steps of the CIMO. First, the *context* of the case is introduced. Thereafter, the narrated is analysed to identify the *interventions and mechanisms* present in the case. The chapter then concludes with the identification of the case *outcomes and outputs* delivered by these *mechanisms.*

Chapter 9 contribution:

- Through the application of the CIMO-based EHA framework, the chapter contributes an analysis of the underlying dynamics and mechanisms that supported and hindered an academic-industry collaboration research project.

Chapter 9 objectives:

- Define the research design of the case study (§9.1).
- Provide background of the AM of WC-Co project (§9.2).
- Narrate the AM of WC-Co project case (§9.3).
- Identify the context and motors of innovation that led to development (§9.4.1).
- Identify the underlying structural drivers and barriers of the motors of innovation (§9.4.1).
- Identify the influence these IS structures and motors of innovation have on the outcomes and outputs of the case (§9.4.2).

9.1. Case approach

As the focus of this case is an academic R&D project on the additive manufacturing of WC-Co machining tools, the unit of analysis for the case is a technology. Therefore, a research-level technology innovation system (TIS) perspective is applied in this case.

Similar to the previous case, the empirical work for this case relied on the construction of a narrative. As the project is manufacturing and metallurgically focused, limited information and literature regarding the `innovation story' of the project were available. The only available published information relevant to this study was a press release released by Fraunhofer ILT to announce the commencement of the project [391], [392] and a short description of the project on RWTH Aachen University's website [393]. Therefore, to gain the necessary information to formulate the case and narrative, three semi-structured interviews were conducted with the researchers involved in the project. The researchers told and verified the project narrative, detailed the drivers and barriers experienced throughout the project along with their impacts, and validated the final analysis conducted on the narrative. Rabionet's [353] six-step interview process for researchers, §7.4, was used to guide the semi-structured interviews. Cresswell's [50] qualitative data analysis process, as discussed in §7.5, was used to collect the event data in a database.

9.2. Introduction to the case

Section 4.2 mentioned that for inventions discovered in research studies to be implemented in the market, the inventions must pass through the development Valley of Death (VoD) and be commercialised. The section mentioned that traditional VoD authors ascribed the difficulty of bridging the Valley of Death to a shortage of governmental financial support within the valley. They argued that applications for governmental support of early-stage research studies are evaluated based on scientific merit, and economic impact is only superficially considered. As a result, overinvestment in fundamental research leads to inflated scientific output, which does not necessarily correlate with industry needs and resources. More recently, VoD authors have argued that, in addition to the shortage of financial support, uncertainty related to investment in untested, unproven, or unknown technologies also hinders development through the valley [19], [20], [163], [175]. Therefore, to bridge the valley of insufficient funding and uncertainty relating to new manufacturing technologies, the VoD authors have encouraged research collaborations between academia, industry, and government to ensure industry-focused research studies, effective funding distribution and knowledge transfer [18]–[20], [163], [174], [175] (§4.2).

The previous case narrated the South African government's efforts to stimulate additive manufacturing (AM) adoption and development within the South African manufacturing industry. The narrative highlighted the CSIR's and the DST's efforts to stimulate fundamental AM research and its adoption in industry through research collaborations with academia's virtual network of actors. Associations such as RAPDASA and funding programmes such as THIRP (industry-government cost-sharing programme) were also established to connect academic and industry partners.

The research project studied in this case is an example of a government-supported industry-focused research study conducted by a university and research organisation in collaboration with industry partners. The case demonstrates the German government's efforts to stimulate collaboration between a research organisation (Fraunhofer ILT), academic research groups (from Aachen University) and industry through research funding. The German Federation of Industrial Research Associations' "Otto von Guericke e.V." (AiF) working group awarded the governmental research funding for this project. The group's focus is to encourage applied research and development (R&D) for the benefit of SMEs [394]. Therefore, the group encourages research groups to submit research proposals, and upon the submission of the proposals, the committee investigates the potential benefit the projects could offer SMEs. If a potential benefit is identified, government funding is obtained and awarded to the projects with the precondition that industry partners be included in the project. The experienced industry partners are encouraged to share their technical knowledge and experience with the researchers throughout the project. Similarly, the researchers are encouraged to share their results, progress, and observations. Upon the project's conclusion, the project outputs and the knowledge obtained throughout the project are compiled in a project document by the project researchers and handed over to the project's industry partners. In this way, the Otto von Guericke e.V. group enables research groups to perform fundamental research studies, the participating SMEs' competitiveness increases and the technologies and products developed are diffused into industry [394].

The following sections will look at the dynamics of the AM of WC-Co project from 2018 to 2021. By analysing the project's innovation activities and activity sequences through the innovation system (IS) framework and the CIMO-based EHA framework, motors of innovation and underlying structural drivers and barriers may be identified to answer §1.3's case study research questions.

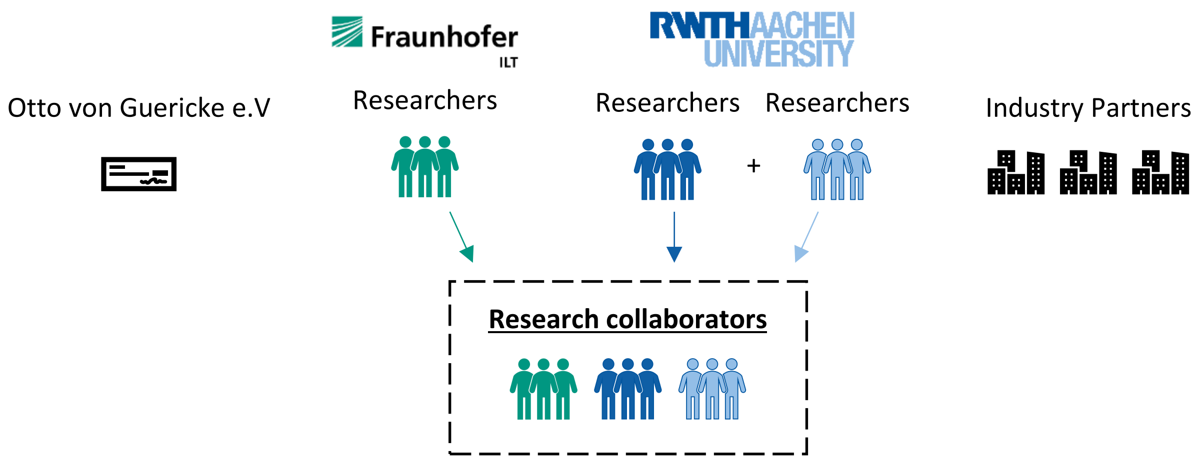


Figure 9.2: Case II participating actors

9.3. Event history analysis

In this section, the AM of WC-Co project is given as a chronological narrative. The IS functions corresponding to the events are denoted by **[F1/EA, F2/KDev, … F7/CoL]** along with a `-1 or 1' to indicate their influence. Furthermore, events related to the research collaborators (Figure 9.2), the Fraunhofer researchers, Aachen

University researchers, regulator bodies, the German Federation of Industrial Cooperative Research Associations "Otto von Guericke" and the industry partners are indicated as **[RC]**, **[FH]**, **[Aach]**, **[Reg]**, **[OvG]**, and **[Ind]**, respectively. *Finally, at the end of the narrative, Figure 9.3 summarises the case's main events. Readers may therefore skip the narrative to Figure 9.3.*

In January 2018, additive manufacturing (AM) researchers from Fraunhofer ILT were exploring new research opportunities, particularly for AM-related industry needs and opportunities **[FH (P) F2/KDev]**. It was a common culture in Germany that government research funding was mainly awarded to research projects with industry-driven topics and that industry participation was a prerequisite to research funding **[OvG (P) F4/GoS]**.

In April 2018, in response to the research studies on AM as a manufacturing technology for hardmetal products that were conducted globally, researchers from Fraunhofer ILT identified an opportunity to manufacture hardmetal cutting tools with a low (< 10%) cobalt proportions with AM technology **[FH (P) F2/KDev]**.

The Fraunhofer ILT researchers were knowledgeable about the additive manufacturing of metals. Moreover, they knew that the two research groups from RWTH Aachen University were knowledgeable of microstructure and mechanical properties of carbides and post-processing techniques. Therefore, the Fraunhofer ILT researchers invited the Aachen researchers to collaborate with them on feasibility studies to test the potential of their solution **[FH (G), Aach (R) F3/KDif, F4/GoS]**.

In June 2018, the researchers from Fraunhofer ILT and Aachen combined resources and conducted feasibility studies to test their solution **[FH, Aach (P) F2/KDev, (G) F3/KDif, F6/RM]**. As the studies proved their solution feasible **[FH (P), Aach (P) F2/KDev]**, the researchers decided to launch an official collaboration **[FH (G), Aach (G) F3/KDif]** to conduct an official research project to develop their solution **[RC (P) F1/EA]**. Furthermore, as the research would be beneficial and implementable in industry, the researchers decided to apply for Otto von Guericke e.V funding **[GoV (G), RC (R) F5/MF]**.

As industry involvement was a prerequisite to obtaining research funding **[GoV (G), RC (R) F4/GoS]**, the researchers invited numerous manufacturing companies throughout Germany and Europe to collaborate on the AM of WC-Co project **[RC (G), Ind (R) F4/GoS]**. As the companies did not have to invest in the project financially but were receiving valuable insight into the development of implementable research, eighteen SMEs experienced in either AM technology or hardmetal properties had agreed to participate in the project by February 2019 **[RC (G), Ind (R) F3/KDif, Ind (G), RC (R) F7/CoL]**. Sixteen were SMEs from Germany, and two were from Switzerland and Austria.

In March 2019, the researchers submitted their project proposal to the Otto von Guericke e.V group **[RC (G), OvG (R) F4/GoS]**. The project involved twenty researchers with two PhD studies and was projected to last thirty months, commencing in October 2019. As the project proved to be potentially beneficial to industry and already had industry participation, the project was awarded approximately €700,000 for thirty months **[OvG (G), RC (R) F6/RM, F7/CoL]**.

In June 2019, Cobalt was classified as a hazardous, carcinogenic, mutagenic, and toxic substance in Switzerland **[Reg (P) F5/MF]**. Furthermore, the regulations stated that all persons working with cobalt power should wear impervious protective suits with protective gloves and face masks **[Reg (P) F5/MF]**. As it was commonly known that regulations set out by the Swiss Safety Commission regarding hazardous materials are generally also implemented by the European Union, the Swiss SME informed the researchers of the new regulations shortly after the release **[Ind (G), RC (R) F4/GoS]**. As these regulations influenced the tasks of the Fraunhofer researchers, the researchers ordered the impervious protective gear they required **[RC (P) F6/RM]**.

In September, the researcher groups and industry partners came together for a kick-off meeting **[RC (G), Ind (R) F3/KDif]**. The researchers shared their objectives as well as the initial barriers they would experience **[RC (G), Ind (R) F4/GoS]**. The industry partners collaborated to find solutions and shared their visions and the resources they could offer the researcher if required **[Ind (P) F3/KDif, RC (R), Ind (G) F4/GoS]**.

On October 1, 2019, the AM of WC-Co research project officially launched **[RC (P) F1/EA]**. The research groups began their respective studies on the process technology for the laser-based AM, the microstructure and mechanical properties of the additively manufactured carbides and post-processing concepts for additively manufactured cutting tools **[RC (P) F2/KDev]**. The project funding was distributed evenly among the three research groups, and monthly group progress meetings were scheduled **[RC (P) F3/KDif]**.

In November, the Fraunhofer ILT researchers presented the project at the Formnext 2019 international conference, where two more industry partners agreed to join their collaboration **[RC (G), Ind (R) F3/KDif, F4/GoS]** [391].

In February 2020, the Cobalt Institute and the European Chemical Agency announced that the European Union approved the harmonised classification and labelling of Cobalt as a hazardous, carcinogenic, mutagenic, and toxic substance **[Reg (P) F5/MR]** [395], [396]. In addition to the Swiss regulations, the European Union's regulations required all workspaces and machines where cobalt powder is handled to be encapsulated **[Reg (P) F5/MR]**.

These regulations brought the laboratory and testing aspects of the project to a temporary pause as the workstations firstly had to be encapsulated **[RC (P) -F2/KDev]**. As this unforeseen expense was not part of the project budget, each research group had to pay for their encapsulations and impervious protective gear from their own funds **[RC (P) -F6/RM, F6/RM]**.

In April 2020, Germany announced a nationwide lockdown in response to the COVID-19 pandemic **[Reg F5/MR]**. This forced the researchers to work from home, continuing with all facets of their research that did not include laboratory testing and manufacturing **[RC (P) -F2/KDev]**.

The COVID-19 pandemic required all medical personnel globally to wear impervious protective gear. Furthermore, as hospitals and clinics quickly reached maximum capacity, encapsulated work and testing areas were set up to accommodate the infected patients. Due to the global demand for impervious protective gear and encapsulations to address the pandemic, preference was given to parties supporting the fight against the COVID-19 pandemic **[Reg (P) F5/MF]**.

Therefore, by October 2020, the researchers had not yet received their impervious protective gear, and their encapsulations had not yet been manufactured **[RC (P) -F6/RM]**. This meant that although the lockdown regulations permitted their laboratory work to continue, the cobalt regulations did not **[-F2/KDev, F5/MR]**. As seven months had passed since the cobalt regulations were released and the pandemic lockdown commenced, the researchers realised that their studies would not be completed within the time they had left. Furthermore, the tests and studies the Aachen researchers conducted depended on the samples the Fraunhofer researchers had to manufacture. Therefore, the research groups applied for a twelve-month project extension from the Otto von Guericke group **[RC (G), OvG (R) F4/GoS]**. The extension was granted from March 2022 to March 2023 without the provision of additional funding **[RC (R), OvG (G) F4/GoS]**.

Finally, in December 2020, the researchers received their impervious protective gear **[RC (P) F6/RM]**. The installations of the encapsulations of their workspace and machines commenced in January 2021 **[RC (P) F6/RM]**. In February 2021, when the researchers' workspaces and machines were encapsulated, and the German lockdown regulations once again enabled the researchers to continue their laboratory work **[Reg (G), RC (R) F5/MF]**, the manufacturing and testing aspects of the project continued **[RC (P) F2/KDev]**.

From March 2021, to enable the Aachen researchers to continue their studies, the research groups had weekly meetings to discuss the progress each group had made **[RC (P) F2/KDev, F3/KDif, F4/GoS]**. Through these meetings, the researchers quickly realised that they required more WC-Co powder which the industry partners then provided them with **[RC (G), Ind (R) F4/GoS, Ind (G), RC (R) F6/RM]**.

By June 2021, the researcher had samples to prove their techniques and methods worked **[RC (P) F2/KDev]**. In addition, they were hoping to have samples close to the quality of conventionally manufactured material to show to their industry partners by the end of the year **[RC (G), Ind (R) F4/GoS]**.

From July 2021 to May 2022, the research collaborators continued with their respective research focus areas and conducted investigative research **[RC (P) F2/KDev]**. During these eleven months, the research collaborators sent regular updates to their industry partners, who in turn provided them with advice or encouragement **[RC (G, R), Ind (R, G) F4/GoS]**. Furthermore, the Fraunhofer researchers found that the breakthroughs made and insights gained in the research collaboration project during these months supported and contributed to their other research projects **[RC (G), FH (R) F2/KDev]**.

By the end of May 2022, the hardmetal parts were ready for field testing **[RC (P) F2/KDev]**. Four industry partners volunteered to conduct the tests for the research collaborators **[Ind (P) F2/KDev]**. During these tests, the research collaborators shared their progress at the 20th Plansee Seminar in Austria per their research funding agreement to make their research available in the public domain **[RC (G), Ind (R) F3/KDif, F4/GoS]** [391].

The key events during the WC-Co project are illustrated in Figure 9.3. The green dots indicate events related to the project launch and project funding. The blue dots indicate external market conditions influencing the project, and the green diamonds indicate other important events.

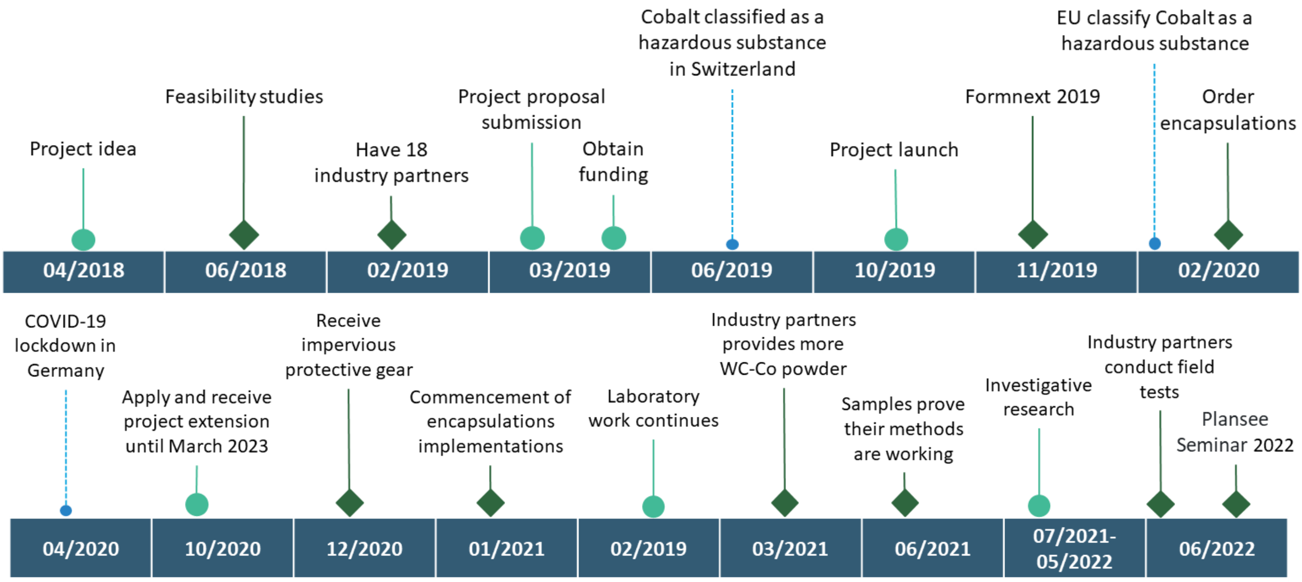


Figure 9.3: Timeline of the AM for WC-Co project

9.4. CIMO-based EHA data analysis

The data analysis phase of the CIMO-based EHA framework may be applied to the narrative events to identify the functional dynamics that led to development within the case. First, the *case context may be defined to shed* light on the circumstances that formed the initial case setting (Table 9.2). The objective of the research collaboration between the researchers from Fraunhofer ILT and Aachen University was to develop a laser-based additive manufacturing technique to manufacture near-net-shape hardmetal cutting tools [257], [259]. To achieve this aim, the researchers applied for research funding from the Otto von Guericke working group (driver). They also invited SMEs from industry to collaborate with them as it was a prerequisite to government funding. In addition, it was common for the Europe Union to implement similar regulatory trends regarding hazardous materials as the Swiss Safety Commission.

Table 9.1: Defining the context of Case II

Context step	Application
Defining the system boundary	The research collaboration project was conducted by researchers Fraunhofer ILT and Aachen University, in Aachen, Germany, from January 2018 to June 2021.
Defining the phase of development	Research and development (R&D) project of a university and research institution.
Defining the system objective	<u>Primary objectives:</u> • The researchers aim to develop a laser-based additive manufacturing technique to manufacture near-net-shape hardmetal cutting tools with less than 10% cobalt percentages, internal contour-adapted cooling channels and achieve performance that is at least equal to that of sintered cutting tools [257], [259]. <u>Capital objectives:</u> • Financial: Obtain research funding for the research project • Intellectual: Develop a laser-based additive manufacturing technique • Produced: Develop near-net-shape hardmetal cutting tools
Identifying the IS structures	<u>Actors:</u> • Researchers: Fraunhofer Institute for Laser Technology ILT and RWTH Aachen University • Funders: The German Federation of Industrial Research Associations' Otto von Guericke e.V. working group
	<u>Networks:</u> • The Fraunhofer ILT researchers were knowledgeable of the research conducted by the research groups from Aachen University (driver). • The researchers from Aachen University were knowledgeable of the research conducted by the Fraunhofer ILT researchers (driver).
	<u>Institutions:</u> • Research collaboration with industry is a prerequisite for movement research funding (driver). • Companies are not required to contribute to research projects but should learn from researchers' research studies (driver). • The Europe Union typically implemented similar regulatory trends regarding hazardous materials as the Swiss Safety Commission.
	<u>Infrastructure:</u> • The research groups all have the necessary equipment to conduct their research (driver). • Financial support from the Otto von Guericke e.V. working group (driver).

To get an overview of the IS functional development of the case and the participating actors, Figure 9.4 and Figure 9.5 were developed. Figure 9.4 indicates that the *Knowledge Diffusion* **[F3/KDif]** function was developed the most during the narrative, closely followed by the *Guidance of Search* **[F4/GoS]** and

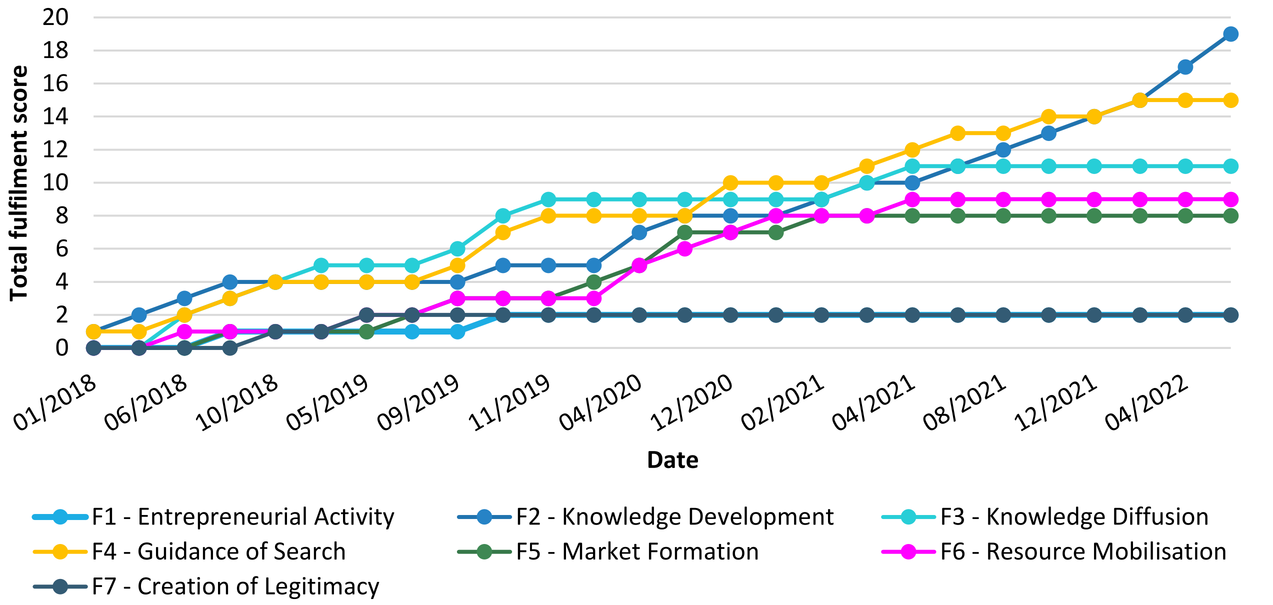


Figure 9.4: The functional development of the *Additive Manufacturing of Machining Tools out of WC-Co* project

Knowledge Development **[F2/KDev]** functions. As expected from a research study, Figure 9.5 indicate that **[F2/KDev]**, typically associated with research studies, was contributed primarily by the research collaborators and the Fraunhofer ILT researchers. Furthermore, in line with the expectations of this case's funding organisation, Figure 9.5 indicate that functions **[F3/KDif, F4/GoS]** were primarily contributed by the research collaborators and the industry companies. These functions are typically associated with activities with joint ventures, alliances between actors, and communicating vision, expectations, and research outcomes. Finally, as expected from regulatory bodies, Figure 9.5 indicate that this case's regulatory bodies were the primary contributors to the market formation **[F5/MF]** function.

Finally, the Entrepreneurial Activities [F1/EA] and Creation of Legitimacy [F7/CoL] functions were the least developed functions of the case. These functions relate to activities such as commercialising products, establishing new firms and lobbying. Therefore, it is expected that these functions are least developed from an early-stage research study such as this case.

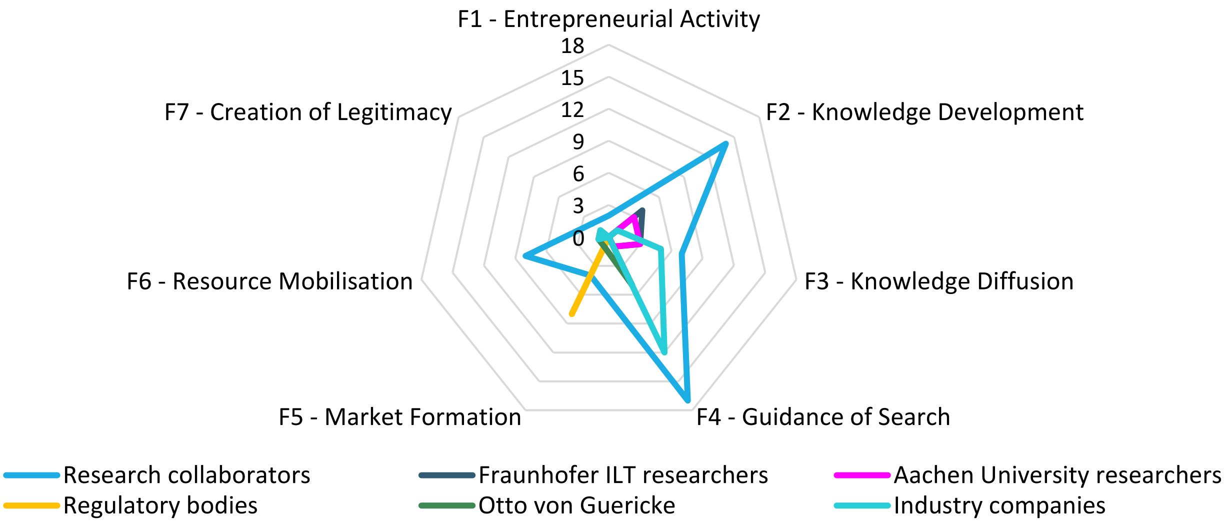


Figure 9.5: Functional contributions of the six participating actors map of the *Additive Manufacturing of Machining Tools out of WC-Co* project

9.4.1. Interventions and mechanisms

Given the overview of the development of the IS functions over the project's timespan up to June 2021, the next step is to identify if sequences of events and motors of innovation were present in the narrative. The project was initiated when the Fraunhofer ILT researchers identified the additive manufacturing of WC-Co products as a new industry-related research opportunity **[F2/KDev]**. The Fraunhofer ILT researcher contacted researchers from RWTH Aachen University to conduct feasibility studies with them **[F2/KDev, F3/KDif]**. When the studies proved their solution feasible, they launched an official research project **[F3/KDif]**. The invited industry partners to join the research project and drafted a project proposal **[F4/GoS]**. When funding was awarded **[F6/RM]**, the research project officially launched **[F1/EA]**. When the market regulations affecting the project changed **[F5/MF]**, the industry partners informed the researchers **[F4/GoS],** and the researchers ordered the necessary gear **[F6/RM]**. When the research studies commenced **[F2/KDev]**, the researchers met monthly to discuss their progress and discoveries **[F3/KDif, F4/GoS]**. When further market regulations affected the project **[F5/MF]**, the researchers had to order more gear **[F6/RM],** and some research studies **[-F2/KDev]** were temporarily suspended. Further market regulations (Covid-19) **[F5/MF]** followed, which temporarily suspended further research studies **[-F2/KDev]** and delayed the obtainment of the ordered gear **[F6/RM]**. Due to the time delays of the suspended research studied, the researchers were granted their requested extension time **[F4/GoS]**. When the ordered gear finally arrived **[F6/RM]**, the research study continued **[F2/KDev],** and the researchers once again researchers met often to discuss their progress **[F3/KDif, F4/GoS]**. Eventually, the researcher had samples proving their techniques and methods to work **[RC (P) F2/KDev]**.

Despite the *Market Formation* activities, the research collaboration activities, namely *Knowledge Development, Knowledge Diffusion*, and *Guidance of Search*, continued with the support of the *Entrepreneurial Activities* and *Resource Mobilisation* activities and delivered a manufacturing method and technique that works. Therefore, it seems fit to label the research collaboration causation cycle with its supporting feedback loops and external influences as a motor of innovation. Therefore, the motor of innovation, schematically represented in Figure 9.6, can be referred to as a *Research collaboration motor*. A reflection of the period's structural components and their drivers, barriers and impacts are presented in Table 9.2.

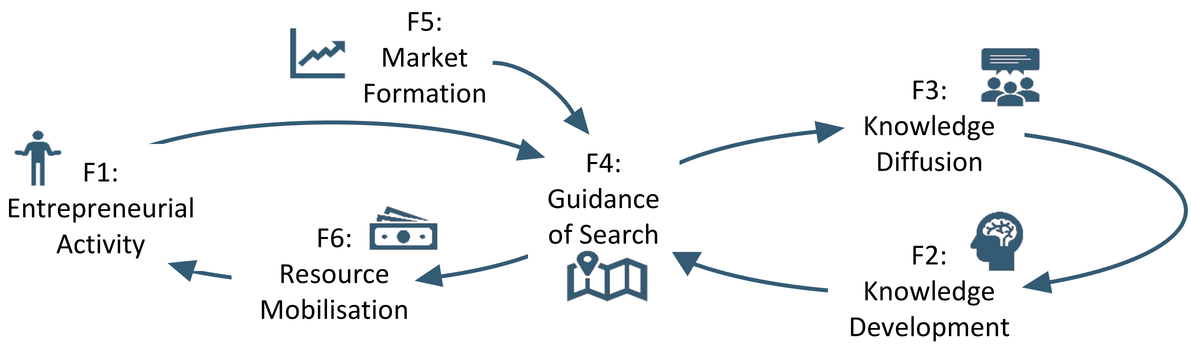


Figure 9.6: Research collaboration motor

Table 9.2: The structural components and their drivers, barriers and impacts of the AM for WC-Co project

	Actors	Interactions	Institutions	Infrastructure
Drivers	• The primary enactors are the Fraunhofer ILT, IWM, and WZL researchers who initiated and drove the project. • The Otto von Guericke e.V working group are the primary selectors as they funded the project. • The industry partners are selectors as they provided the researchers with powders, advice and informed them of the Swiss cobalt regulations.	• Academic-industry collaboration is a prerequisite for governmental research funding. • The three research groups co-operated well as they previously collaborated. • The industry partners got along well with the researchers and aided them when they required assistance.	• It was a German culture that government research funding was mainly awarded to industry-focused research projects. • As the working group believed that SMEs could benefit from the research outputs, the funding was awarded to the project.	• The project funding was provided by the Otto von Guericke e.V working group. • Machinery and facilities provided by each research group. • The encapsulations and impervious protective gear the research groups purchased.
Barriers	• The COVID-19 pandemic lockdown prohibited the research groups and industry partners from physically working together and meeting up face-to-face.	• The COVID-19 pandemic lockdown prohibited the research groups and industry partners from physically working together and meeting up face-to-face.	• Cobalt was classified as a hazardous substance by the European Union. • The COVID-19 pandemic caused global lockdowns.	• The researchers had to acquire encapsulations and impervious protective gear before they could continue with their research.
Impacts	• The researchers developed samples to prove that their techniques and methods were working. • The researchers informed the industry partners of the cobalt regulations and the necessary precautions that should be taken when working with the cobalt powders.	• The Swiss industry partner warned the researchers of the cobalt regulations. • Industry partners provided support, advice, and materials to the researchers. • The researchers demonstrated the necessary precautions that should be taken when working with the cobalt powders to the industry partners.	• Encapsulations and impervious protective gear were required due to Cobalt's hazardous classification. • The encapsulations and protective gear were inaccessible due to pandemic restrictions and preferences. • The project was delayed by several months.	• The lead time on the encapsulations and protective gear delayed the project by several months. • The acquisition of the protective gear and the installation of the encapsulations enabled the continuation of the project.

To gain an overview of the functions *performed, given,* and *received* in the *Research collaboration motor*, Figure 9.7 was developed. Figure 9.7 indicates no significant difference between the number of events *performed* by single actors and the events shared between actors (*given* and *received*). However, there is a difference between the *performed, given*, and *received* functions. For example, functions **[F1/EA, F2/KDev]** were primarily *performed* by actors. In contrast, the functions representing communication and collaboration, functions **[F3/KDif, F4/GoS]** were both *received* and *given* by actors, indicating that these functions were shared between actors. Finally, Figure 9.7 indicates that function **[F6/RM] w**as *performed, received,* and *given* by actors.

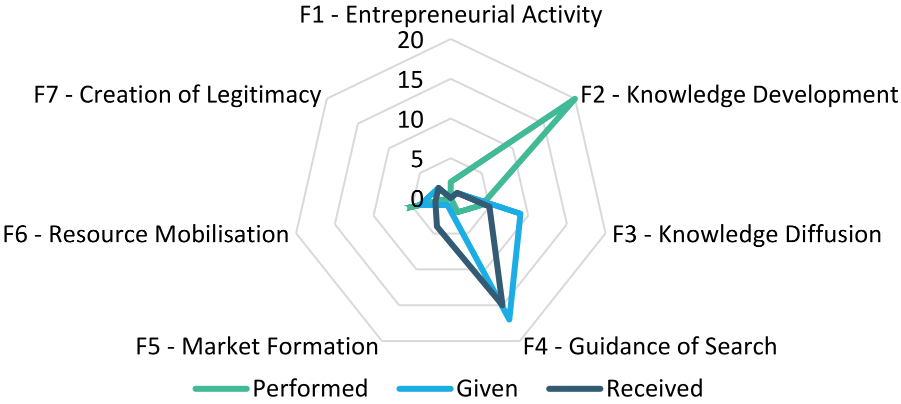


Figure 9.7: Performed-Give-and-Receive functional interaction map of the Research collaboration motor

To determine the functional contribution of each *Research collaboration motor* actor and identify which actors *performed, gave,* and *received* which functions, Figure 9.8 and Figure 9.9 were developed. The *research collaborators*, representing the research members from Fraunhofer and the research groups from RWTH Aachen University, were the primary actors of the case as they contributed to all seven functions. First, they were the primary contributors and *performers* of the **[F1/EA]** function. They launched the research project **[F1/EA]** to develop a laser-based AM technique to manufacture near-net-shape hardmetal cutting tools and demonstrate the development thereof to SMEs. Furthermore, they were the primary contributors and *performers* of the **[F2/KDev, F3/KDif]** functions. This reflects the collaborators' research and their collaboration with the industry partners. Furthermore, Figure 9.9 indicate the research outcomes the researchers continuous shared with the industry partners **[F4/GoS]** and the feedback they received from the partners **[F4/GoS]**. Furthermore, the research collaborators also experienced (*received)* several unexpected

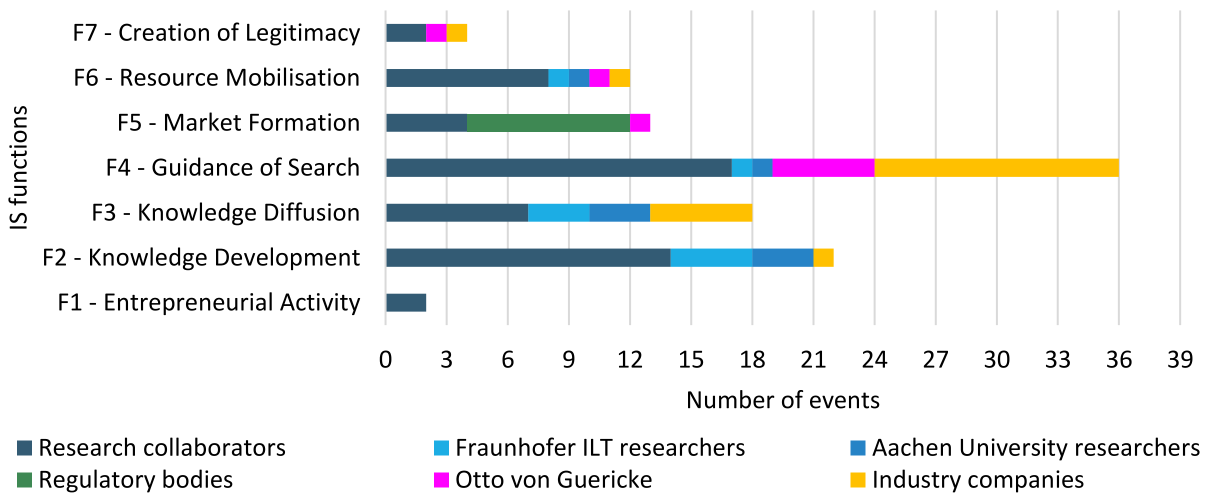


Figure 9.8: The number of events each participating actor contributed (performed, given and received combined) to the IS functions

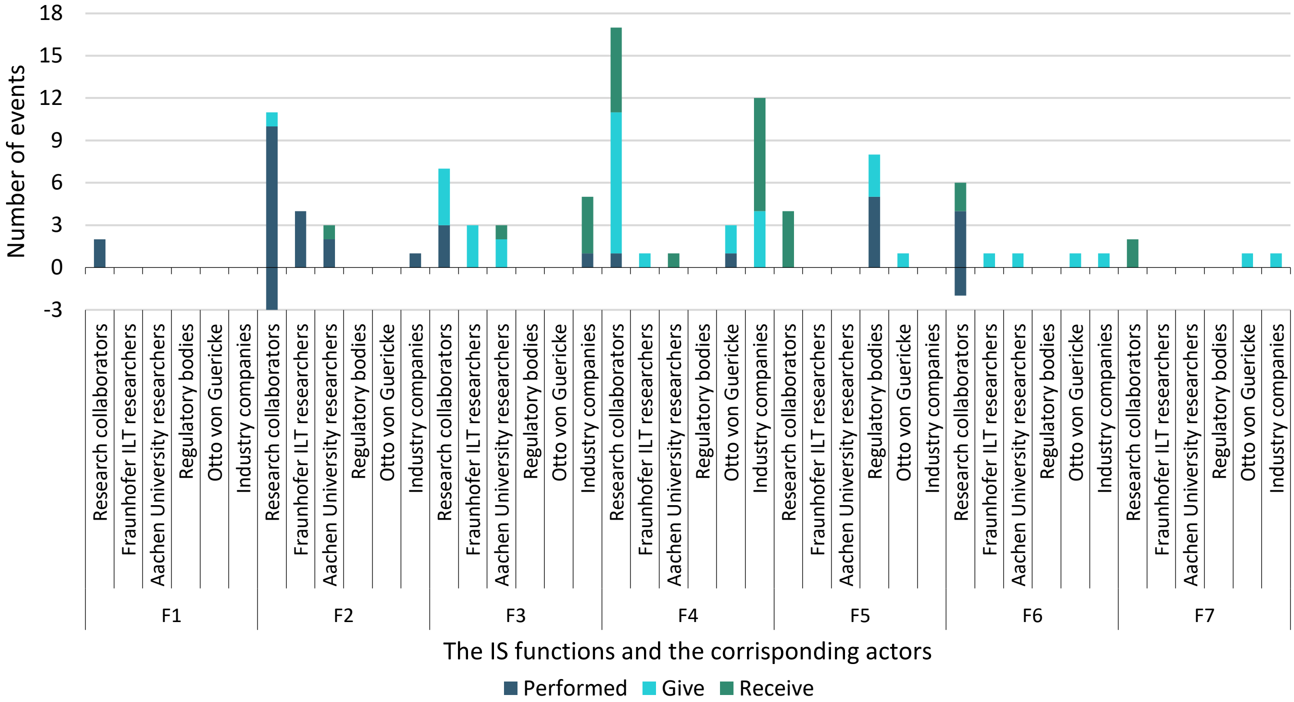


Figure 9.9: The functional Performed- Give-and-Receive map of the Research collaboration motor's actors

market regulations and conditions **[F5/MF]** that severely delayed their research projects. This included the hazardous classification of Cobalt and the COVID-19 pandemic regulations. In response to the regulations, the research collaborators also had to acquire (*performed*) additional impervious protective equipment **[F6/RM]** to protect them against the hazardous cobalt powders. Most importantly, the collaborators received research funding **[F6/RM]** from the Otto von Guericke group, which enabled their research project. Finally, Figure 9.8 and Figure 9.9 indicate the advocacy **[F7/CoL]** the researchers received from the eighteen industry partners who agreed to collaborate with them and the Otto von Guericke group who funded their research project. Finally, it is evident that the research collaborators fulfilled the role of the researchers in the *Research collaboration motor* as they conducted the research studied, obtained the necessary collaborators, and continuously communicated their research outcomes to their partners.

In this case, the Otto von Guericke group fulfilled the role of the research funder and thus enabler of the research project as they provided the research funding of the project. This is reflected in Figure 9.8 and Figure 9.9 through the group's **[F5/MF, F6/RM]** contribution. Although the contribution looks relatively insignificant compared to the fulfilment of some of the other functions, the funding they provided to the research collaborators on a once-off basis enabled the entire research project. This is a typical example of why the sequence in which events are performed should be traced over time. Furthermore, to obtain the Otto von Guericke group's funding, the group had prerequisites they communicated to the research collaborators **[F4/GoS]**, such as the involvement of SMEs and the period in which the project should be completed. They also granted the research collaborators a time extension in response to the unexpected market conditions that delayed their progress.

Figure 9.8 indicates the industry companies' contribution to the **[F3/KDif, F4/GoS]** functions. Figure 9.9 reflects the collaboration invitations the industry companies received from the researchers to participate in their research collaboration project **[F3/KDif]**. Furthermore, Figure 9.9 reflects feedback and advice the participating companies provided the researchers **[F4/GoS]** on the research project and market conditions and the research progress feedback they received from the researchers. The figures thus indicate that the industry companies fulfilled the role in the Otto von Guericke funding organisation intended for them, namely, to observe the research studies and receive and provide feedback to the researchers.

The Fraunhofer and RWTH Aachen University actors contributed the same functions **[F2/KDev, F3/KDif, F4/GoS, F6/RM]**. These actors collaborated **[F3/KDif]** and conducted the initial research studies **[F2/KDev]** from which the research project developed. They identified the research opportunity **[F4/GoS]**, provided resources to conduct the tests **[F6/RM]** and then communicated their research to industry SMEs **[F4/GoS]**. They also convinced the SMEs to collaborate with them on the research collaboration **[F3/KDif]** and obtained the research funding to finance the project **[F6/RM]**. Therefore, similar to the researchers from the *Technology Push motor*, these researchers acted as research and collaboration catalysts as they initiated the research project to obtain the necessary research funding.

As expected from *Regulatory bodies*, Figure 9.8 indicate that they primarily contributed to **[F5/MF]**. Figure 9.9 indicates that regulatory bodies *performed* and *gave* function **[F5/MF]**. This reflects the Swiss and European Chemical Agencies' hazardous, carcinogenic, and toxic classification of Cobalt and their corresponding PPE regulations. Additionally, **[F5/MF]** reflects the German lockdown regulations in response to the COVID-19 pandemic. As previously mentioned, all these regulations were unexpected external influences that delayed the research collaborators' research studies. In Case I, no unexpected external market influences was reported to negatively affect research studies. From the two research studies, an assumption can be hypothesised that researchers should always schedule additional research time as unexpected external market conditions may severely influence the project's timeline.

9.4.2. Outcome

Due to the Research collaboration motor and the actor dynamics who initiated and drove it, the research collaborators could develop samples to prove that their techniques and methods worked. However, due to unforeseen market regulations, the collaborators could not develop the AM technique by the date they had hoped. However, to lessen the effects of the project time delays, the researcher collaborators applied for a time extension, which the Otto von Guericke group granted.

In addition to the primary objectives, the motor delivered three capital outcomes: social, financial, and intellectual capital. Figure 9.10 indicates the sequence in which the capital outcomes developed in the case and the relevant actors involved. Finally, Table 9.3 summarises the interventions, mechanisms, and outcomes the *Research collaboration motor* delivered.

- Social capital: The Fraunhofer and RWTH Aachen University researchers collaborated to form the research collaborators group and convinced the industry partners to join their collaboration to gain the Otto von Guericke funding.
- Financial capital: The research collaborators group obtain funding from the Otto von Guericke group.
- Intellectual capital: The researcher developed samples to prove their techniques and methods worked. They, therefore, developed intellectual capital in developing a working technique and method.

Table 9.3: The CIMO interventions, mechanisms and outcomes of the R&D motor, along with the involved actors

<table>
<tr><th colspan="6">Intervention</th><th rowspan="3">Mechanism (Motor of innovation)</th><th colspan="2">Outcome</th></tr>
<tr><th rowspan="2">IS functions</th><th colspan="5">Actors involved</th><th rowspan="2">Objectives achieved</th><th rowspan="2">Unachieved objective and the mitigation strategy implemented</th></tr>
<tr><th>Research Collaborators</th><th>Fraunhofer and Aachen University researchers</th><th>Industry partners</th><th>Otto von Guericke</th><th>Regulator bodies</th></tr>
<tr><td>[F1] Entrepreneurial Activity</td><td>Researchers</td><td></td><td></td><td></td><td></td><td rowspan="6">**Research collaboration motor**

F3 -> F2 -> F4 ->F6 -> F1 ->F5 ->F4 -> F3</td><td rowspan="6"><u>Primary objectives achieved</u>

The research collaborators were able to develop samples to prove that their techniques and methods were working.

<u>Capital outcomes achieved</u>

• *Social capital*

The Fraunhofer and RWTH Aachen University researchers collaborated to conduct research. They also obtained industry collaboration in the project.

• *Intellectual capital:*

Technique and method developed by the research.

• *Financial capital*

The research collaborators group obtain research funding from the Otto von Guericke group.</td><td rowspan="6"><u>Unachieved objective</u>

The researchers aim to develop a laser-based AM technique to manufacture near-net-shape hardmetal cutting tools with less than 10% cobalt percentages, internal contour-adapted cooling channels and achieve performance that is at least equal to that of sintered cutting tools.

↓

<u>Mitigation strategy implemented</u>

The researcher collaborators applied for a time extension of the project, which the Otto von Guericke group granted.</td></tr>
<tr><td>[F2] Knowledge Development</td><td>Researchers</td><td>Research catalysts</td><td>Research observers</td><td></td><td></td></tr>
<tr><td>[F3] Knowledge Diffusion</td><td>Research collaborators</td><td>Collaboration catalysts</td><td></td><td></td><td></td></tr>
<tr><td>[F4] Guidance of Search</td><td>Researchers</td><td></td><td>Informants of market regulations</td><td></td><td></td></tr>
<tr><td>[F5] Market Formation</td><td></td><td></td><td></td><td></td><td>External market influencers</td></tr>
<tr><td>[F6] Resource Mobilisation</td><td></td><td></td><td></td><td>Funders</td><td></td></tr>
</table>

Figure 9.10: Capital outcomes delivered by the Research collaboration motor

9.5. Chapter 9 summary

This chapter presented the second instantiation of the Design Science Research case demonstration and the CIMO-based EHA framework, an academic-level case. The chapter started with an introduction to the case actors. Thereafter the research project was narrated. Subsequently, CIMO steps of the CIMO-based EHA framework were applied. The CIMO context indicated that the project was conceptualised based on the common German culture that research funding was mainly awarded to research projects with industry-driven topics and that industry participation was a prerequisite to research funding. The CIMO interventions and mechanism identified the research collaboration model and the functions the research institute, university, industry, and governmental actors contributed to the motor in terms of performed, give, and receive. Finally, the case-specific outputs and development capital outcomes were derived due to the research collaboration model. Figure 9.11 presents a summary of the case. This chapter contributes to objectives IV and V, as mentioned in §1.4.

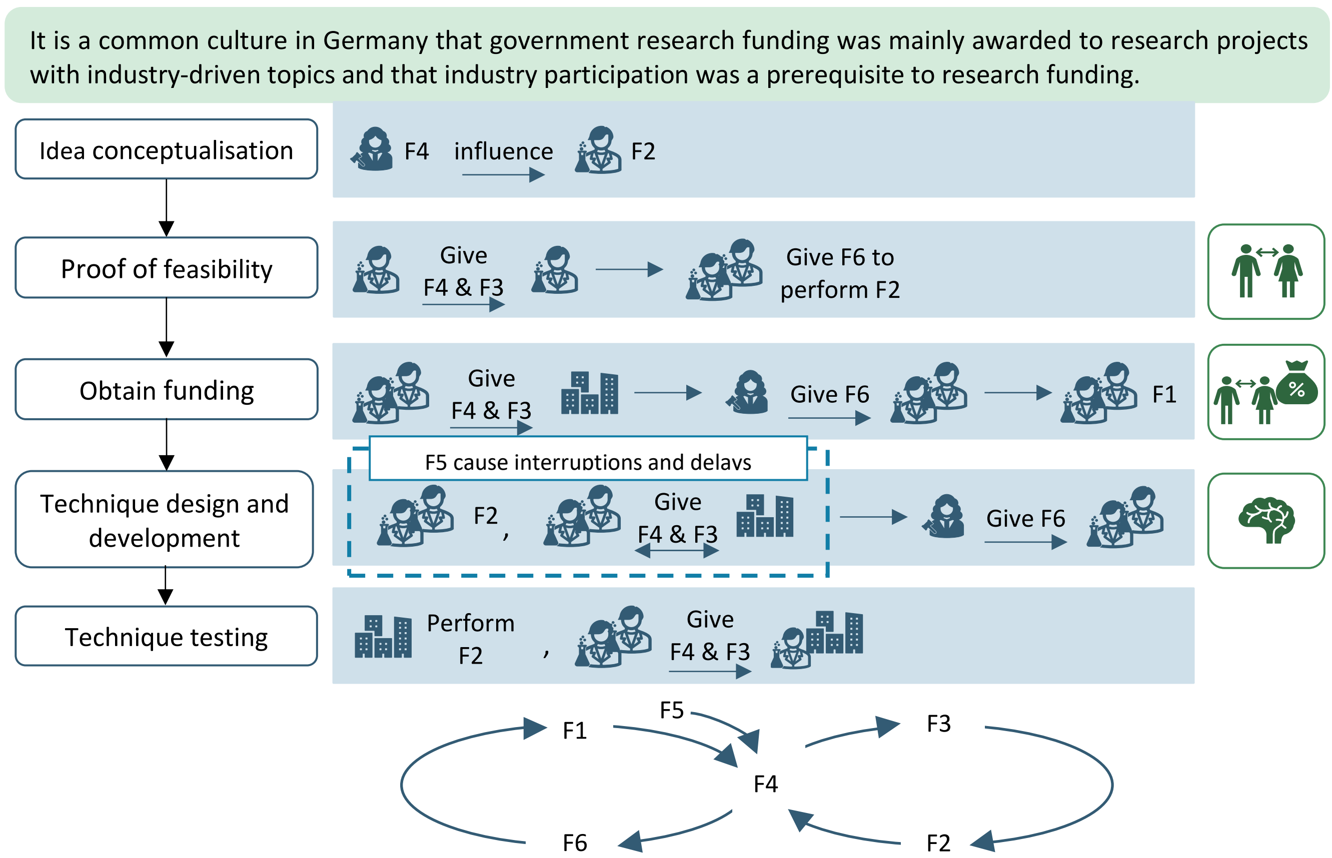


Figure 9.11: Case II process steps along with the research collaboration motor, the actors performing the functions and the capitals developed

Chapter 10

Case III: Dyze Design's Hardmetal Nozzle

The previous chapter studied the dynamics involved in a research collaboration project. This chapter explores the dynamics of a start-up company developing and commercialising a new product. The CIMO-based EHA framework is used to analyse the case of Dyze Design's hardmetal 3D printer nozzle from 2015 to 2021. Dyze Design was selected as they are a multi-award-winning start-up company from Montreal, Canada, which grew rapidly due to the commercialisation of their hardmetal 3D printer nozzles. The actors involved in this case are the Dyze Design team and the Canadian government. This case study's position in the framework is indicated in Figure 10.1 in dark blue, while the previous case studies are indicated in light blue. This chapter contributes to objectives IV and V, as mentioned in §1.4.

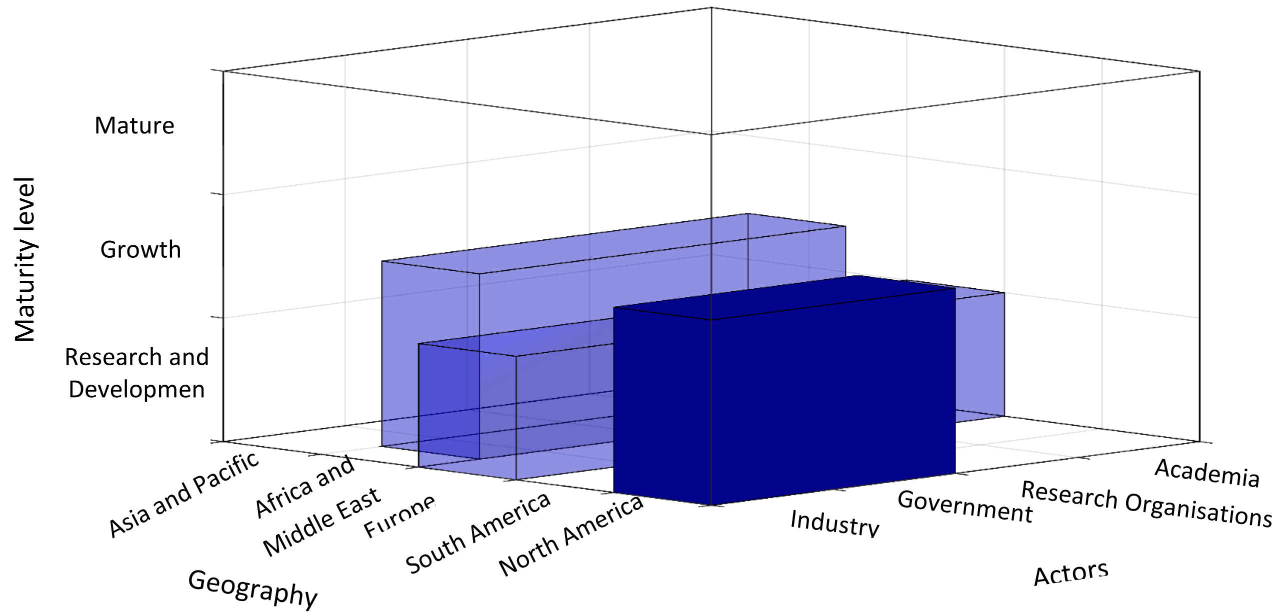


Figure 10.1: Third case in case study framework

The chapter starts with an introduction to the case approach. Thereafter follows background information on Dyze Design and the case narrative. Then the application of the CIMO-based EHA framework's four steps follows. First, the *context* of the Dyze Design case is introduced. Thereafter, the narrated is analysed to identify

Chapter 10 contribution:

- Through the application of the CIMO-based EHA framework, the chapter contributes an analysis of the underlying dynamics and mechanisms that supported and hindered a startup enterprise's R&D project.

Chapter 10 objectives:

- Introduce Dyze Design and their hardmetal nozzles (§10.1).
- Narrate the start-up enterprise case study (§10.3).
- Identify the context and motors of innovation that led to development (§10.4.1 and 10.4.2).
- Identify the underlying structural drivers and barriers of the motors of innovation (§10.4.1 and 10.4.2).
- Identify the influence these IS structures and motors of innovation have on the outcomes and outputs of the case (§10.4.1 and 10.4.2).

the *interventions and mechanisms* present in the case. The chapter then concludes with the identification of the case *outcomes and outputs* delivered by these *mechanisms*.

10.1. Case approach

In this case, the technology innovation system (TIS) perspective is applied at a company level. As in the previous chapter, the empirical work for this case relied on the construction of a narrative. As Dyze Design is a start-up company that did not publish literature articles, limited information and literature regarding their company and hardmetal nozzles were available. Therefore, to gain the necessary information to formulate a case study, several semi-structured interviews were conducted with the Dyze Design staff members involved with the nozzles. These staff members told and verified the Dyze Design innovation success story for the narrative, detailed the drivers and barriers experienced along with their impacts, and validated the final analysis conducted on the narrative. Rabionet's [353] six-step interview process (*§* 7.4) guided the interviews, while Cresswell's [50] qualitative data analysis process (*§*7.5) was used to collect and code the event data in a database.

10.2. Introduction to Dyze Design

This case explores the innovation actors, activities, and motors of innovation involved in a start-up company's growth and R&D studies. The case aims to identify how the motors of innovation involved in the case evolved from technology in the R&D stage through the Valley of Death to commercialisation. This case documents the event history of a Canadian start-up company, Dyze Design, which developed and commercialised cemented hardmetal 3D printer nozzles after identifying several shortcomings in the tool steel nozzles available in the market.

Dyze Design is a 3D printer component and accessory development company based in Montreal, Canada [397], [398]. The company was established in 2015 and launched a research and development (R&D) project to develop a hardmetal nozzle for personal 3D printers in 2016. Dyze Design has since won several innovation awards for being one of Canada's most innovative technology-oriented start-up companies. The awards include: the 2015 National Bank Award [399], the 2015 Montreal Foundation Inc grant [351], the 2017 Start-up Nation Pitch contest [352], 2020 CCIRS Excellence Award for innovation and technology [351]. They were also finalists for the 2017 Berlin G20YEA Pitch Contest and the 2020 ADRIQ Innovation Awards [351], [400].

The Dyze Design case was selected for study as it demonstrates how an innovative, award-winning start-up company with minimal resources and business expertise utilised intermediary support to develop a hardmetal AM product through the VoD to commercialisation. In addition to the development of the AM product, the case demonstrates the effects intermediaries have on the entire Dyze Design IS.

The hardmetal nozzles Dyze Design developed is the final component of a 3D printer's extrusion system, as seen in Figure 10.2, and is one of the essential components of the printer [397]. The feeding mechanism of the extruder system pushes the printing filament into the hot end, where the filament is melted and pushed through the nozzle orifice [401]. The pressure generated by the feeding mechanism can reach a pressure as high as 25 MPa [402]. When plastic is used as filament, any metal nozzle can withstand the pressure. However, when plastic filaments with hard reinforcement fibres such as carbon and glass are used, the reinforcement fibres scratch the inner wall of the nozzle orifice as they pass due to the flow and pressure [397]. As glass and carbon are much harder than any metal, abrasion occurs within the nozzle [397], [402]. Therefore, Dyze Design chose the ceramic hardmetal as the manufacturing material of the nozzle due to its excellent wear and abrasion resistance, hardness and thermal conductivity [397], [402].

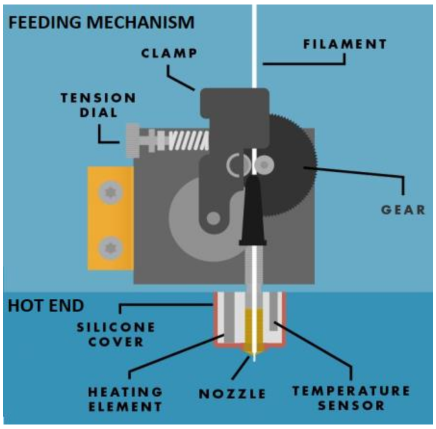


Figure 10.2: Schematic representation of the extruder components of a 3D printer [401]

The following sections will look at the progressive development of Dyze Design's hardmetal nozzle's TIS from 2015 to the end of 2021. By analysing the development of the product through the TIS perspective and the EHA method, motors of innovation and underlying structural drivers and barriers may be identified, which will explain the development of both the hardmetal product and the Dyze Design company. Based on the development phases of the nozzles, the narrative may be divided into two primary stages, namely, a *development stage* and an *entrepreneurial stage,* as seen in Table 10.1.

Table 10.1: Stages of the Dyze Design case

Stage	Period	Description
Development	Research and development	Dyze Design was established. The company entered several innovation competitions and launched its 3D printer nozzle R&D project.
	Nozzle production	Dyze Design launched a fundraising campaign to raise money to produce the hardmetal nozzles.
Entrepreneurial	Nozzle commercialisation	After production, Dyze Design wanted to build on its international client base. They identified new distribution channels and market opportunities and launched another R&D project.
	Company expansion	To serve the profile of its newly identified audience, Dyze Design expanded its company and updated two of its business approaches. They increased their investment in tradeshows and collaborated with several universities.

10.3. The event history of Dyze Design's Hardmetal Nozzle

In this section, an outline of the development and commercialisation of Dyze Design's hardmetal nozzle from 2015 to the end of 2021 is given as a chronological narrative. During each narrative period, the IS functions corresponding to the events are denoted by **[F1/EA, F2/KDev, … F7/CoL]** along with a `-1 or 1' to indicate their influence, and a **(P)**, **(G)** or **(G)** to indicate whether functions were performed, given, or received. Furthermore, events related to Dyze Design, the Canadian government, suppliers, customers, investors and academia are indicated as **[DD]**, **[Gov]**, **[Sup]**, **[Cus], [Inv]** and **[Aca]**, respectively. At the end of each stage, Figure 10.3, Figure 10.4, Figure 10.5 and Figure 10.6 summarises each period's main events. *Readers may skip the period descriptions and follow the summary figures and tables.*

10.3.1. Development stage: Research and development (July 2015 - December 2017)

Dyze Design was established in July 2015 **[DD (P) F1/EA]** when the Dyze Design team saw a market opportunity for high-performance 3D printer components and accessories, specifically deposition components of 3D printers **[Cus (P) F5/MF]**. As Dyze Design was located in Quebec, Canada, they knew that finding investors to invest in their company would be challenging as the Quebec community was known to be risk-averse **[Inv (P) -F5/MF]**. Dyze Design, therefore, decided to participate in several of the entrepreneurial competitions offered by the Quebec and Canadian governments **[DD (P) F1/EA, Gov (P) F5/MF]**.

In August 2015, Dyze Design won the Montréal Foundation Inc innovation competition for being one of the most innovative technology-oriented start-up companies in Montréal and received a CAD 10,000 grant **[DD (P) F1/EA, (R) F6/RM, F7/CoL, Gov (G) F5/MF, F6/RM, F7/CoL]** [351]. In November of the same year, they were announced as the winners of the Accelerator competition, an entrepreneurial support competition aimed at start-up companies in the Quebec, Canada technology sector, National Bank Award **[DD (P) F1/EA, (R) F7/CoL, Gov (G) F5/MF, F7/CoL]** [352]. The award included a CAD 10,000 grant **[DD (R), Gov (G) F6/RM]**, twelve-week professional development training and two mentoring sessions with one of Canada's most successful entrepreneurs **[DD (R) F2/KDev, F4/GoS, Gov (G) F3/KDif]**.

At the end of February 2016, Dyze Design launched a research and development (R&D) project to develop a high-performance, affordable 3D printer nozzle to improve the 3D printer nozzles available in the global market **[Cus (G) F5/MF, DD (P) F1/EA, F2/KDif]**. Therefore, in the following three months, Dyze Design considered a variety of materials to identify a material that would improve the properties of the 3D printer nozzles **[DD (P) F2/KDev]**.

In June 2016, Dyze Design identified hardmetal as the most suitable nozzle material because of its extreme abrasion resistance and high thermal performance **[DD (P) F2/KDev]**. As Dyze Design did not have the machines to manufacture the nozzles in-house **[DD (P) -F6/RM]**, they searched for suppliers. As they aimed to produce nozzles with minimal orifice diameters **[DD (G) F4/GoS]**, finding suppliers were difficult **[Sup (G) -F3/KDif]**. By August 2016, Dyze Design had found five adequate suppliers **[DD (G), Sup (R) F3/KDif]**. For the following sixteen months, Dyze Design collaborated with its suppliers and conducted numerous iterations of feasibility studies and quality tests **[DD (P) F2/KDev, (G) F3/KDif, Sup (G) F3/KDif]**. In addition, Dyze Design received tax incentives from the Canadian Government's Scientific Research and Experimental Development Tax Incentive Programme **[DD (R), Gov (G) F5/MF]**.

In May 2017, Dyze Design was chosen to be part of Centech's Propulsion development program, a world-class government-supported business incubator based in Montreal **[DD (P) F1/EA, DD (R), Gov (G) F5/MF, F7/CoL]** [403]. As part of the 24-month program, Dyze Design received rigorous supervision along with technical and business guidance to develop their business and products **[DD (R) F2/KDev, Gov (G) F3/KDif, F4/GoS]**.

As Dyze Design still required capital to manufacture the nozzles **[DD (G) F4/GoS, (P) -F6/RM]**. Therefore, during the R&D of the nozzle, Dyze Design searched for investors to invest in their product but did not find any, as the investors were more interested in software products **[Inv (G) -F3/KDif, F4/GoS]**.

By December 2017, Dyze Design had a working prototype **[DD (P) F2/KDev]**. Although they were still collaborating with their suppliers to test a few parameters **[DD (G), CSoc (G) F3/KDif]**, they were ready for pre-production. The key events of the research and development period are illustrated in Figure 10.3. The light green dots indicate key millstones for the Dyze Design company. The dark green diamonds indicate the nozzle project activities, and the blue dashed lines indicate the funding and professional development training Dyze Design obtained.

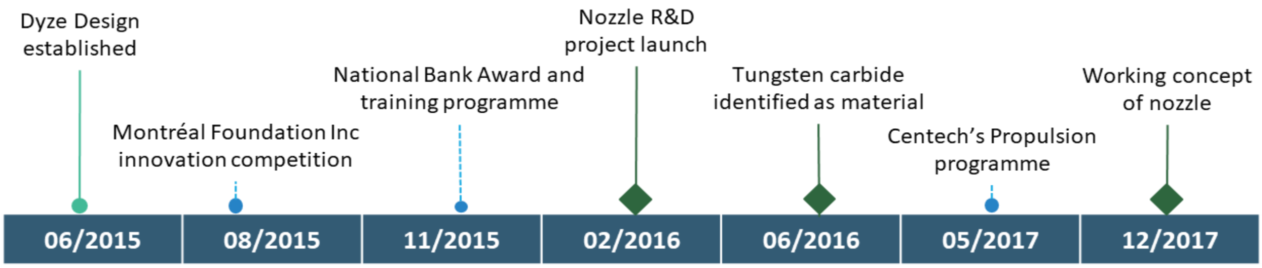


Figure 10.3: Development stage - Research and Development (July 2015 - December 2017)

10.3.2. Development stage: Nozzle production (January 2018 - January 2019)

In February 2018, Dyze Design contacted numerous websites, companies and journals within the 3D printing and hardmetal communities to announce that they are hosting a crowdfunding campaign to raise funds to produce the hardmetal nozzles **[DD (G), Cus (R), Sup (R) F3/KDif]** [404]. They reported that they were launching a month-long crowdfunding campaign where four nozzle sizes were available for pre-order to raise CAD 15,000 [404] **[DD (G) F4/GoS]**.

The Kickstarter campaign launched on March 6, 2018 **[DD (P) F1/EA, F3/KDif]**. Within the first ten days, Dyze Design raised its goal of CAD 15,000 **[DD (R), Cus (G) F6/RM]** [404]. In response, Dyze Design released photos of objects printed with the prototypes to thank their supporters **[DD (G), Cus (R) F4/GoS]** [404]. When the campaign ended in April, 355 buyers from, amongst others, the United States, France, Netherlands, the United Kingdom, Italy, and Australia pre-ordered the nozzles, and CAD 34,572 was raised **[DD (R), Cus (G) F6/RM, F7/CoL]**. Dyze Design once again released photos of the nozzles and thanked their supporters **[DD (G), Cus (R) F4/GoS]** [404]**.**

When the pre-production phase continued, several manufacturing and quality difficulties were encountered, which delayed the production of the nozzles **[DD (P) -F2/KDev, DD (G), Sup (G) F3/KDif]**. To reassure their customers of their process, Dyze Design regularly updated their supporters over the Kickstarter platform **[DD (G), Cus (R) F4/GoS]**. Finally, in September 2018, the nozzles production commenced **[DD (P) F2/KDev]**, and by the end of January 2019, all the nozzles were delivered to their buyers (Figure 10.4.).

In addition to the funding raised, the campaign connected Dyze Design to global customers and created awareness for the entire company. As a result, their website visitation and other product sales increased significantly **[DD (R), Cus (G) F3/KDif, F6/RM, F7/CoL]**.

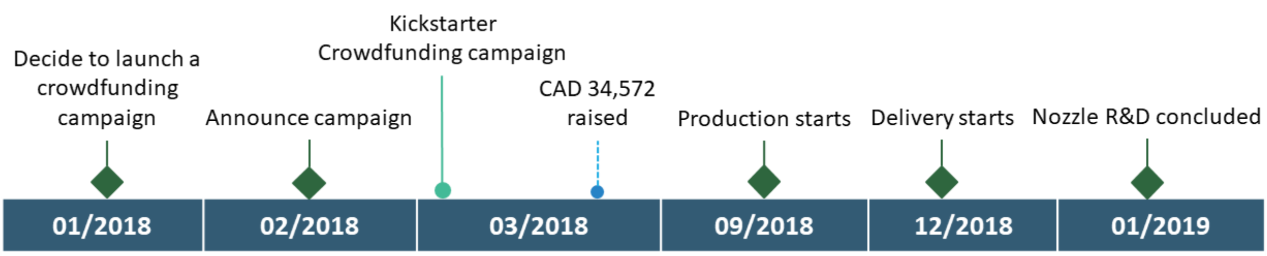


Figure 10.4: Development stage - nozzle production (January 2018 - January 2019)

10.3.3. Entrepreneurial stage: Nozzle commercialisation (June 2018 – December 2019)

During the pre-production, Dyze Design decided to sell the nozzles both as separate nozzles and as part of their extruder systems to build on their international client base from the campaign **[DD (P) F1/EA]**. Therefore, they contacted numerous internet stores worldwide to advertise their hardmetal nozzles and extrusion components **[DD (G), Cus (R) F4/GoS]**. Through these internet stores, Dyze Design found several European distributors willing to sell their products to the European market **[DD (G), Cus (R) F3/KDif]**. In addition, Dyze Design wrote blogs about its products and converted its website into an electronic store where its products could be purchased **[DD (P) F1/EA, F6/RM]**. Furthermore, to see the latest global AM trends, Dyze Design attended numerous international trade shows in North America for the last six months of 2018 **[DD (P) F1/EA, DD (G), Cus (R) F3/KDif]**. Here, they reached countless international customers who bought their products **[DD (R), Cus (G) F6/RM]**.

At these trade shows, Dyze Design quickly realised that as personal 3D printers were globally becoming less expensive, their tungsten extruder product was too expensive for their 3D printing enthusiasts' target market **[DD (R), Cus (G) -F4/GoS, -F7/CoL]**. Their extruder systems were CAD 300-350, while personal 3D printers globally became available at CAD 250. However, they noticed that their tungsten extruders were used in some industrial 3D printers worth CAD 60,000 **[DD (R), Cus (G) F4/GoS, F7/CoL]**. Dyze Design decided to develop high-quality, high-performance hardmetal extruders for industrial 3D printers **[DD (P) F1/EA]**.

Therefore, in February 2019, Dyze Design launched another R&D project to develop extruders for industrial 3D printers with the capital raised from the previous trade shows **[DD (P) F2/KDev, F6/RM]**. During the following months, they attended numerous international trade shows in North America and Germany to sell their products and promote their upcoming industrial extruders **[DD (P) F1/EA, (G) F3/KDif, (G) F4/GoS, (R) F6/RM, Cus (R) F3/KDif, (G) F6/RM]**.

In September 2019, Dyze Design released a prototype of the industrial extruders to test the product's potential in the global market **[DD (P) F1/EA, F2/KDev, DD (G), Cus (R) F3/KDif]**. As the prototype received excellent feedback from customers globally **[DD (R) Cus (G) F4/GoS]**, Dyze Design went ahead with the production and commercialisation of the product **[DD (P) F1/EA, F2/KDev]**. At the end of 2019, Dyze Design released the typhoon extruder into the global market **[DD (P) F1/EA]** (Figure 10.5).

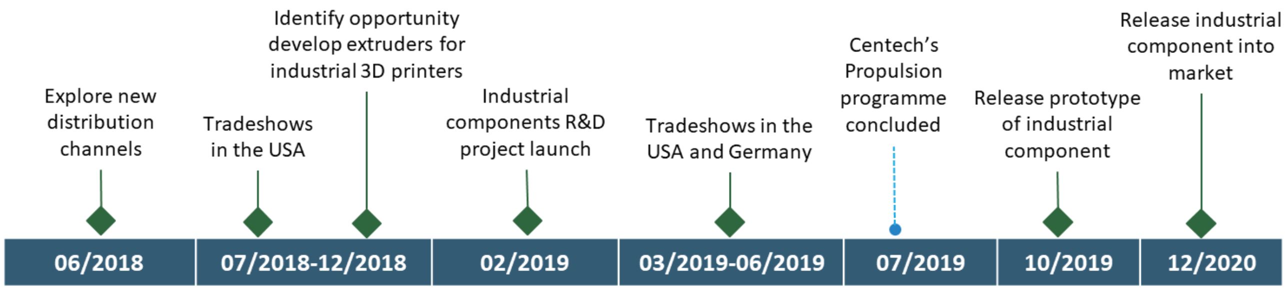


Figure 10.5: Entrepreneurial stage - nozzle commercialisation (June 2018 – December 2019)

10.3.4. Entrepreneurial stage: Company expansion (January 2020 – December 2021)

Based on the knowledge gained from the entrepreneurial development programs, Dyze Design realised they had to change some of their business approaches as their target market now also included the industrial 3D printing community. Therefore, Dyze Design appointed a sales representative to tend to the needs of their new customers **[DD (P) F1/EA, F6/RM]**.

Throughout 2020, Dyze Design also showcased their nozzles and extruders at several international conferences in North America and Europe, where they reached numerous personal and industrial 3D printer clients **[DD (P) E1/EA, (G) F3/KDif, (R) F6/RM, Cus (G) F4/GoS, F6/RM]**. To gain the necessary funding and technical equipment to attend the trade shows, Dyze Design partnered with financial and entrepreneurial support organisations supported by the Canadian government **[DD (R), Gov (G) F5/MF, F6/RM]**.

One of the leading clients Dyze Design met at the trade shows was universities. In September 2020, Dyze Design partnered with several German, Dutch, and Canadian universities to supply research groups with nozzles and different extruders systems **[DD (P) F1/EA, F2/KDev, DD (R), Aca (G) F3/KDif]**. The universities were impressed by the low-priced, high-quality products Dyze Design offered **[Aca (G) F4/GoS, Aca (G), DD (R) F7/CoL]**. Furthermore, Dyze Design partnered with universities in Montreal to allow students pursuing their engineering degrees to complete their internship credits at Dyze Design **[Aca (R), DD (G) F3/KDif]**. This partnership enabled Dyze Design to share its expertise with students and establish relationships with potential future employees **[DD (G) F3/KDif, Aca (G) F2/KDev]**. The Canadian government supported Dyze Design's relationship with these universities through tax incentives of the internship salaries **[DD (R), Gov (G) F5/MF]**.

To improve its credibility and financial position, Dyze Design continued to participate in entrepreneurial competitions and programs offered by the Quebec and Canadian governments **[DD (P) F1/EA, Gov (P) F5/MF]**. In June 2020, Dyze Design won the Innovations and Technology Excellence Awards of CCIRS - Chambre de commerce et d'industrie de la Rive-Sud **[DD (P) F1/EA, DD (R), Gov (G) F5/MF, F7/CoL]**, and in November, they were finalists for the ADRIQ innovation award **[DD F1/EA, F7/CoL, Gov F5/MF, F7/CoL]** (Figure 10.6). In addition to their website blogs, Dyze Design also started to write more scientific literature **[DD F3/KDif, F7/CoL]**.

Figure 10.6: Entrepreneurial stage: Company expansion (January 2020 – present)

10.4. Case analysis

As the two stages of the Dyze Design case have been narrated, the event data can be subjected to interaction pattern and trend analyses. The interaction patterns of each stage shed light on the IS functions, the CIMO *interventions,* and motors of innovation into the CIMO *mechanisms* that enabled Dyze Design to cross the VoD. Therefore, the sequence in which the functions were performed is traced to determine the interaction patterns. Additionally, given the interaction patterns, the trend analysis determines the primary actors performing the IS functions and driving the interaction patterns.

To get an overview of the development of the IS functions throughout the two stages as well as the functions Dyze Design, the government, investors, customers, suppliers, and academia contributed, Figure 10.8 and Figure 10.8 was developed. In Figure 10.8, the function-fulfilment time graph presents the fulfilment of each IS function over time, while the pie charts indicate the percentage each function contributed to the narrative stages. Figure 10.8 and Figure 10.8 indicate that all the functions were present during the narrative and that **[F3/KDif]** and **[F1/EA]** were the slightly more dominant function of the narrative. This indicates that activities such as alliances between actors, awareness campaigns, conferences, demonstrations, and projects with commercial aims were often performed in the narrative. This case, therefore, demonstrates that entrepreneurial activities and creating awareness of innovations are fundamental to crossing the VoD and should be focused on to enable a company to cross the VoD. Furthermore, functions **[F5/MF]** and **[F7/CoL]** were performed slightly less than the other functions. However, further investigation into these functions' impacts is studied below.

Furthermore, as suspected from literature, Figure 10.8 indicates the Government's large **[F5/MF]** contribution while customers contributed mainly to **[F3/KDif]** and **[F4/ GoS]**. As expected, the transformation of knowledge and resources into beneficial business opportunities **[F1/EA]** was also solely performed by Dyze Design, along with most of the knowledge development **[F2/KDev]**.

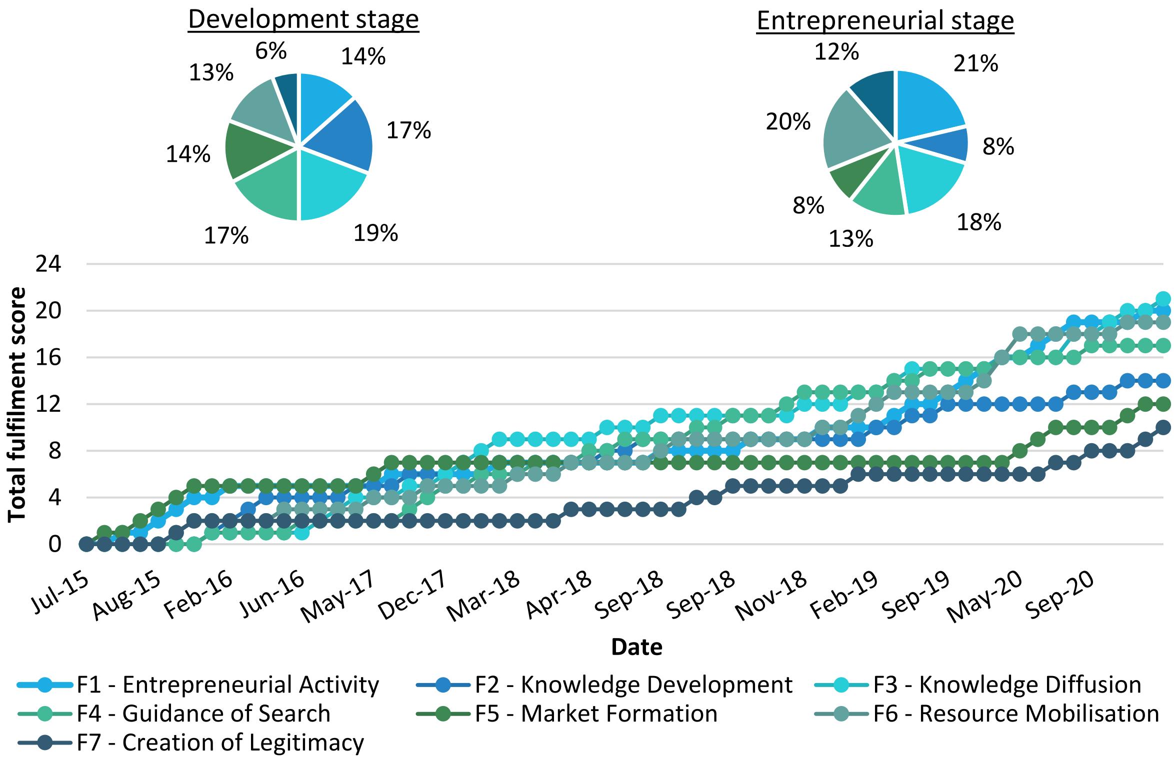


Figure 10.8: The function-fulfilment time graph of the Dyze Design case

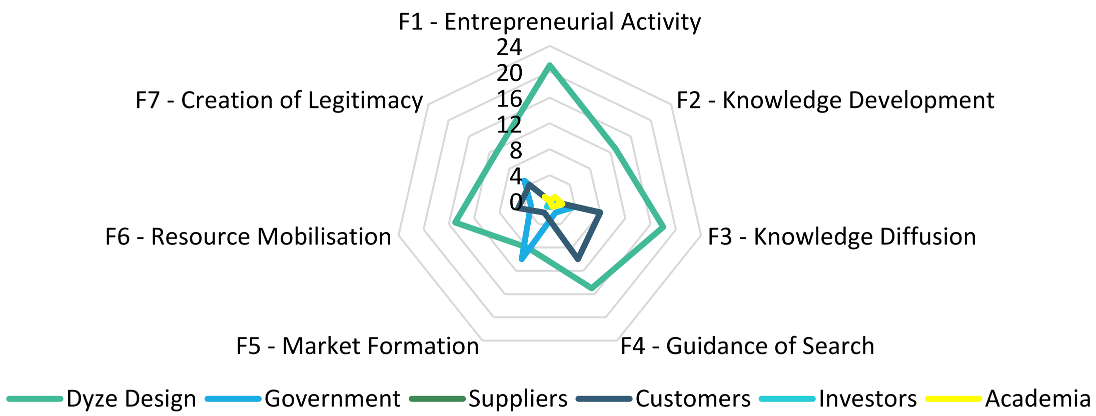


Figure 10.8: Functional contribution per actor

10.4.1. CIMO analysis of the Development stage

Before the Development stage can be subjected to the interaction patterns and trend analysis, the context of the stage is summarised in Table 10.2 to shed light on the circumstances that formed the initial setting for the Development stage. The Development stage started when Dyze Design was founded to establish its brand in the Montreal community and develop 3D printer nozzles. However, Dyze Design was then situated in a risk-averse community (development barrier) where innovative (start-up) companies were predominantly supported through government-supported competitions and development programs (development driver) that offer money and business training (driver). Furthermore, Dyze Design had limited financial and physical infrastructure and business knowledge (barrier) but is well-trained in AM technologies.

Table 10.2: The Context defining the starting setting for the Development stage

Context steps	Dyze Design application
Defining the system boundary	The Dyze Design company from July 2015 to January 2019.
Defining the phase of development	The development stage of the nozzles until the end of the nozzle production.
Defining the system objective	<u>Primary objectives:</u> • Establish Dyze Design in the Montreal community. • Gain investors to invest in Dyze Design and teach them business operations • Develop a hardmetal 3D printer nozzle. <u>Capital objectives:</u> • Financial capital: Gain investment support and money to fund the nozzle production. • Produced capital: Develop marketable hardmetal 3D printer nozzles. • Social capital: Create awareness and a sense of trust in the company's brand and products.
Identifying the IS structures	<u>Actors:</u> • The Dyze Design team – enactors • The governmental awards and training organisations – selectors
	<u>Networks:</u> • Dyze Design has no significant relationship with suppliers or end-users (barrier).
	<u>Institutions:</u> • Dyze Design is situated in a risk-averse community culture (barrier). • Montreal and Canada support innovative start-up companies through grants and development programmes (driver).
	<u>Infrastructure:</u> • Dyze Design has minimal financial and physical resources (barrier). • They have in-depth knowledge of additive manufacturing (driver).

Given this context, the interaction patterns shed light on the IS structures and functions that led to the nozzles' and the company's development. Therefore, a Performed-Give-and-Receive radar graph may be developed to visualise which Development stage's IS functions were performed by actors and which were shared (given and received) between actors. Figure 10.9 indicates that functions **[F1, F2]** were primarily performed most by actors indicating that activities such as projects with commercial aims and research studies were not shared between actors but conducted by, from Figure 10.8, Dyze Design. Furthermore, **[F3, F4]** mainly were given and received

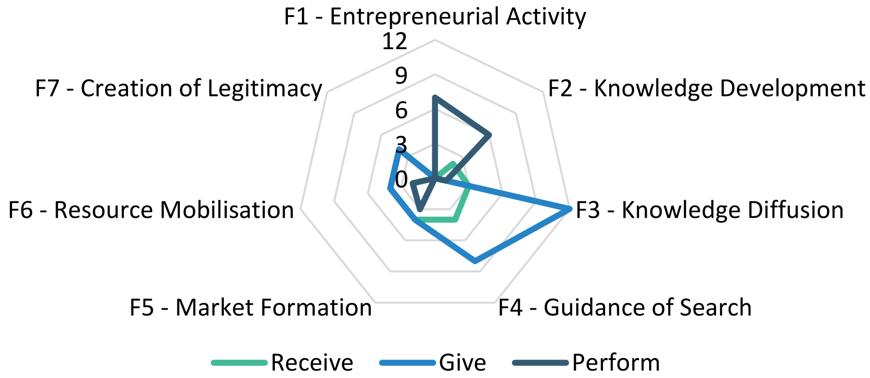


Figure 10.9: Give-and-Receive functional interaction map of the Development stage

most by participating actors, indicating that activities such as communicating vision, research outputs and expectations, alliances between actors, awareness campaigns, and conferences were often shared. Functions **[F5, F6, F7]** were also shared (given and received) among actors. To determine how the given and received functions correspond to the performed functions, the sequence in which the functions were performed may be traced in the following section.

During the Development stage's R&D period, Dyze Design was founded **[F1/EA]** in response to a market opportunity identified **[F5/MF]**. To raise capital, awareness and gain knowledge to develop the company, they participated in and won several competitions funded by the Canadian government **[F1/EA, F5/MF, F7/CoL]**. Consequently, Dyze Design obtained grants **[F6/RM]** and professional development training opportunities **[F2/KDev**, **F3/KDif]**. These grants and training enabled Dyze Design to launch an R&D project **[F1/EA, F2/KDev]**, collaborate with several suppliers **[F3/KDif, K4/GoS]** and conduct numerous feasibility studies to develop a working concept **[F2/KDev]**.

During the nozzle production period of the development stage, Dyze Design continued to collaborate with their suppliers to develop and manufacture their nozzles **[F2/KDev, F3/KDif]** while the company was obtaining funding **[F6/RM]** through customer relationships established **[F3/KDif]** from the crowdfunding campaign **[F1/EA, F4/GoS]**.

A pattern and virtuous causation cycle thus exist in the development stage as the identification of market opportunities led to participation in development competitions to acquire funding, professional training, which enabled R&D leading to more funding acquisition and product development. Therefore, given the sequence of the IS functions within the causation cycle, the cycle could be referred to as a development cycle. Furthermore, as the development cycle enabled Dyze Design to accomplish its goals of developing a working concept while developing its company, it seems fit to label the cycle a motor of innovation, therefore referring to it as the *Development motor*, as schematically represented in Figure 10.10. The *Development motor* is thus the CIMO *mechanism* of the Development stage.

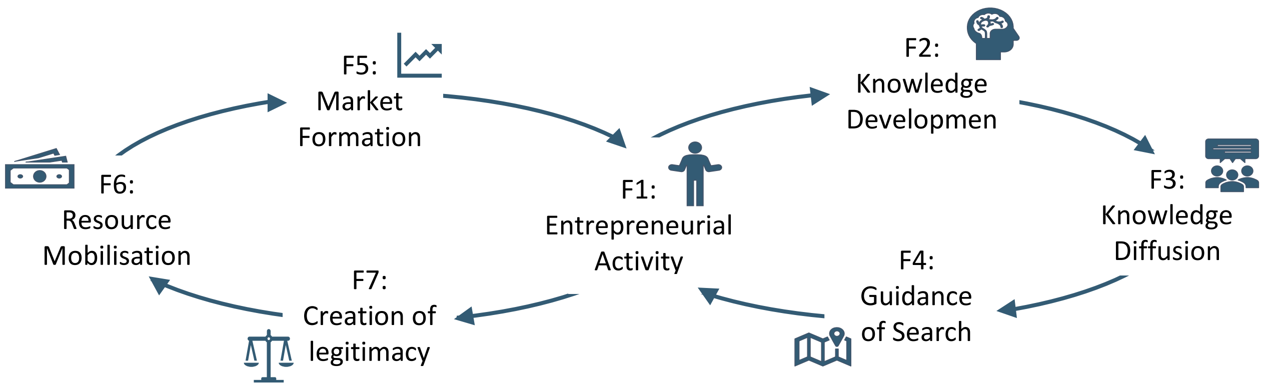


Figure 10.10: The Development motor

To determine the impact the driver and barrier IS structures had on the *Development motor* and thus the development stage, Table 10.3 was developed. To determine the functional contribution of each *Development motor* actor, Figure 10.13, Figure 10.13 and Figure 10.13 were developed.

The figures indicate that Dyze Design exclusively performed the *Development motor's* **[F1/EA**, **F2/KDev]** functions. This is due to the innovation competitions Dyze Design participated in and the nozzle R&D project they conducted (in line with Ford *et al.* [20] and Hudson's [175] motivation for fundamental research at a firm level). Furthermore, Dyze Design primarily performed and was *givers* of the **[F3/KDif, F4/GoS]** functions as they collaborated with suppliers and shared their expectations, outputs and requirements with their suppliers and customers. Finally, although Dyze Design did not have many physical or financial resources **[-F6/RM]**, Dyze

Table 10.3: The structural components and their drivers, barriers and impacts on the Development stage

	Actors	Interactions	Institutions	Infrastructure
Drivers	• Dyze Design researchers who drive the R&D projects are the primary enactors. • Dyze Design managing partners hosting the Kickstarter campaign and participating in the competitions and development programmes are the primary selectors. • The Canadian government funding development programmes are selectors.	• Dyze Design continually collaborated with its suppliers to develop the nozzles successfully. • Relationships were established with entrepreneurs from the National Bank Award's and Centech's Propulsion programmes. • Dyze Design communicated its progress with its supporters throughout the Kickstarter campaign.	• In response to risk-averse culture, the Canadian government supports innovative start-up companies through entrepreneurial development programmes.	• Company capital • The Montreal Foundation Inc grant • The National Bank Award grant • The knowledge gained from the National Bank Award training programme and Centech's Propulsion development programme. • The Kickstarter campaign raised more than double the funding goal.
Barriers	• Investors did not want to invest in the nozzle project. • It was challenging to find suppliers that could manufacture nozzle moulds and assemble the nozzles.	• It was challenging to find suppliers that could manufacture nozzle moulds and assemble the nozzles.	• The Quebec community is risk averse. It was, therefore, difficult to gain investors for the company.	• Dyze Design had limited capital along with none of the required machinery. • Investors and venture capitalists did not invest in the project. • Dyze Design had to outsource production to suppliers.
Impacts	• Dyze Design's crowdfunding campaign raised more than double the initial funding goal. • Dyze Design successfully manufactured good quality hardmetal nozzles.	• Good quality hardmetal nozzles were manufactured. • The Dyze Design supporters did not complain about the nozzle delivery delay.	• The development programmes taught Dyze Design business skills. • Investors and venture capitalists did not invest in the project.	• Dyze Design had funding to produce the hardmetal nozzle. • Dyze Design established relationships with end-users

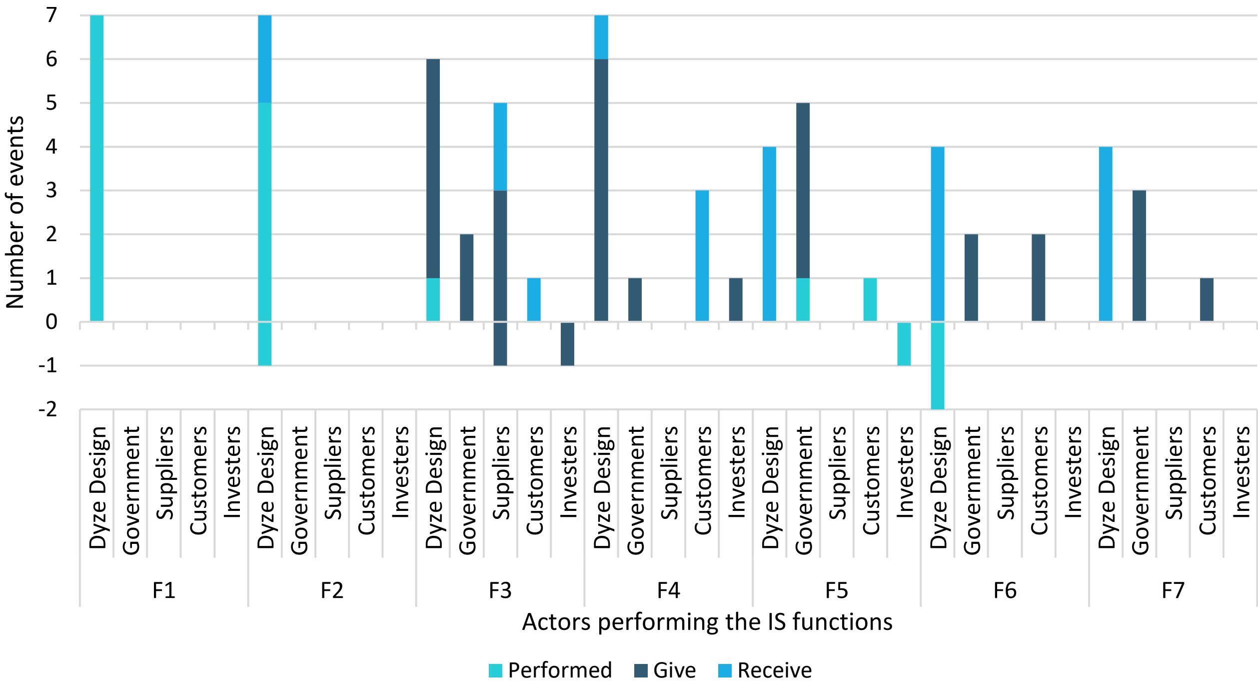


Figure 10.13: The functional Give-and-Receive map of the Development motor's actors

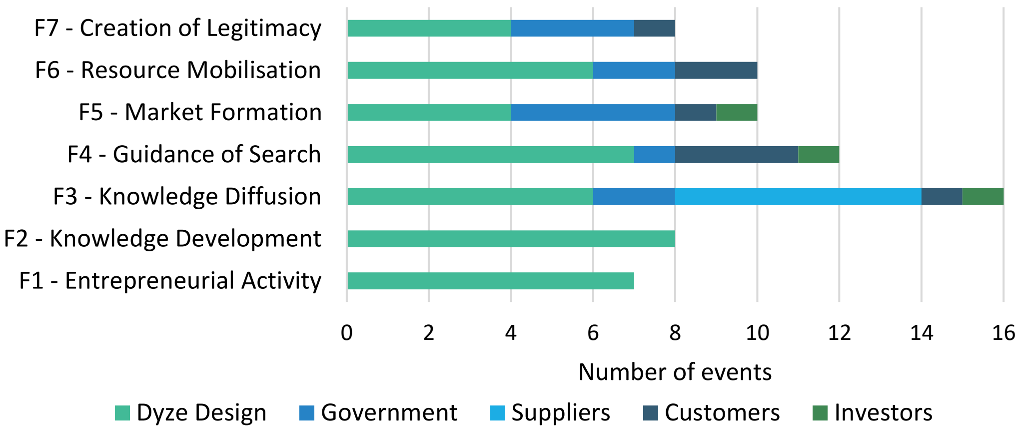


Figure 10.13: The number of events associated with the Development motor's functions and the actors who performed them

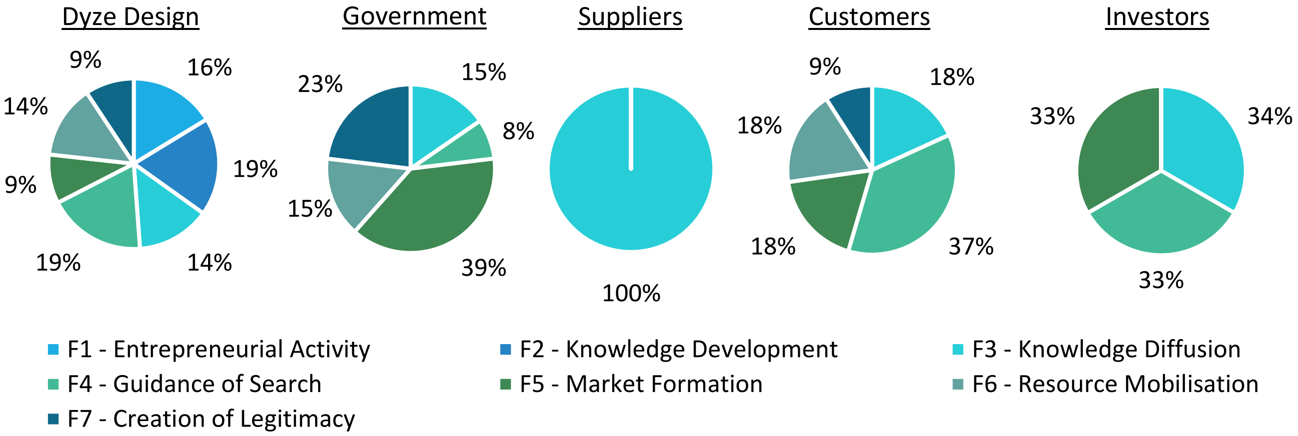


Figure 10.13: The case actors and the IS functions they performed during the Development stage

Design received the investments **[F6/RM]** and advocacy **[F7/CoL]** provided by the government and customers through innovation competitions' advocacy, grants and training and the crowdfunding campaign. As mentioned in §4.2, VoD authors often highlight the necessity of government support for niche markets and innovations[18],

[20], [141], [163], [174], [175]. Figure 10.13, Figure 10.13 and Figure 10.13 indicate that support for niche markets and innovations **[F5/MF, F7/CoL]** were predominantly offered by the government. This is due to the innovation competitions and training the government created for innovative start-up companies to mitigate the effects of the surrounding community's (investors) risk-averse culture **[-F3/KDif]** (Figure 10.13, Table 10.3). They also contributed to **[F6/RM]** as they rewarded grants to the competition winners. Thus, in this case, the government's supportive environment significantly impacted Dyze Design as they received funding, business training, and advocacy for their company brand. In this case, the government and intermediaries thus demonstrated that although funding is ideal, equipping small companies with the necessary business knowledge and *advocating* their approval of a company's brand provide tremendous support. Therefore, in line with the recommendations of the VoD authors [18], [20], [141], [163], [174], [175], the government fulfilled the role of the *Development motor's* external funder and support creators. Furthermore, the government-supported intermediaries fulfilled the role of external trainers through their development programmes.

In addition to the government, the customers also contributed to the **[F4/GoS, F5/MF, F6/RM, F7/CoL]**, indicating the support and funding they provided to Dyze Design during the crowdfunding campaign (Table 10.3). Furthermore, Dyze Design's customers and suppliers also contributed to the **[F3/KDif]** function, both as receivers and givers. This was done through supplier alliances and customer participation in the crowdfunding campaign. This is thus an indication of the start of the commercialisation of the nozzles and the bridge of the VoD. The case thus indicates the importance of awareness creation **[F3/KDif]** and governmental and intermediary advocacy coalition towards an innovation to bridge the VoD. Consequently, the suppliers and customers fulfilled the role of the suppliers and product end-users in the *Development motor*.

Given the sequence in which Dyze Design, the government, suppliers, customers and investors performed the functional interventions, they developed the *Development motor* mechanism, which enabled them to establish Dyze Design within the Montreal community and develop and produce hardmetal 3D printer nozzles. However, due to the risk-averse culture of the Montreal investors, Dyze Design did not gain investors to invest in Dyze Design and teach them business operations.

Therefore, Dyze Design hosted a crowdfunding campaign as a mitigation strategy and asked their customers to pre-order the nozzles. Furthermore, they participated in Government supported competitions to win business training opportunities. Consequently, Dyze Design raised more than double the goal amount for the nozzles' production and gained the necessary skills through the training initiatives. The capital outcomes Dyze Design achieved are Social, Financial, Human and Produced, as illustrated in Figure 10.14, along with the actors who triggered them.

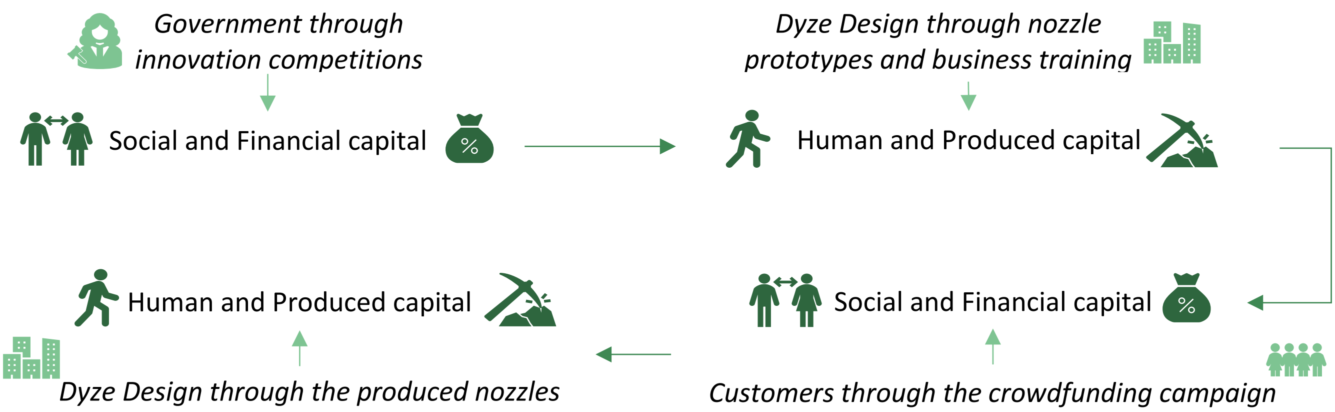


Figure 10.14: The development capitals Dyze Designed gained in the Development stage along with the actors who triggered them

Table 10.4: The CIMO interventions, mechanisms and outcomes of the Development motor along with the involved actors

<table>
<tr><th colspan="4">Intervention</th><th rowspan="3">Mechanism (Motor of innovation)</th><th colspan="3">Outcome</th></tr>
<tr><th rowspan="2">IS functions</th><th colspan="3">Actors involved</th><th rowspan="2">Objectives achieved</th><th rowspan="2">Unachieved objectives and the consequences thereof</th><th rowspan="2">Mitigation strategy and outcome achieved</th></tr>
<tr><th>Dyze Design</th><th>Government</th><th>Customers and suppliers</th></tr>
<tr><td>[F1] Entrepreneurial Activity</td><td>Resource acquisitionists (Company demonstrations)</td><td>-</td><td>-</td><td rowspan="7">The Development motor

F5 -> F1 -> F7 -> F6 -> F5

F1 -> F3 -> F2 -> F4 -> F1</td><td rowspan="7"><u>Primary objectives achieved</u>
• Establish Dyze Design in Montreal
• Produce hardmetal nozzles

<u>Capital outcomes achieved</u>
• Financial capital
Money through grants and the campaign.
• Produced capital
The produced hardmetal 3D printer nozzles.
• Human capital
Gained business skills and nozzle knowledge.
• Social capital
Relationships with suppliers, customers, and brand awareness.</td><td rowspan="7">Due to the risk-averse culture of the Montreal investors, Dyze Design did not gain investors to invest in Dyze Design and teach them business operations.
↓
Consequently, they did not have money for production or the desired business skills.</td><td rowspan="7">Dyze Design hosted a crowdfunding campaign and asked their customers to pre-order the nozzles.

Dyze Design participated in Government supported competitions to win business training opportunities.
↓
Dyze Design raised more than double the goal amount for the nozzles' production and gained the necessary skills at the training initiatives.</td></tr>
<tr><td>[F2] Knowledge Development</td><td>Product developers (R&D project)</td><td>-</td><td>-</td></tr>
<tr><td>[F3] Knowledge Diffusion</td><td>Product developers (Collaboration for R&D project)</td><td>Support creator (Development programmes)</td><td>End-users Suppliers (R&D and purchasing of the nozzles)</td></tr>
<tr><td>[F4] Guidance of Search</td><td>Product developers (R&D project)</td><td>-</td><td>-</td></tr>
<tr><td>[F5] Market Formation</td><td>-</td><td>Support creator (Innovation competitions)</td><td>-</td></tr>
<tr><td>[F6] Resource Mobilisation</td><td>Resource acquisitionists (Competitions and training)</td><td>Funder (Grants)</td><td>End- users (Purchasing of the nozzles)</td></tr>
<tr><td>[F7] Creation of Legitimacy</td><td>-</td><td>Support creator (Innovation competitions)</td><td>-</td></tr>
</table>

Finally, the Development stage's CIMO interventions, mechanisms, and outcomes are summarised in Table 10.4. This table is valuable for future decision-making as it provides insight into which activities (IS functions) were performed, by whom they were performed, the sequence in which they were performed, and the obtained outcome. Therefore, desired outcomes can be recreated with more ease in future endeavours as the mechanism and involved actors are known, while undesired mechanisms and outcomes may be mitigated.

10.4.2. CIMO analysis of the Entrepreneurial stage

Given the completion of the Development stage, the context of the Entrepreneurial stage is summarised in Table 10.5. Dyze Design still had limited capital which kept them from attending various trade shows (barrier). However, several entrepreneurial support organisations offered financial support to start-up companies (driver). Furthermore, 3D printers were becoming less expensive, making Dyze Design's nozzles too expensive (barrier). However, industrial 3D printing companies and universities were interested in Dyze Design's nozzles (driver). The government also encouraged university-industry relationships through tax incentives (driver).

Table 10.5: The Context defining the starting setting for the Entrepreneurial stage

Context steps	Dyze Design application
Defining the system boundary	The Dyze Design company from June 2018 to December 2021
Defining the phase of development	The nozzles' commercialisation and the company's expansion into the industrial 3D printing market.
Defining the system objective	Primary objectives: • Commercialise the hardmetal 3D printer nozzle. • Expand the company's international client base established with the crowdfunding campaign. Capital objectives: • Financial capital: Gain investment support and money to fund travels to tradeshows. • Produced capital: Develop marketable extruders with the 3D printer nozzles. • Social capital: Increase awareness and trust in the company's brand and products. • Human capital: Appoint a sales representative
Identifying the IS structures	Actors: • The Dyze Design team – enactors • The governmental award and funding organisation– selectors • Product end-users
	Networks: • Industrial 3D printing companies and universities were interested in Dyze Design's nozzles (driver).
	Institutions: • 3D printers were becoming less expensive, which meant that Dyze Design's nozzles were too expensive • Industrial 3D printing companies and universities were interested in Dyze Design's nozzles (driver). • The government also encouraged university-industry relationships through tax incentives (driver).
	Infrastructure: • Dyze Design has minimal financial and physical resources (barrier). • Several entrepreneurial support organisations offered financial support to start-up companies (driver).

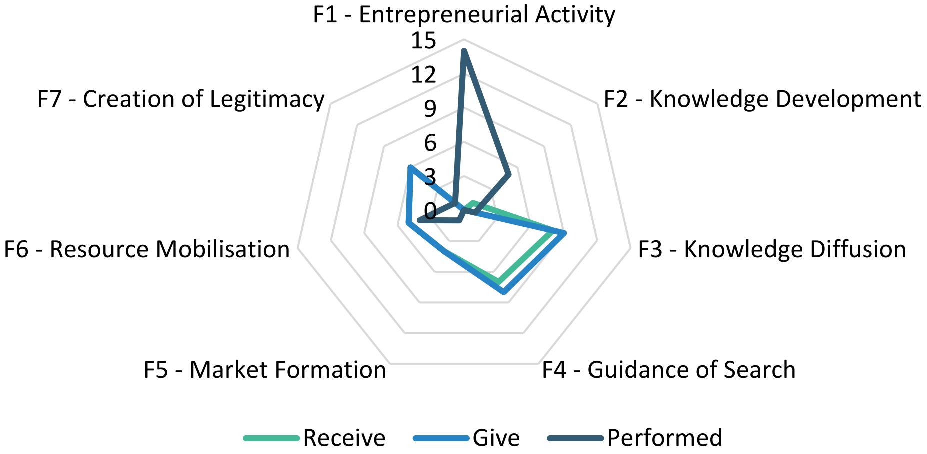


Figure 10.15: Give-and-Receive functional interaction map of the Entrepreneurial stage

Given this context, Figure 10.15 presents the Give-and-Receive graph of the Entrepreneurial stage's IS functions interacted in terms of giving and receiving. Figure 10.15 indicates that functions **[F1, F2]** were primarily performed most by actors indicating that activities such as projects with commercial aims and research studies were not shared between actors, but conducted by, from Figure 10.8, Dyze Design. Furthermore, **[F3, F4]** were given and received most by actors, indicating that activities such as communicating vision, research outputs and expectations, alliances between actors, awareness campaigns, and conferences were often shared between actors. Functions **[F5, F6, F7]** were also shared (given and received) amongst actors. To determine how the given and received functions correspond to the performed functions, the sequence in which the functions were performed may be traced.

In the Nozzle commercialisation period, Dyze Design aimed to expand their international client base **[F1/EA]**, established through the Kickstarter campaign. Therefore, they explored new channels to promote and sell their products to international customers **[F3/KDif, F4/GoS]**. These channels included international internet stores, their website, and the most successful channel, exhibiting at trade shows. At the trade shows, Dyze Design sold their nozzles **[F3/KDif, F4/GoS, F6/RM]**, identified global AM trends, realised that their nozzles were too expensive for their target audience **[F4/GoS]** and identified an opportunity to develop industrial 3D printer nozzles **[F1/EA, F4/GoS]**. They, therefore, designed **[F2/KDev]** the nozzles in collaborated with their suppliers [**F3/KDif]** to produce the industrial nozzles and released prototypes into the market to gain the market's feedback [**F4/GoS]** before commercialising them **[F1/EA]**.

During the company expansion period of the entrepreneurial stage, Dyze Design realised that they had to change some of their business processes. Therefore, they explored and found new channels to promote and sell their products to international customers **[F3/KDif, F4/GoS]**, such as through internet stores, electronic store websites and exhibiting at trade shows **[F1/EA, F6/RM]**. As a result, Dyze Design reached numerous international customers and established R&D partnerships and collaborations with several German, Dutch, and Canadian universities **[F3/KDif]**. They also competed in more innovation competitions **[F5/MF, F7/CoL]** and collaborated with government-supported initiatives to raise funding to attend the trade shows **[F5/MF]**.

As Dyze Design once again manufactured nozzles and participated in government-supported initiatives, the Development motor continued. However, as the entrepreneurial stage aimed to increase the company's client base, an additional entrepreneurial loop that includes this aim may be considered. As the entrepreneurial loop led to increases in sales and the identification of an opportunity to manufacture the new nozzles and increase the company's product range and client base, the loop may be added to the Development motor, namely an entrepreneurial loop. Therefore, as presented in Figure 10.16, the original Development motor (loops 2 and 3) may be drawn with an additional entrepreneurial loop (loop 1).

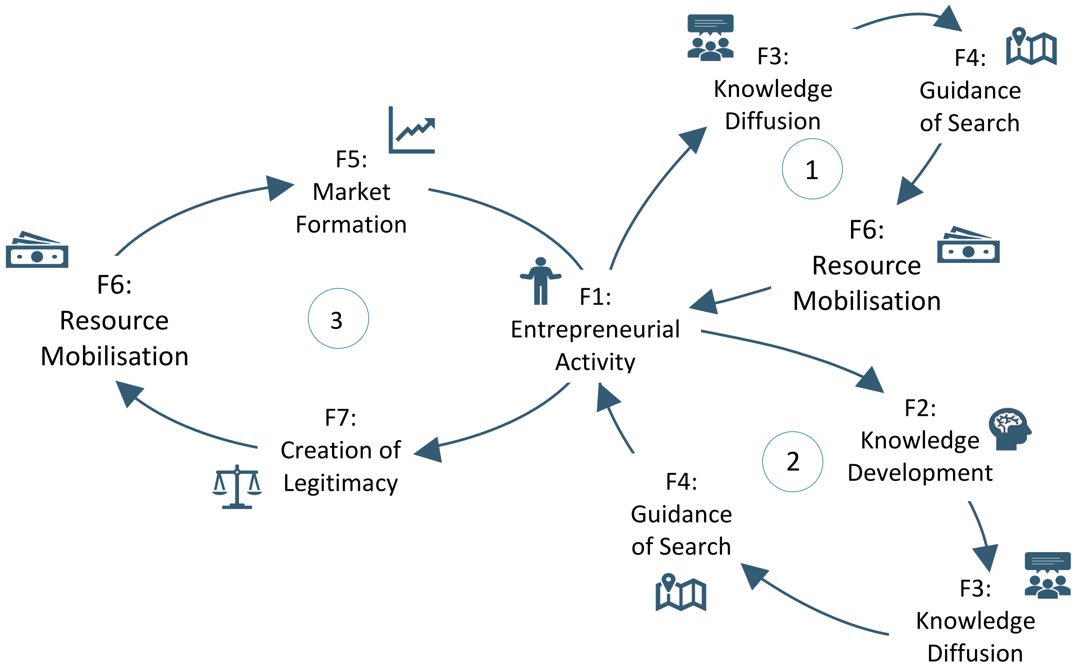


Figure 10.16: The Development motor with the entrepreneurial loop (loop 1)

To determine the impact the driver and barrier IS structures had on the *Entrepreneurial motor* and thus the entrepreneurial stage, Table 10.6 was developed. To determine the functional contribution of each of the *Development motor*'s actors, Figure 10.19, Figure 10.19 and Figure 10.19 were developed. Figure 10.19, Figure 10.19 and Figure 10.19 indicate that Dyze Design performed the *Development motor's* **[F1/EA]** and primarily gave the **[F2/KDev, F3/KDif]** functions. This is due to all the demonstrations and collaborations they performed to expand their client base and the new product distribution channels (portfolio expansions) they pursued to suit the profiles of their new clients. They also identified the market opportunities to develop a range of industrial nozzles (fundamental research at firm-level recommended by [20], [175]) and nozzles for university research groups (academic-industry collaboration recommended by [18], [20], [174]).

Furthermore, Dyze Design primarily contributed to **[F6/RM]** as they raised income from the nozzles they sold through their distribution channels and appointed a sales representative to tend to the needs of their new clients. Additionally, Dyze Design received customer investments **[F6/RM]** and advocacy **[F7/CoL]** from the innovation competitions, industrial customers and academia. Consequently, Dyze Design once again performed the role of the product developer. However, in contrast to the *Development motor's* resource acquisitionists, Dyze Design performed the role of entrepreneurs due to the creative channels they implemented and the collaborations they established to sell their products. The case, therefore, demonstrates that the *Development motor* requires resource acquisitionists to develop inventions while entrepreneurs are required to commercialise the inventions to innovations in the *Entrepreneurial motor*.

Figure 10.19, Figure 10.19 and Figure 10.19 indicate that the government and the intermediaries performed **[F5/MF]**. This is again due to the government's supportive environment through innovation competitions (Table 10.6), where they advocated for the winner's brands. In addition, they also supported Dyze Design's travels to trade shows through government-supported financial support **[F6/RM]** organisations and provided tax incentives when Dyze Design collaborated with the universities in their surrounding community, in line with the triple-helix model the VoD authors recommended [18], [20], [174]. The government, therefore, again fulfilled

Table 10.6: The structural components and their drivers, barriers and impacts of the Entrepreneurial stage

	Actors	Interactions	Institutions	Infrastructure
Drivers	• Dyze Design's researchers and marketing partner promoting their products at trade shows. • Dyze Design's researchers developing new industrial printer components. • Dyze Design's managing partners, who upgraded the company's business, is the primary selector. • The primary selector is the Canadian government, who financially supports financial and entrepreneurial support organisations and encourages university-industry relationships.	• Dyze Design established important relationships with the internet stores and their customers at the trade shows they attended. • Dyze Design established R&D relationships with several German, Dutch, and Canadian universities. • The Canadian government encourages and stimulates university-industry relationships through tax incentives.	• Industrial 3D printing companies were investing in Dyze Design's hardmetal nozzles and extruders. • Dyze Design aimed to improve its global market credibility. • Universities were motivated to collaborate with Dyze Design as their products were high-quality and not as expensive as their competitors.	• The Kickstarter platform established an international customer base. • Dyze Design appointed a sales representative. • Dyze Design increased its investment in trade shows and sold many of its products there. • Dyze Design partnered with organisations such as LOJIQ and Del for financial and entrepreneurial support. • The Canadian supports Dyze Design's relationship with the engineering universities through tax incentives of the internship salaries.
Barriers	• 3D printer enthusiasts wanted less expensive 3D printer components. • Dyze design had limited capital resources to appoint a new sales representative.	• Exhibiting and travelling to trade shows were expensive, so Dyze Design could not attend all the trade shows hosted during this period.	• Personal 3D printers were becoming less expensive. Therefore, customers demanded cheaper components. • Dyze Design had to change some of its business approaches to accommodate the profile of its new industrial clients.	• Exhibiting and travelling to trade shows were expensive. • Dyze Design had to change some of its business approaches to accommodate the profile of its new industrial clients. • Dyze Design had limited capital resources.
Impacts	• Dyze Design launched a second R&D project. • Dyze Design exhibited at several intentional trade shows.	• Dyze Design established R&D partnerships and collaborations with several German, Dutch, and Canadian universities	• Dyze Design identified an opportunity to produce products for the industrial 3D printing market. • Dyze Design won an innovation award. • Dyze Design started to write more scientific literature whitepapers.	• Dyze Design changed its sales and customer interaction approach and appointed a sales representative. • Dyze Design exhibited at several intentional trade shows.

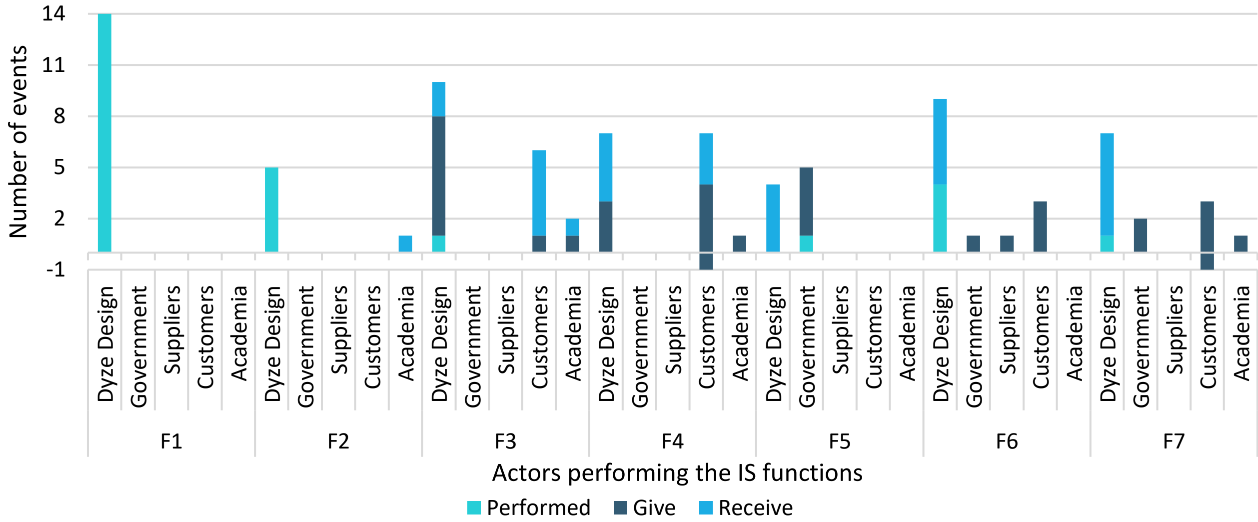


Figure 10.19: The functional Give-and-Receive map of the Entrepreneurial motor's actors

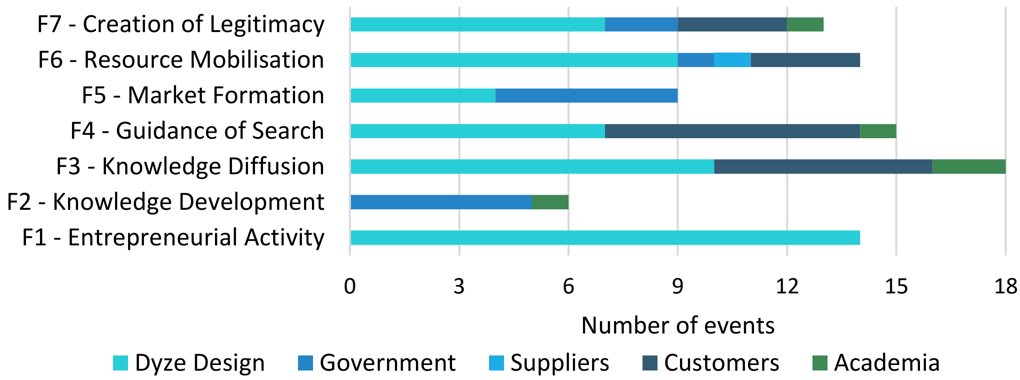


Figure 10.19: The number of events associated with the Entrepreneurial motor's functions and the actors who performed them

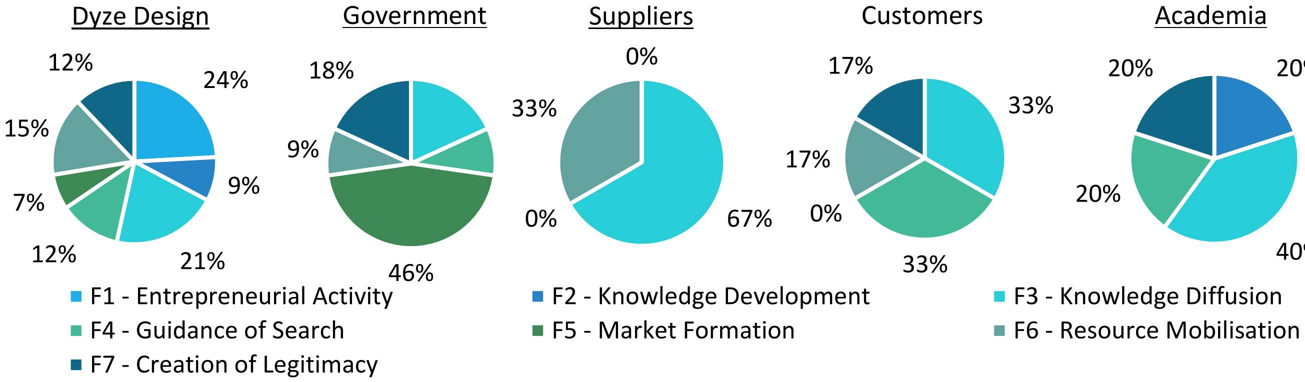


Figure 10.19: The case actors and the IS functions they performed during the Entrepreneurial stage

the role of an external funder and the intermediaries of the support creators. However, the supporting role of the government in the *Entrepreneurial motor* is less significant than in the *Development motor,* as Dyze Design raised capital through the commercialisation of their nozzles to customers and universities (end-users).

Therefore, this case study indicates that less governmental and intermediary support is required during the *Entrepreneurial motor* than the *Development motor* as the *Entrepreneurial motor* builds on the client base and brand awareness created in the *Development motor,* and money is raised internally from the nozzles sold to end-users.

The customers once more contributed to **[F3/KDif**, **F4/GoS**, **F6/RM, F7/CoL]**, indicating that they shared their expectations with Dyze Design, collaborated with them, and invested in their products through the online stores and trade shows. Consequently, customers once more fulfilled the role of the product end-users in the *Entrepreneurial motor*.

Furthermore, academia contributed to **[F2/KDev, F3/KDif, F4/GoS, F7/CoL]** as several universities valued Dyze Design's nozzles and collaborated with them to develop nozzles for their research groups (Table 10.6). Additionally, the university students from the nearby community who participated in their internship programs contributed to these functions. Numerous VoD authors [18], [20], [163] have encouraged academic-industry collaboration to enable the commercialisation of academic inventions. This case, however, proved that academia might also fulfil end-user roles in the academic-industry collaboration when they collaborate to use the industry products that have already crossed the VoD.

Given the context in which Dyze Design sold their nozzles and expanded their company and the functional interventions they, the government, customers, suppliers, and academia performed, the *Entrepreneurial motor* mechanism was developed. This motor enabled Dyze Design to achieve its primary objectives of commercialising the hardmetal 3D printer nozzles and expanding the international client base established with the crowdfunding campaign. A new market segment, the industrial 3D printing market, was also identified and entered.

The capital outcomes Dyze Design achieved are Social, Financial, Human and Produced, as illustrated in Figure 10.20 along with the actors who triggered them. Furthermore, the Entrepreneurial stage's CIMO, interventions, mechanisms, and outcomes are summarised in Table 10.7.

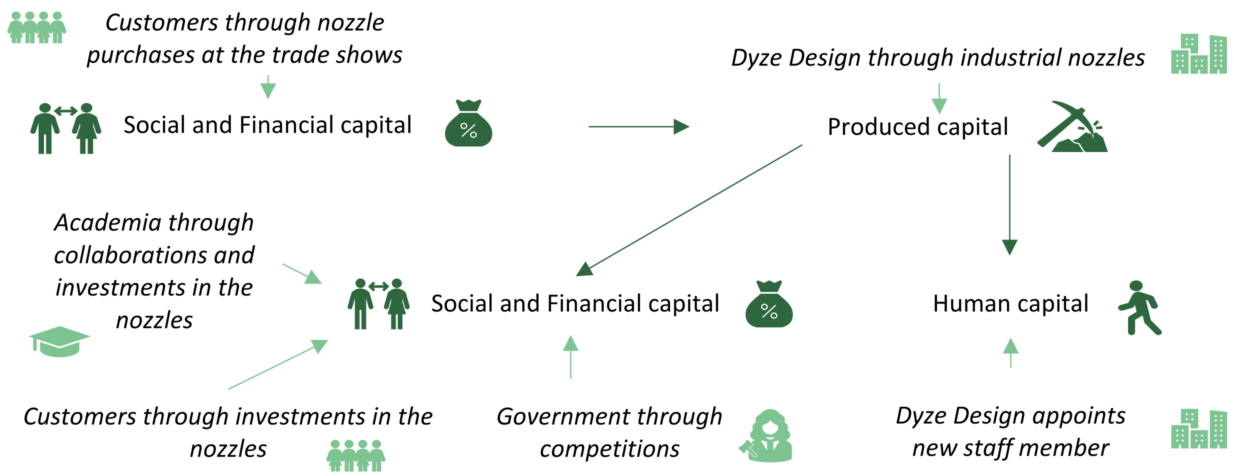


Figure 10.20: The development capitals Dyze Designed gained in the Entrepreneurial stage along with the actors who triggered them

10.5. Chapter 10: Conclusion

This chapter explored the dynamics of a start-up company developing and commercialising a new product. The CIMO-based EHA framework was used to analyse the case of Dyze Design's hardmetal 3D printer nozzle from 2015 to 2021. Dyze Design was selected as they are a multi-award-winning start-up company from Montreal, Canada, which grew rapidly due to the commercialisation of their hardmetal 3D printer nozzles. The chapter started with an introduction to the case actors, and thereafter the research project was narrated. Subsequently, the CIMO-based EHA framework's CIMO steps were applied. First, the CIMO interventions and mechanisms identified the Development motor responsible for idea conceptualisation to product development and testing phases. Dyze Design, the government, customers, and suppliers contributed to the functions of the Development and delivered the financial, produced, human and social capitals. Figure 10.22 summarises the Development motor.

Furthermore, CIMO interventions and mechanisms identified the Entrepreneurial motor responsible for the commercialisation of the nozzles and the development of subsequent products. Dyze Design, the government, customers, suppliers, and academia contributed to the functions of the Entrepreneurial motor and delivered the social, financial, human, and produced capitals. Figure 10.21 summarises the Development motor. This chapter contributes to objectives IV and V, as mentioned in §1.4.

Table 10.7: The CIMO logic and actors of the Entrepreneurial motor

<table>
<tr><th colspan="5">Intervention</th><th rowspan="3">Mechanism (Motor of innovation)</th><th rowspan="3">Outcome</th></tr>
<tr><th rowspan="2">IS functions</th><th colspan="4">Actors involved</th></tr>
<tr><th>Dyze Design</th><th>Government</th><th>Customers and suppliers</th><th>Academia</th></tr>
<tr><td>[F1] Entrepreneurial Activity</td><td>Entrepreneur (Nozzle sales)</td><td>-</td><td>-</td><td>-</td><td rowspan="6">F1 -> F3 -> F4 -> F6

F5 -> F6
F5 -> F7 -> F1</td><td rowspan="6"><u>Primary objectives achieved:</u>
Commercialise the hardmetal 3D printer nozzle. Expand the international client base established with the crowdfunding campaign.
<u>Capitals achieved:</u>
• Financial capital
Money raised through sales at tradeshows and grants.
• Produced capital
Produce products for the industrial 3D printing market and academia.
• Social capital
Established relationships with international clients and universities and won two innovation prizes.
• Human capital
Appointed a sales representative.</td></tr>
<tr><td>[F3] Knowledge Diffusion</td><td>Product developer Entrepreneur</td><td>-</td><td>End-users (Purchasing of the nozzles)</td><td>End-users (R&D of the nozzles)</td></tr>
<tr><td>[F4] Guidance of Search</td><td>Product developer Entrepreneur</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>[F5] Market Formation</td><td>-</td><td>Support creator (Competitions, tax incentives, support organisations)</td><td>-</td><td>-</td></tr>
<tr><td>[F6] Resource Mobilisation</td><td>Entrepreneur (Nozzle sales)</td><td>Funder (Support organisations)</td><td>End-users (Purchasing of the nozzles)</td><td>End-users (Purchasing of the nozzles)</td></tr>
<tr><td>[F7] Creation of Legitimacy</td><td>Entrepreneur (Innovation competitions)</td><td>Support creator (Innovation competitions)</td><td>-</td><td>-</td></tr>
</table>

Dyze Design was established in a risk averse community in Canada where the local and national Government tried to stimulate, and support innovate companies through funding, training, and lobbying opportunities.

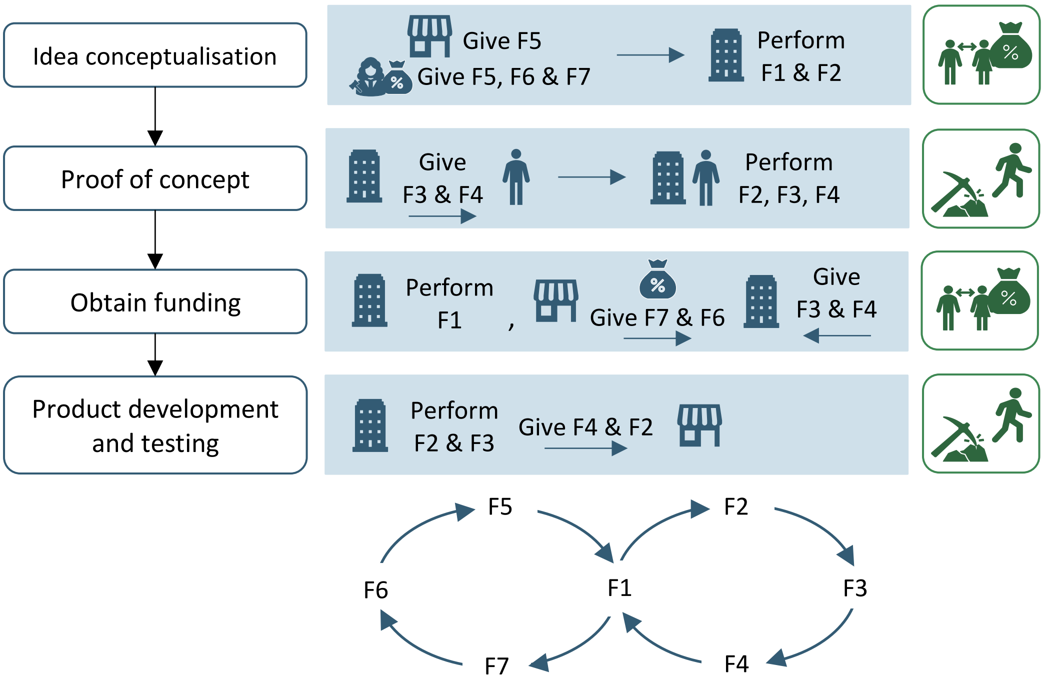


Figure 10.22: Case III's Development motor, along with the actors performing the functions and the development capitals developed

Dyze Design wants to commercialise the hardmetal 3D printer nozzles expand the company's international client base established with the crowdfunding campaign. They continue to participate in the initiatives funded by the government.

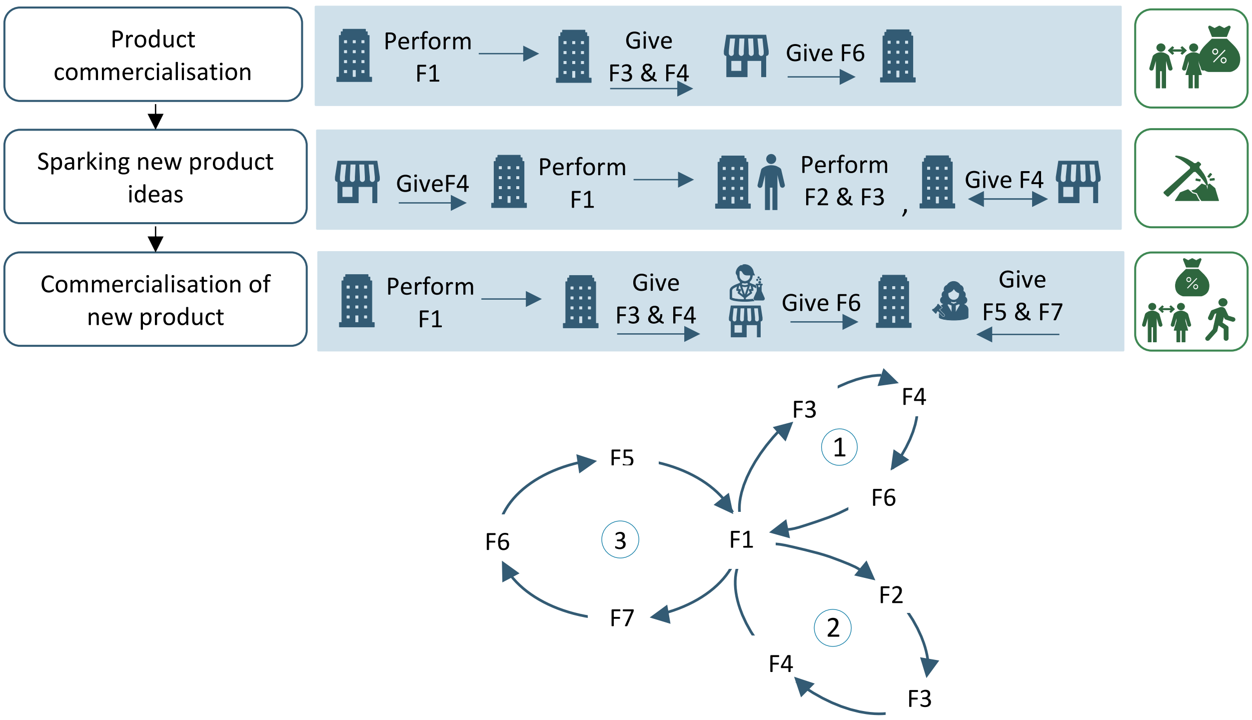


Figure 10.21: Case III's Entrepreneurial motor, along with the actors performing the functions and the development capitals developed

Chapter 11

Case IV: Sandvik and Varel's high-precision nozzles

The previous chapter studied the development of a Canadian start-up company to gain insight into the dynamics involved in developing an emergent company implementing a novel technology, namely additive manufacturing. This chapter explores the dynamics of a research and development project conducted by a well-established Swedish multinational engineering company that developed an AM process and collaborated with a subsidiary company to improve their process and apply it to a product. The CIMO-based EHA framework is used to analyse the collaboration project between Sandvik and Varel to manufacture high-precision cemented carbide oil drilling nozzles using Sandvik's AM process. As Sandvik has an AM R&D Centre and is known to be the market leader the South African hardmetal enterprises look up to, this project was selected for study. It sheds light on world-class engineering companies' innovation activities and their R&D projects and commercialisation processes. Furthermore, as the R&D activities were supported by Sandvik and performed by both Sandvik and Varel, no governmental assistance was required. Therefore, in contrast with the previous cases, this case only involves industry actors. This case study's position in the framework is indicated in Figure 11.1 in dark blue, while the previous cases are indicated in light, transparent blue. This chapter contributes to objectives IV and V, as mentioned in §1.4.

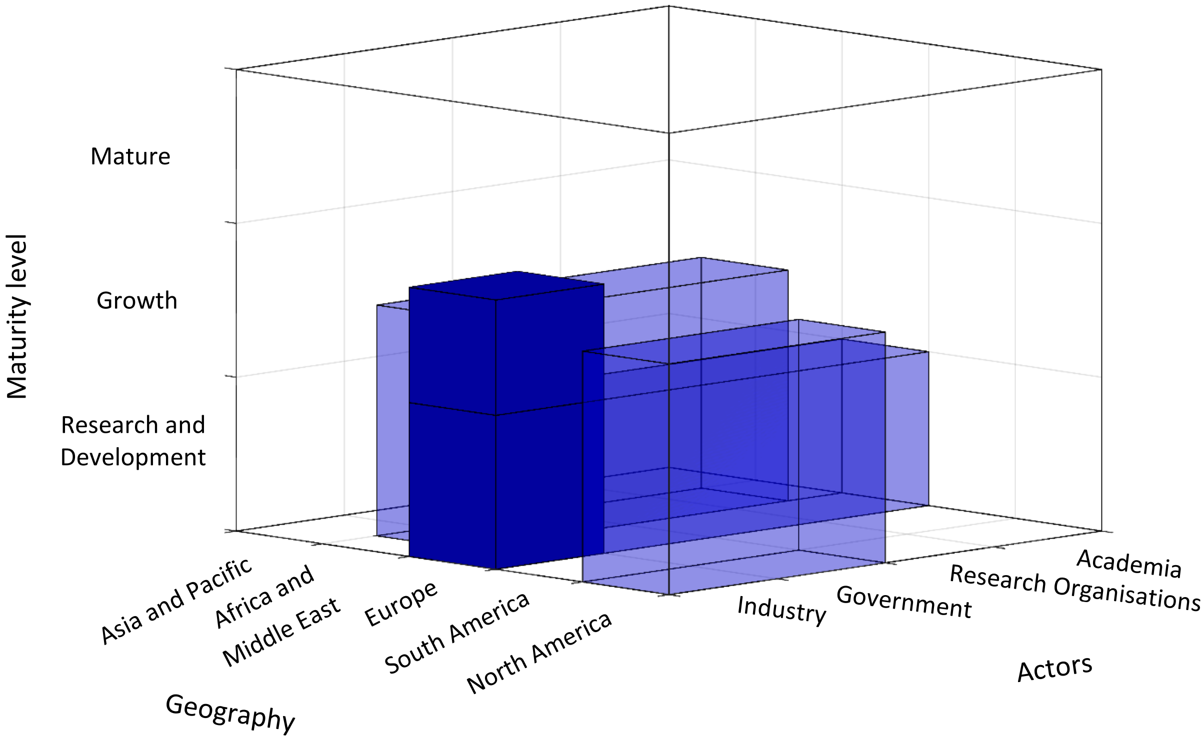


Figure 11.1: Fourth case in case study framework

The chapter starts with an introduction to the case approach, the companies, and the nozzles. Then, subsequently, the case study is presented as a narrative. Thereafter follows the application of the CIMO-based EHA framework's four steps. The chapter continues with the *context* definition of the case. Thereafter, the narrated is analysed to identify the *interventions and mechanisms* present in the case. The chapter then concludes with the identification of the case *outcomes and outputs* delivered by these *mechanisms.*

Chapter 11 contribution:

- Through the application of the CIMO-based EHA framework, this chapter contributes an analysis of the underlying dynamics and mechanisms established manufacturing enterprises use to commercialise their products and gain market share.

Chapter 11 objectives:

- Provide background of the research collaboration project between Sandvik and Varel (§11.2).
- Narrate the Varel high-precision nozzles case (§11.3).
- Identify the context and motors of innovation that led to development (§11.4.1).
- Identify the underlying structural drivers and barriers of the motors of innovation (§11.4.1).
- Identify the influence these IS structures and motors of innovation have on the outcomes and outputs of the case (§11.4.2).

11.1. Case approach

The R&D project studied for this case involves an established, international company with an additive manufacturing (AM) R&D centre. The company has over a hundred and fifty years of experience, a knowledge base of cemented carbides that date back eighty years, and an extravagant R&D budget. The objective of the AM R&D centre is to evaluate the capability of the AM printing technologies and different materials to identify opportunities for the company to firmly establish itself within the global AM market. In addition to improving the products available in the global AM market, the centre aims to develop products and technologies that add value to its customers' products.

This case, therefore, differs from the previous case and thus sheds light on a few new dynamics. Firstly, this case provides insights into the dynamic and innovation processes involved when an established manufacturing company implements new technology. Secondly, insight is gained into the R&D approach large companies apply to new technology, their R&D objectives, and the resources they are willing and able to invest. Finally, the case sheds light on the procedures established companies follow to evaluate and further develop and commercialise their R&D findings.

The focus of this case is AM technology. Sandvik developed an AM process for hardmetals and collaborated with Varel to further develop their process and apply it to Varel's nozzles. Therefore, the technology innovation system (TIS) perspective is applied in this case. The CIMO-based EHA framework is again used to analyse the dynamics and evolution of this case. Although the high-precision nozzles developed in this case have been approved for production, the project evolution was never documented. Therefore, no literature on the project evolution was available in the public domain. Consequently, several semi-structured interviews were conducted with the Sandvik staff members involved with the nozzles. They told and verified the nozzle project's innovation success story, detailed the drivers and barriers experienced, and validated the final analysis conducted on the narrative. Rabionet's [18] six-step interview process (*§*6.4) guided the interviews, while Cresswell's [7] qualitative data analysis process (*§*6.5) was used to collect and code the event data in a database.

The following sections will look at the progressive development of a research and development project conducted by a Swedish multinational engineering company. By analysing the project from 2016 to 2021 through the TIS perspective and the CIMO-based EHA framework, motors of innovation and underlying structural drivers and barriers may be identified to answer §1.3's case study research questions.

11.2. Introduction to Sandvik and Varel

Sandvik is a global industrial group founded in 1862 in Sweden [405]. Sandvik specialises in the R&D, production, and sales of products and services within four business solutions: manufacturing and machining, mining and construction, rock processing, and materials technology [406]. The Sandvik Group is known for their advanced products. They are world leaders in metal cutting, equipment and tools for mining and construction, stainless materials, special alloys, metallic and ceramic resistance materials, and process systems. They also strongly focus on cemented carbide as they are one of the largest cemented carbide suppliers in the world.

From 2014 to 2019, Varel Energy Solutions (Varel) were part of the Sandvik group [407], [408]. Varel is a global supplier of drilling solutions, particularly drill bits and downhole products for well construction and completion [3]. The oil and gas sector is their primary customer segment.

Before Varel collaborated with Sandvik, they manufactured and used high precision hardmetal nozzles to inject fluid across their fixed cutter bits during underground hard-rock drilling. As a result, the cutter bits and nozzles were exposed to extreme hydraulic conditions [409]. The hardmetal nozzles had a sophisticated, hydrodynamic design that optimised fluid flow for more efficient cooling and cleaning, leading to faster cutting, evacuation of drill debris and optimised hydraulic energy usage. As the nozzles were manufactured with traditional, time-consuming processes with long lead times, Varel kept high inventory levels to serve their customer demand.

In 2016, Sandvik and Varel initiated a collaboration project (Figure 11.2) to develop additively manufactured hardmetal nozzles for Varel's drill bits. Varel's initial interest in the collaboration was to achieve shorter lead times to reduce the stock levels of their existing nozzles. Sandvik was interested in determining its binder jetting AM processes' capabilities and starting its journey as a competitor in the global AM market. In addition, they aimed to create nozzle designs that were impossible to manufacture with the traditional manufacturing techniques and develop nozzles that add real value to Varel's drilling solutions. Sandvik believed that the nozzles were a very inexpensive consumable of Varel's drilling solution that had to be replaced after, for example, every 1000 meters of drilling, reducing the nozzles' price and production lead

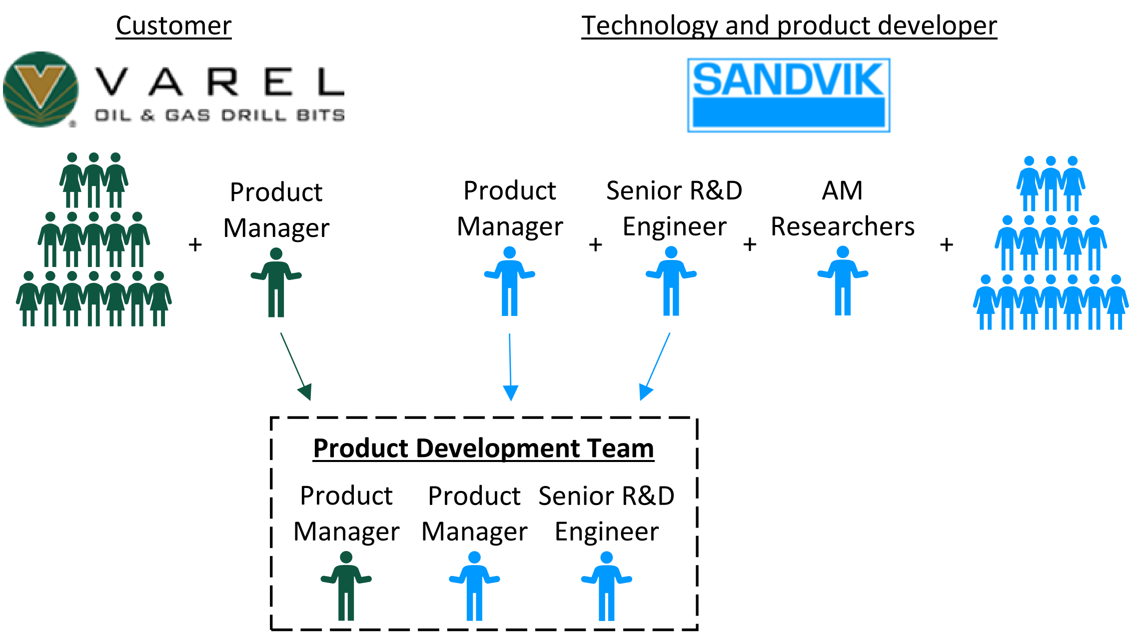


Figure 11.2: The actors from Varel and Sandvik AM who collaborated to develop the AM hardmetal nozzles

times were not adding real value to Varel's drilling solutions. Sandvik, therefore, aimed to develop high-precision nozzles with increased durability and injection efficiency that would last for, for example, 1500 meters or 2000 meters of drilling, which would reduce the overall component replacement time of the entire drilling solution. Thus, instead of saving Varel hundreds of dollars on the nozzles, Sandvik would save them thousands of dollars due to their drilling solutions' reduced drilling time. Figure 11.3 presents an example of two of Varel's drill bits with the hardmetal nozzles near the drill's cutting edges.

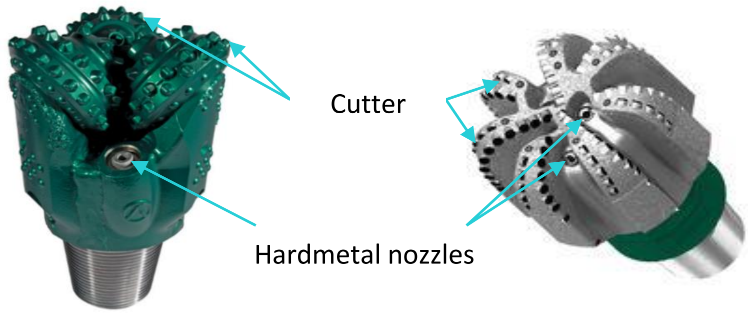


Figure 11.3: Examples of the hardmetal nozzles in the Varel roller cone and fixed cutter drill bits

11.3. The event history of Dyze Design's Hardmetal Nozzle

This section outlines the development of Sandvik and Varel's high-precision nozzles from 2013 to the end of 2021 as a chronological narrative. The IS functions corresponding to the events are denoted by **[F1/EA, F2/KDev, … F7/CoL]** along with a `-1 or 1' to indicate their influence, and a **(P)**, **(G)** or **(G)** to indicate whether functions were performed, given, or received. Furthermore, events related to Sandvik, their AM researchers, their product manager, Varel and the product development team (Figure 11.2) are indicated as **[San]**, **[SanR]**, **[SPM]**, **[Varel]**, and **[PDT]**, respectively. In addition, although Figure 11.2 indicates that Sandvik's senior R&D engineer and product manager are members of the product development team, their roles prior to the collaboration are noteworthy. Therefore, they are coded separately prior to the collaboration. Finally, Figure 11.4 summarises the narrative's main events. *Readers may therefore skip the period description to the summary figure.*

In 2013, Sandvik established a centrally funded AM R&D Centre **[San (P) F1/EA, F6/RM]**. The centre's objective was to test the capability of the AM printing processes and start the journey to become a global competitor in the AM market **[San (P) F4/GoS]**. They evaluated different AM technologies and had a specific interest in binder jetting. Furthermore, as Sandvik has an extensive application in the mining industry, they evaluated various hard and robust materials, such as cemented carbides and different tool steels **[SanR (P) F2/KDev]**.

In 2015, researchers from the AM R&D centre started testing cemented carbide printing **[SanR (P) F2/KDev]**. Their objective was to develop cemented carbide printing processes to manufacture high-quality hardmetal products that could be implemented in the mining industry **[SanR (P) F4/GoS]**. In early 2016, the researchers developed a binder jetting method to print good-quality cemented carbides **[SanR (P) F2/KDev]**. As the researchers had been busy with R&D projects for almost three years, Sandvik was anxious to identify application opportunities and commercialise some of their findings, amongst them the binder jetting method for cemented carbides **[San (G), SanR (R) F4/GoS]**.

In April 2016, the AM researchers contacted a product manager from the carbide division within the Sandvik group **[SanR (G), SPM (R) F3/KDif]**. The product manager was knowledgeable of Sandvik's carbide products and the carbide market, so the researchers informed him of their binder jetting progress with cemented carbides. They invited him to join them at the AM centre to assist them with the commercialisation of their R&D findings **[SanR (G), SPM (R) F4/GoS]**. A few R&D findings were presented to the product manager and considered for further development and commercialisation. However, as there were no suitable economic market opportunities, they were eliminated **[SanR (R) F4/GoS, SPM (G) -F4/GoS]**. Industry was still sceptical about AM technology as the manufacturing time was much slower than the traditional manufacturing technologies and a lot more expensive **[SPM (P) -F5/MF]**. Furthermore, industry partners who were excited to invest in AM technology were unfamiliar with cemented carbide materials **[SPM (P) -F5/MF]**. As it was Sandvik's culture to develop new technology in collaboration with customer products, finding a collaboration partner was essential. Therefore, as Varel was part of the Sandvik group, collaboration and application opportunities with Varel were considered feasible **[SanR (R) F4/GoS, SPM (P) F5/MF, (G) F4/GoS]**.

As Sandvik had a manufacturing technology and was looking for possible applications, Sandvik's senior R&D engineer contacted Varel to share their binder jetting progress **[SanR (G) F4/GoS, F7/CoL, Varel (R) F4/GoS]**. In addition, he invited Varel to share their ideas for (new) products that could be improved or developed with Sandvik's binder jetting process **[SanR (G), Varel (R) F4/GoS, F7/CoL]**. Several months later, Varel aspired to reduce its nozzle stock levels. Varel then contacted Sandvik and proposed their cemented carbide nozzles as an application for Sandvik's binder jetting process **[Varel (G), SanR (R) F4/GoS]**.

In May 2017, Sandvik's senior R&D engineer and carbide product manager submitted their collaboration proposal to Varel **[SanR (G), SPM (G), Varel (R) F3/KDif, F4/GoS]**. In June 2017, Sandvik's senior R&D engineer and product manager and Varel's product application manager officially launched the R&D to develop their cemented carbide nozzles with the binder jetting technology **[PDT (P) F1/EA, F2/KDev, F3/KDif]**. The project had no predetermined timeline or budget, only an objective to manufacture implementable cemented carbide nozzles and add value to Varel's drilling solutions **[San (G), PDT (R) F4/GoS, F6/RM]**.

The product development team commenced work to print externally threaded cemented carbide nozzles **[PDT (P) F2/KDev]**. As the binder jetting printing process was used, it was essential to evaluate the nozzles' metallurgical and mechanical properties in parallel with the geometrical capabilities. For the following year, the three collaborators studied and developed the AM process in parallel with the development of the nozzles **[PDT (P) F2/KDev]**.

By May 2018, the collaborators realised that the binder jetting process was not sufficient for the stable production of the threaded nozzles **[PDT (P) F2/KDev, PDT (G), Varel (R), San (R) -F7/CoL]**. The nozzles required precision threads that the process could not deliver as deformations occurred in the subsequent sintering processes. In addition, the team realised that, although the AM process would reduce the nozzle lead times by 50-70%, it would not improve Varel's drilling performance and could be manufactured with traditional manufacturing techniques **[PDT (G), Varel (R), San (R) -F4/GoS, -F7/CoL]**. Therefore, the collaborators decided to investigate new nozzle designs that were impossible with traditional manufacturing techniques **[PDT (P) -F2/KDev]**.

In June 2018, the collaborators commenced work on the second-generation nozzles **[PDT (P) F1/EA, F2/KDev, F3/KDif]**. These nozzles were easier to manufacture with AM as they had no threads. The nozzles also had curved internal channels to optimise the fluid injected across the drill cutter bits. The curved channels improved the nozzles' performance and increased the entire drill bits' performance. As a result, the drill bits could drill faster, more efficiently and for more extended continuous periods, reducing drilling time in the field and thus adding significant value to Varel's drilling solutions. The curved channels of the nozzles were also impossible to manufacture with traditional techniques but very easy to manufacture with the binder jetting process. It, therefore, also correlated with Sandvik's objective to create real value with AM technology **[PDT (G), San (R) F4/GoS]**. Therefore, it was decided that all the research efforts and resources would be redirected towards the second-generation nozzles **[PDT (R), San (G) -F6/FM, San (G), PDT (R) F6/RM]**. Consequently, in July 2018, the threaded nozzles (first-generation nozzles) were put on hold indefinitely **[PDT (P) -F1/EA, -F2/KDev]**.

The development and refinement of the second-generation nozzles continued for a year **[PDT (P) F2/KDev]**. Finally, in June 2019, the nozzles were ready for laboratory testing **[PDT (P) F2/KDev]**. As the nozzles passed their laboratory testing **[PDT (P) F2/KDev, F7/CoL]**, the nozzles were prepared for field testing by August 2019. Therefore, the product development team applied for an opportunity to field test the nozzles at Varel's facilities **[PDT (G), Varel (R) F4/GoS]**. As Varel was busy with numerous other projects, the field testing of the nozzles commenced in September 2020 **[Varel (P) F2/KDev]**. By June 2021, the field testing successfully **[Varel (P), F2/KDev, Varel (G), PDT (R) F7/CoL]** concluded. Consequently, the nozzles were ready to be manufactured and implemented into Varel's drilling solutions **[PDT (P) F2/KDev, PDT (G) F4/GoS, F7/CoL, Varel (R) F4/GoS, Sand (R) F7/CoL]**.

As good progress was made with the second-generation nozzles, further funding was obtained **[San (G), PDT (R) F6/RM]**. The collaborators commenced designing the third-generation nozzles in May 2021 **[PDT (P) F1/EA, F2/KDev, F3/KDif, F7/CoL]**. These nozzles will have even more advanced geometrical and mechanical properties and will be impossible to manufacture with traditional manufacturing techniques. The third-generation process will add more value to Varel's drilling solutions as they enable improved quality with improved directional and precision flow under higher pressures **[PDT (G), San (R) F7/CoL]**. The third-generation process will also allow Sandvik to produce an even broader product range **[PDT, San F7/CoL]**.

Throughout the development of the three nozzle generations, the collaboration between the product development team members grew into a partnership **[PDT (P) F3/KDif]**. Therefore, although Varel is no longer part of the Sandvik group, the collaboration between the two groups continues, and more products for different applications are currently being developed **[San (P), Varel (P) F1/EA, F2/KDev]**. Figure 11.4 presents Case IV's milestone events - the blue lines indicate Sandvik's milestones, the light green dots are the millstones of the nozzle generations, and the dark green diamonds are the research activities. Table 11.1 depicts the drivers, barriers and impacts of Case IV's IS structures.

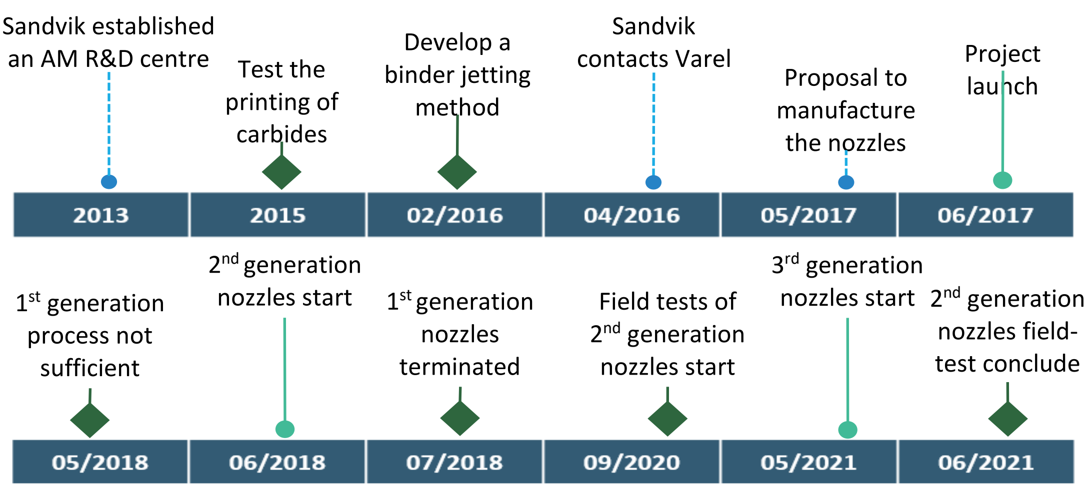


Figure 11.4: Timeline of Varel's high-precision nozzles project

Table 11.1: The structural components and their drivers, barriers and impacts of Varel's high-precision nozzles project

	Actors	Interactions	Institutions	Infrastructure
Drivers	• The primary enactors were Sandvik's senior AM R&D researcher and Varel's product application manager, who designed and developed the nozzles. • Sandvik's carbide product manager, who provided market insight and was involved in the nozzle development, was also a primary enactor. • Sandvik AM is the primary selector as they funded the project.	• The Sandvik AM's R&D researchers trusted the carbide product manager's and marketeer's expertise. • The collaboration project established an alliance between Sandvik AM and Varel.	• Sandvik aimed to create value for Varel's drilling solutions and improve their performance, not just reduce their stock levels. • Sandvik's R&D culture enabled the development of numerous AM R&D findings.	• Sandvik established a centrally funded AM R&D Centre. • Sandvik provided unlimited resources and funding to the collaboration project. • The collaboration project had no predetermined timeline or limited budget.
Barriers	• The industry partners who were sceptical about AM technology or were unfamiliar with cemented carbides hampered the commercialisation opportunities of Sandvik's R&D findings.	• The industry partners who were sceptical about AM technology or were unfamiliar with cemented carbides hampered collaboration projects with Sandvik and the commercialisation of their R&D findings.	• Industry partners were sceptical about AM technology and were unfamiliar with cemented carbides. As a result, they hampered collaboration projects with Sandvik and the commercialisation of their R&D findings.	• The first-generation binder jetting process could not be perfected to deliver stable production of the threaded nozzles. Therefore, resources were redirected to the second-generation processes and nozzles.
Impacts	• Due to the project funding from Sandvik, the project collaborators developed two nozzle generations, and a third generation is being designed. • Sandvik's carbide product manager assisted the AM R&D researchers in identifying commercialisation opportunities for their R&D findings.	• Industry implementable nozzles were developed and tested. • Third-generation nozzles are being designed. • An alliance was established between Sandvik AM and Varel, and additional products are being developed.	• Second-generation cemented carbide nozzles enabled Varel's drill bits to drill faster, more efficiently and for more extended continuous periods. • Due to the value-added by the second-generation nozzles, third-generation nozzles are being designed along with other Varel products.	• Due to the project funding from Sandvik, two generations of nozzles could be developed. • Due to the value-added by the second-generation nozzles, third-generation nozzles are being designed along with other Varel products.

11.4. CIMO data analysis

The data analysis phase of the CIMO-based EHA framework may be applied to the narrative events to identify the functional dynamics that led to development within the case. First, the *case context may be defined to shed* light on the circumstances that formed the case setting (Table 11.2). The case initiates with Sandvik's aim to develop their AM technology in collaboration with a customer product, Varel's nozzles, and to add value to the product through a design that is un-manufacturable with traditional manufacturing technologies. Unlike the other potential industry customers unfamiliar with AM or carbide materials (barriers), Varel is willing to collaborate with Sandvik as they are part of their group and want to reduce their production lead times. Finally, a product development team is set up (driver). Sandvik provides them with all the physical and financial resources they may require (driver).

Table 11.2: Defining the context of Case IV

Context steps	Case IV application
Defining the system boundary	The development of Sandvik and Varel's additively manufactured nozzles from 2013 to June 2021.
Defining the phase of development	R&D phase of the three AM hardmetal nozzle generations
Defining the system objective	Primary objectives: • Sandvik aimed to determine the capabilities of their binder jetting AM processes. • Sandvik aimed to develop an un-manufacturable product design with traditional manufacturing technologies, adding real value to its customers. Capital objectives: • Intellectual capital: Develop an AM technique that adds value to products and delivers high durability products. • Social capital: To establish a relationship with an industry partner who would buy the product developed by the AM technique.
Identifying the IS structures	Actors: • The Product Development Team (PDT): The developers of the nozzles – Primary enactors • Sandvik's Product Manager: Hardmetal market expert and advisor of the AM researchers – enactor • Sandvik's AM researchers: Catalysts of the nozzle project after identifying possible AM applications – enactors • Sandvik: Funder of the R&D project – Primary selector • Varel: Customer and product end-user - selector
	Networks: • From 2014 to 2019, Varel was part of the Sandvik group (driver)
	Institutions: • Sandvik is a multinational, world-class manufacturing company (driver). • Some potential industry partners are unfamiliar with AM technology and believe it to be too expensive (barrier). • Other industry partners are unfamiliar with carbide materials (barrier).
	Infrastructure: • The R&D project has an unlimited budget and no predetermined timeline (drivers). • Sandvik has all the physical infrastructure required for the project (driver).

To get an overview of the development of the IS functions throughout the case and the functions Sandvik, their AM researchers, their product manager, Varel, and the product development team contributed, Figure

11.6 and Figure 11.6 were developed. As suspected from an R&D-focused case, both figures indicate *Knowledge Development* **[F2/KDev]**, performed particularly by the product development team, as the dominating function. This indicates that activities such as research and feasibility studies and laboratory and field trials were frequent in the narrative.

Additionally, *Guidance of Search* **[F4/GoS]**, predominantly performed by Sandvik's AM researchers, was also dominating, particularly during the first half of the case. This indicates that activities such as defining expectations, communicating vision, and communicating research results were frequent during the narrative. Furthermore, the *Creation of Legitimacy* **[F7/CoL]** function was frequently performed in the narrative, particularly by the product development team, indicating that several lobbying activities were performed. Following the dominance of these three functions, it seems as if research outcomes were continuously shared to stimulate advocacy for the product development team and AM technology. To gain further (actors-specific) insight, the sequence in which the functions were performed and by whom they were performed may be studied.

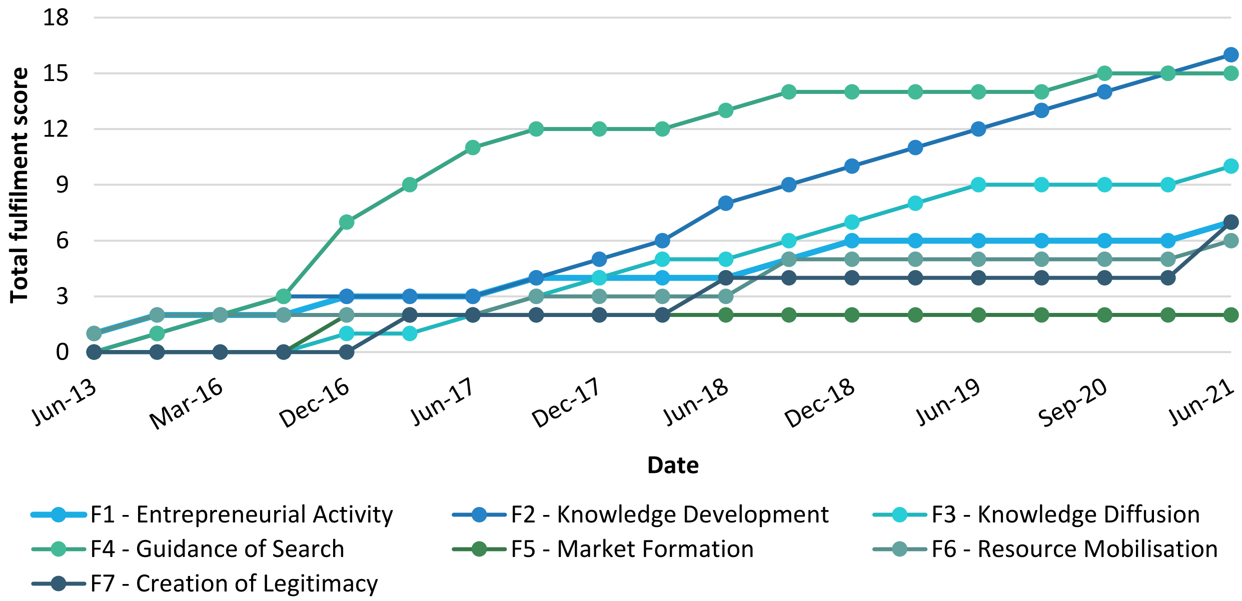


Figure 11.6: The functional development of Varel's high-precision nozzles project

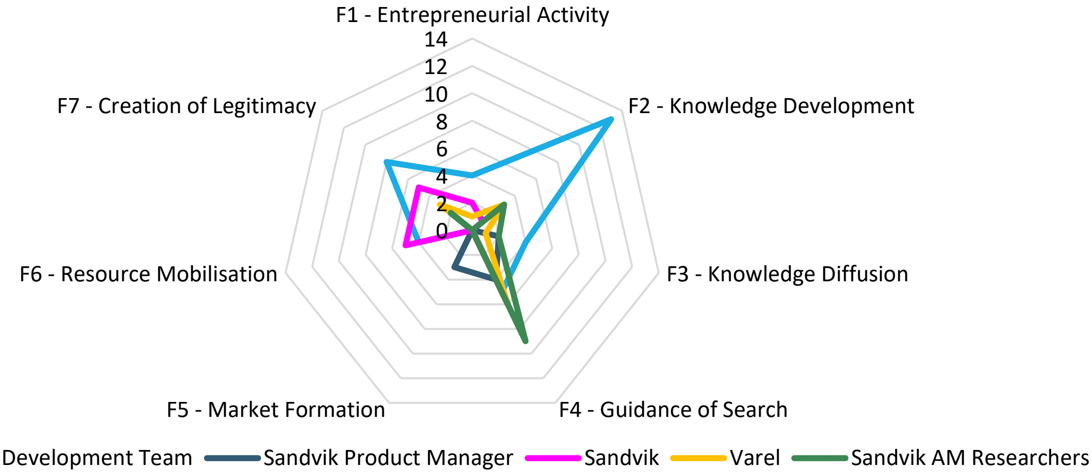


Figure 11.6: Functional contributions of the five actors map of the Varel's high-precision nozzles project

11.4.1. Interventions and mechanisms

The narrative starts when Sandvik invests resources **[F6/RM]** in an AM centre **[F1/EA]** to conduct AM R&D studies **[F2/KDev]**. When the researchers deliver feasible solutions **[F4/GoS]**, a market expert assists joins the team and identifies a feasible potential **[F7/CoL, F3/KDif]**. A collaboration **[F3/KDif]** is established with Varel, and a fully funded R&D collaboration project is launched **[F1/EA, F6/RM]**. The first generations nozzles are designed **[F2/KDev]**, but when the collaborators realise the technology is not sufficient **[-F4/GoS, -F7/CoL]**, the collaborators terminate the project **[-F1/EA, -F2/KDev]** to launch the second degeneration nozzles with the first generation's funding **[F3, KDif, F1/EA, F6/RM]**. The nozzles are developed and subjected to laboratory and field testing **[F2/KDev, F3/KDif]**, where it proves ready to be manufactured and implemented into Varel's drilling solutions [**F4/GoS, F7/CoL]**. Once again, an opportunity for further collaboration is identified to develop a new generation of nozzles **[F1/EA, F3/KDif],** and funding is allocated to the project **[F6/RM]**.

A pattern and causation cycle of commercial research projects with continuous communication of the research findings thus exist in the narrative. Paradoxically, the pattern and causation cycle continues, although adversely during the termination of the first-generation nozzles, but enables a favourable pattern for the second-generation nozzles to be developed. A motor of innovation thus exists within the narrative. As the case studies an R&D project, it seems fitting to label the motor of innovation an *R&D motor of innovation.* The *R&D motor* is schematically represented in Figure 11.7.

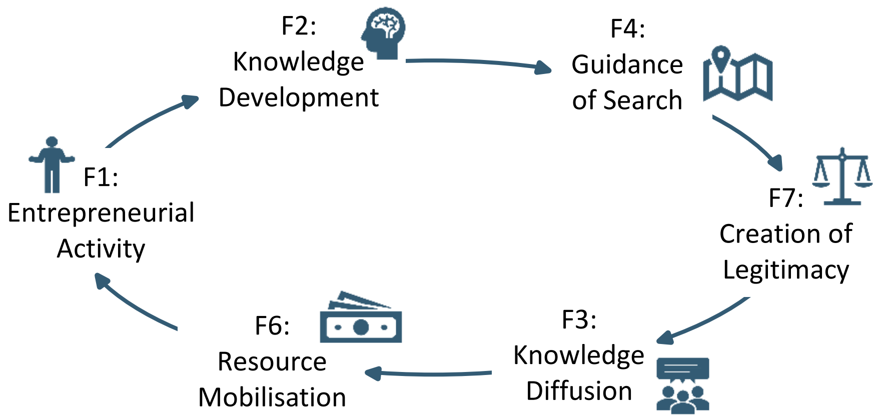


Figure 11.7: The R&D motor

Figure 11.10, Figure 11.10, Figure 11.10 and Figure 11.11 were developed to determine each of the five case actors' functional contributions. As mentioned in Figure 11.2, the product development team consisted of a representative from Varel and Sandvik's product manager and a senior R&D engineer from the group of AM researchers. Therefore, as their contributions prior to the collaboration were noteworthy, they were coded as separate actors prior to the collaboration.

Figure 11.10, Figure 11.10 and Figure 11.10 indicate that prior to the collaboration of the product development team, Sandvik's Product Manager contributed and was the giver of **[F4/GoS]** *Guidance of Search* and **[F5/MF]** *Market Formation*. Therefore, the product manager contributed to the case by communicating their vision, showing interest, and communicating research outcomes, market conditions, and expectations to Sandvik and the AM researchers. This reflects the product manager's role as market expert and consultant as he was the only participating actor knowledgeable of the market opportunities and the actor who suggested the collaboration with Varel. The negative (<0) **[F5/MF]** events indicated in Figure 11.10 indicate the unfavourable market conditions for the commercialisation of AM technology, while the

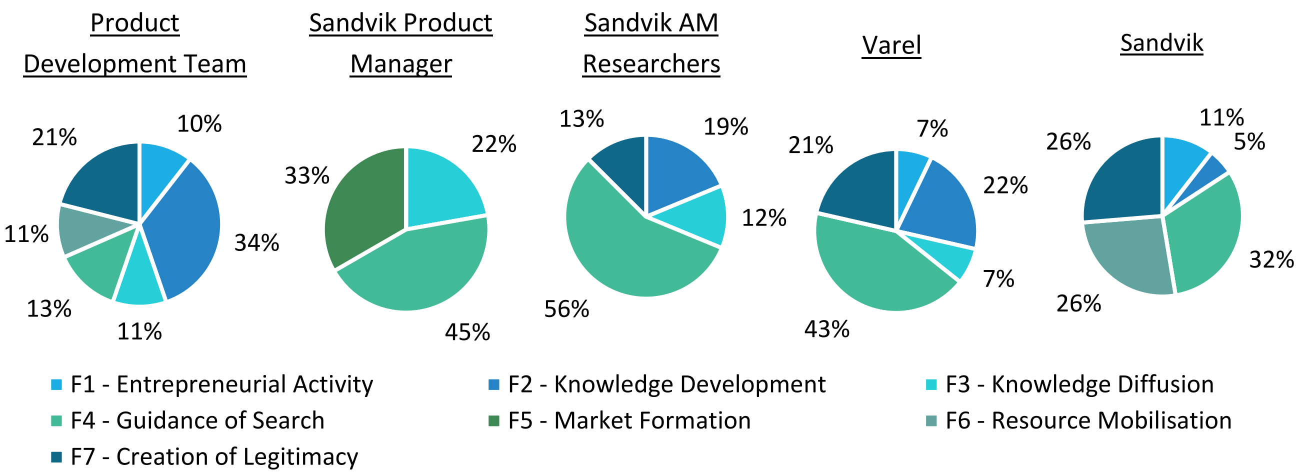


Figure 11.10: The five case actors and the IS functions they performed

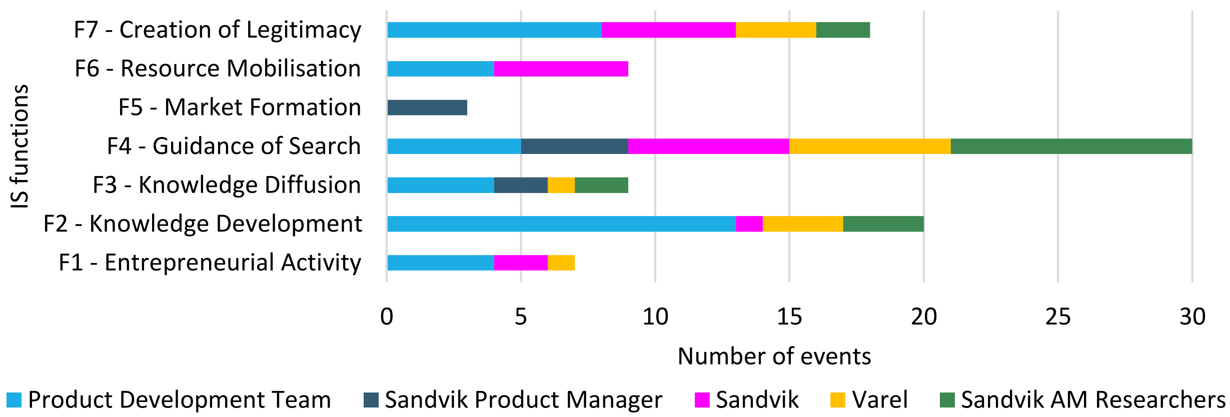


Figure 11.10: The number of events each participating actor contributed (performed, given and received combined) to the IS functions

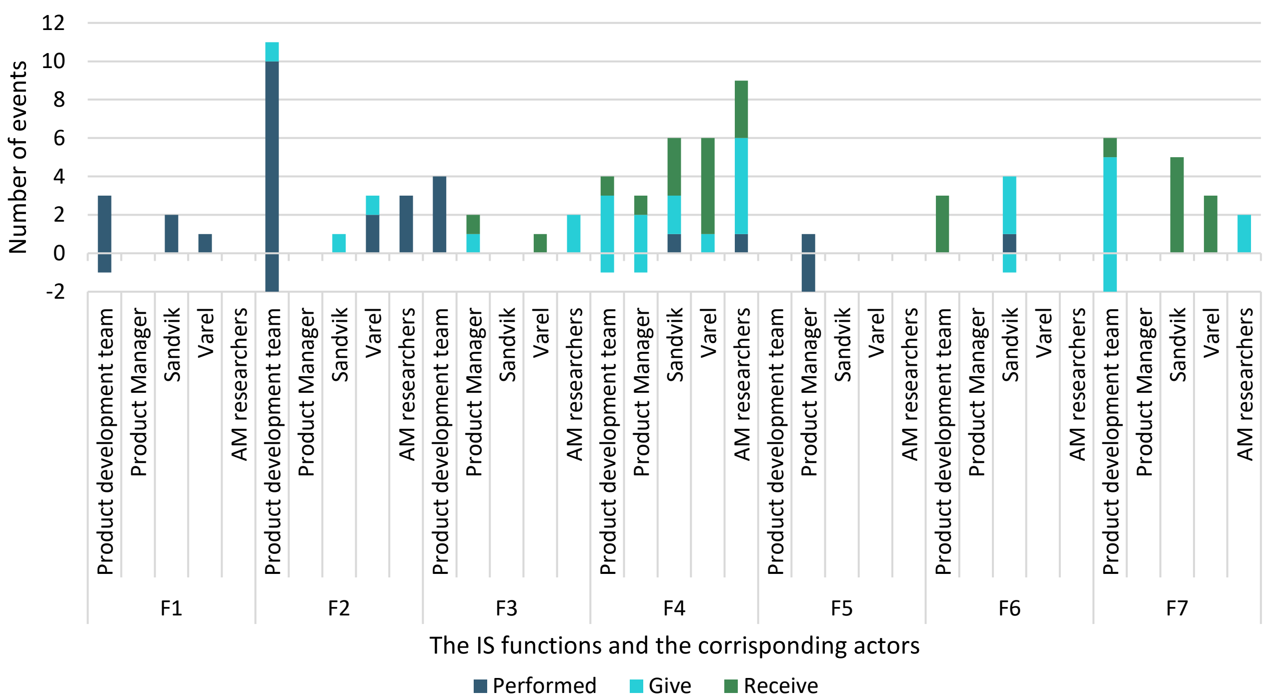


Figure 11.10: The functional contribution of the participating actors in terms of events performed, given and received

positive (>0) **[F5/MF]** events indicate the possible Varel-collaboration market opportunity presented by the

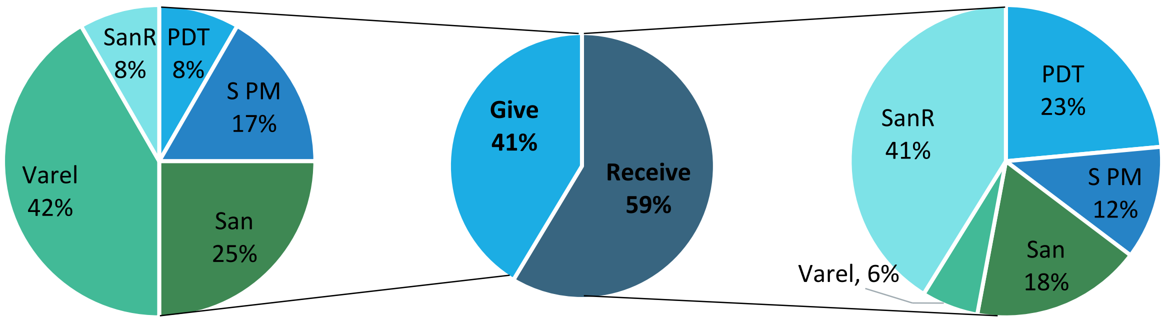


Figure 11.11: The give and receive contributional breakdown of the [F4] *Guidance of Search* function along with the actors who contributed to the function as *givers* and *receivers*

product manager. In addition to Sandvik's product manager, the AM researchers also contributed to the case prior to the development of the product development team. Figure 11.10 and Figure 11.10 indicate the AM researchers' contribution to **[F2, F3, F4, F7]**. From Figure 11.10 and the *R&D motor*, it is evident that the AM research conducted and was the *performer* of the AM research studies **[F2/KDev]** that led to the initial development of Sandvik's binder jetting process, the catalyst process of the research collaboration with Varel. In addition, they were *givers* and initiators of collaboration **[F3/KDif]** and *giver*s and receivers of guidance and information on research outcomes [F4/GoS] as they collaborated with the product developers to share their progress and gain insight into the carbide market. Furthermore, they collaborated **[F3/KDif]** with the product manager to invite Varel to a research collaboration after sharing their research outcomes **[F4/GoS]**. The AM researcher were thus key actors in this case as they are research and collaboration catalysts, and particularly, as they consulted with a market expert, the product manager, before choosing the technologies to further develop for commercialisation.

As expected from actors driving an R&D project, Figure 11.10 indicates the product development team as the primary *performers* of the **[F1, F2]**, indicating the three nozzle generation projects they launched and their research. Furthermore, they are the primary *performers* of **[F3/KDif]** as the team consisted of a researcher and product manager from Sandvik and a member from Varel. Figure 11.10 and Figure 11.11 also indicate the product development team as *givers* and *receivers* of **[F4/GoS]** and **[F7/CoL]**, indicating how often they lobbied and shared their research outcomes, both negative and positive, with Sandvik and Varel and the expectations they *received* in return.

Sandvik's contribution in the case is also noteworthy. Sandvik fulfilled the role of the funder and resource provider as they were the only participating actors to provide resources **[F6/RM]** for both the AM researchers and the product development team. Unlike the previously studied cases, this case had an actor other than the government to finance R&D. They also supported the product development team by providing expectations and guidance **[F4/GoS]**.

In contrast with Sandvik, Varel fulfilled the role of the customer with whom Sandvik collaborated to develop their technology. As the market did not provide many options for product development collaborations, Varel fulfilled a very important and enabling role in this case. Although Figure 11.10 indicates they Varel were primarily *receivers* of **[F3, F4, F7]** and only slightly contributed to or were *givers* of **[F2/KDev]**, they provided the product development team with a collaborative member and, therefore, Sandvik with a customer opportunity to develop their technology. In return, they received a product that added great value to their drilling solutions.

11.4.2. Outcome

Given the sequence and the manner in which the product development team, Sandvik, their AM researchers and product manager, and Varel performed the IS functions (CIMO interventions), the *R&D motor* (CIMO mechanism) developed. Consequently, this motor delivered the initial objectives set by Sandvik. Sandvik added real value to Varel's product through a product design that was un-manufacturable with traditional manufacturing. Furthermore, they improved the capabilities of the binder jetting AM processes.

In addition, the motor also delivered three capital outcomes: social, produced, and intellectual capital.

- Intellectual capital: The AM researchers developed an AM technique that the PDT improved into an AM technique that adds value to products and delivers high durability products.
- Social capital: A relationship was established with Varel to develop the hardmetal nozzles. Due to the nozzle collaboration, Sandvik and Varel now collaborate on more projects.
- Produced capital: The PDT developed nozzles that reduce drilling time in the field and thus add significant value to Varel's drilling solutions.

Figure 11.12 indicates the sequence in which the capital outcomes developed in the case and the relevant actors involved. Finally, Table 11.3 summarises the interventions, mechanisms, and outcomes they delivered.

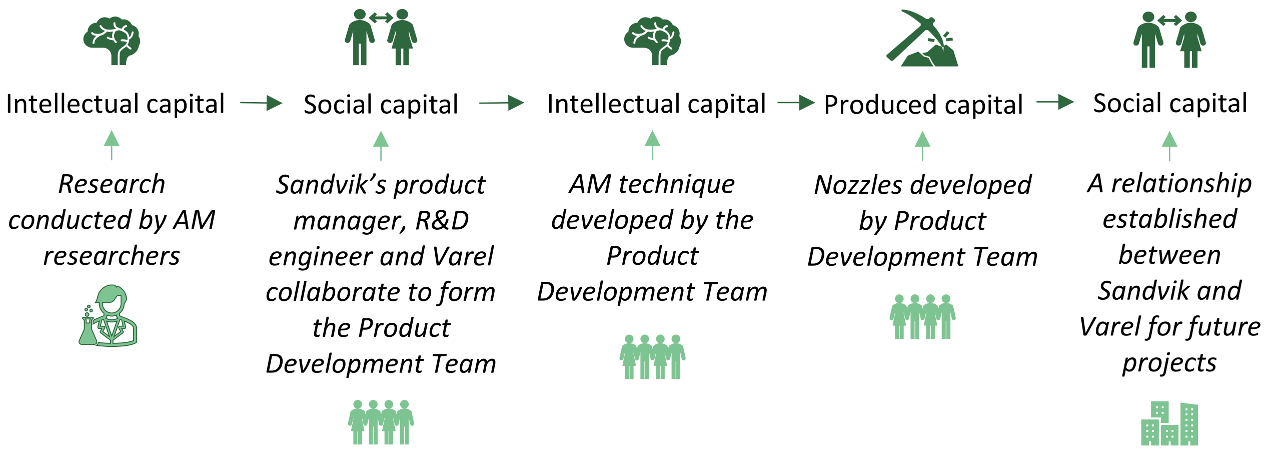


Figure 11.12: The sequence of capital outcomes delivered by the R&D mechanism

Table 11.3: The CIMO interventions, mechanisms and outcomes of the R&D motor, along with the involved actors

<table>
<tr><th colspan="5">Intervention</th><th>Mechanism</th><th>Outcome</th></tr>
<tr><th rowspan="2">IS functions</th><th colspan="4">Actors involved</th><th rowspan="2">Motor of innovation</th><th rowspan="2">Objectives achieved</th></tr>
<tr><th>Product Development Team</th><th>Sandvik's Product Manager</th><th>AM Researchers</th><th>Sandvik and Varel</th></tr>
<tr><td>[F1] Entrepreneurial Activity</td><td>Product developers</td><td></td><td></td><td></td><td rowspan="6">The R&D motor</td><td rowspan="6">Primary objectives achieved
• Sandvik added real value to Varel's product through a product design that is unmanufacturable with traditional manufacturing
• Sandvik improved the capabilities of the binder jetting AM processes
Capital outcomes achieved
• Social capital
Sandvik established a relationship with Varel to develop the hardmetal nozzles. Due to the nozzle collaboration, Sandvik and Varel now collaborate on more projects.
• Produced capital
The PDT developed nozzles that reduces drilling time in the field and thus add immense value to Varel's drilling solutions.
• Intellectual capital:
The AM researchers developed an AM technique which the PDT improved into an AM technique that adds value to products and delivers high durability products.</td></tr>
<tr><td>[F2] Knowledge Development</td><td>Product developers</td><td></td><td>Researchers and research catalysts</td><td></td></tr>
<tr><td>[F3] Knowledge Diffusion</td><td>Research collaborators</td><td></td><td>Collaboration catalysts</td><td></td></tr>
<tr><td>[F4] Guidance of Search</td><td></td><td>Market expert</td><td></td><td>Customer</td></tr>
<tr><td>[F6] Resource Mobilisation</td><td></td><td></td><td></td><td>Funder and resources provider</td></tr>
<tr><td>[F7] Creation of Legitimacy</td><td>Advocators</td><td></td><td></td><td></td></tr>
</table>

11.5. Chapter 11 summary

This chapter studied the last instantiation of four case studies. It explored the dynamics of an enterprise-level research and development project conducted by the world-class Swedish engineering company, Sandvik. As with the previous cases, the CIMO-based EHA framework was used to analyse the collaboration project between Sandvik and Varel to manufacture high-precision cemented carbide oil drilling nozzles using Sandvik's AM process. The chapter started with an introduction to the case actors. Thereafter the research project was narrated. Subsequently, CIMO steps of the CIMO-based EHA framework were applied. The CIMO interventions and mechanism identified the R&D motor and the functions the product development team, Sandvik, their AM researchers and product manager, and Varel contributed to the motor in terms of performed, give, and receive. Finally, the case-specific outputs and development capital outcomes delivered due to the research collaboration model were derived. Figure 11.13 presents a summary of the case. The following chapter will conclude Part III of the case studies by summarising and comparing the findings of the four cases. This chapter contributes to objectives IV and V, as mentioned in §1.4.

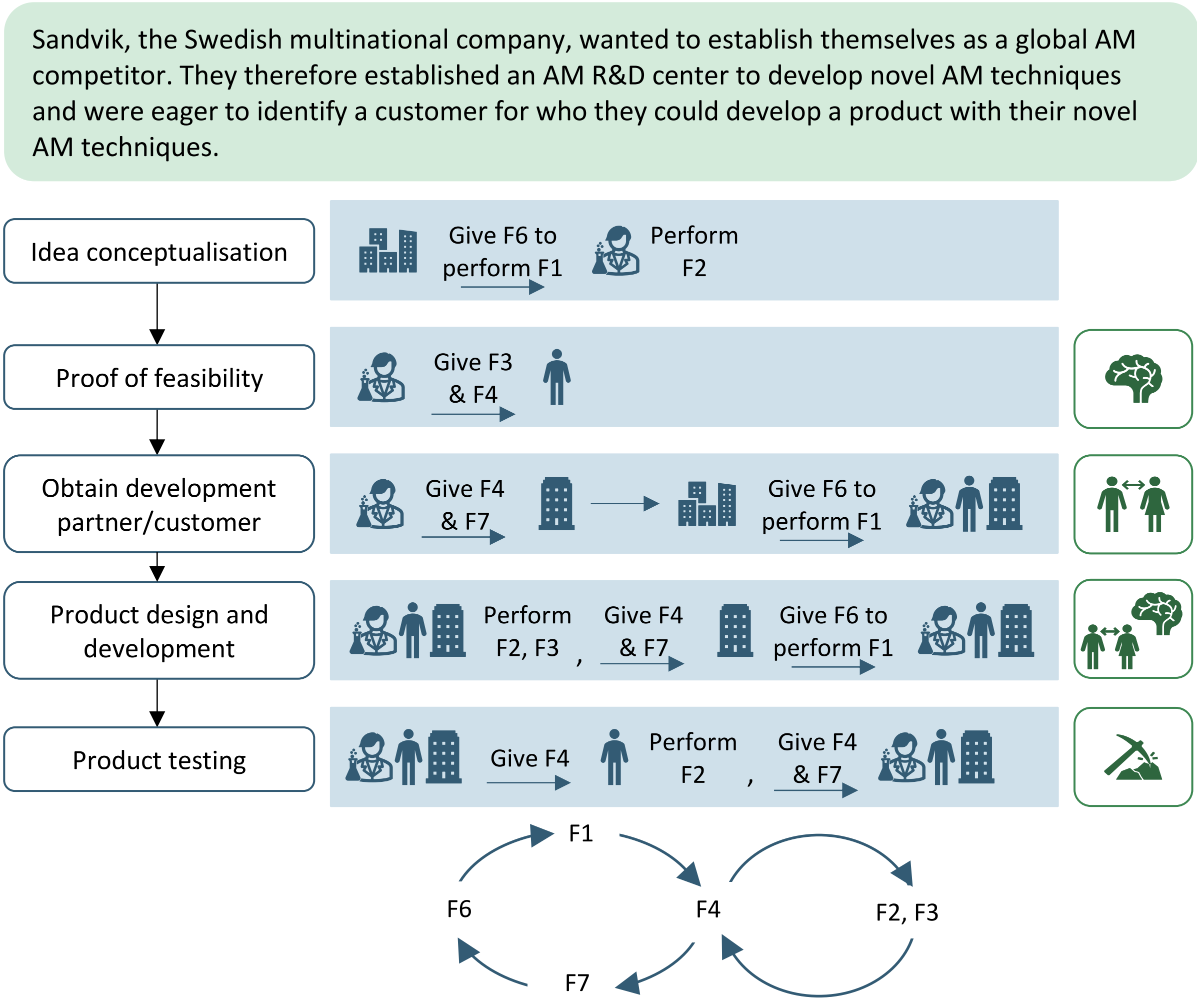


Figure 11.13: Case IV process steps along with the R&D model, the actors performing the functions and the development capitals developed

Chapter 12

Case Synthesis: Contrast and Compare

The previous four chapters studied the dynamics of four additive manufacturing-focused case studies. The cases were studied through the CIMO-based EHA framework to derive integral insights into the underlying innovation system functions, actors and motors of innovation that drove development in each case. In this chapter, the insights derived from cases II, III and IV are compared to identify the contexts, interventions, and mechanisms required to cross the valley of death and achieve desired outcomes. From these insights, this chapter aims to derive hypotheses to be tested in the South African-based industry survey presented in the subsequent chapter. This chapter satisfies objective VI, as mentioned in §1.4.

Chapter 12 contribution:

- This chapter suggest that crossing the Valley of Death implies the successful completion of six distinct R&D innovation process mechanisms.
- Contributions to the Valley of Death body of literature is made on the interventions and mechanisms that may be used to cross the Valley of Death.
- Interventions for stimulating the growth and development of the South African AM innovation system is derived.

Chapter 12 objectives:

- Present a high-level overview of the four cases and why each case was studied (§12.1 and 12.2).
- Reflect on the methods utilised to synthesis the case findings (§12.3).
- Compare the insight gained from the four instantiations of the DSRM and the CIMO-based EHA framework (§12.4).
- Derive a conceptualised framework of R&D process mechanisms (§12.5).
- Derive R&D interventions for stimulating the growth and development of the South African AM innovation system (§12.6).

12.1. Introduction to case synthesis

As mentioned in Chapter 1, this thesis has two primary aims. First, to derive and refine a novel method to study and analyse the evolution of innovation systems. The second aim is to identify the IS functions and dynamics necessary to support the development of the South African AM industry. From Chapter 4, such an industry should be characterised by a high degree of institutionalisation, structuration, stability, and interrelation with its context through various relationships (Figure 12.1).

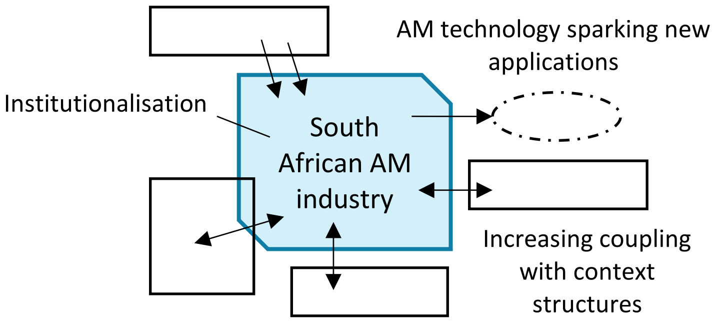


Figure 12.1: TIS-context interaction of a mature South African AM industry with strong couplings, high degree of structurisation and stability

Therefore, to identify the necessary IS functions and dynamics to achieve this aim, best practice examples were sought – from a range of contexts across the globe. Four case studies were studied and analysed in the previous four chapters through the CIMO-based EHA framework. Case I studied the evolution of the South African AM industry to gain insight into the context in which the industry and its various innovation actors developed. Following this contextual case study, a case study in an academic context (Case II) and two industry-based case studies (Cases III and IV) were studied to gain insight into innovation systems dynamics in both an academic and industry environment involved in R&D projects. The rationale for doing these case studies was that deriving these insights may support the direction in which we explore interventions for stimulating the growth and development of the South African AM innovation system.

In this chapter, we explore the insights gained from the academic and industry context cases and derive insight for the South African AM context. Therefore, this chapter starts with a high-level overview of the four cases and why each case was studied. Then, in §12.3, the approach and method applied to synthesise the insights from the previous three chapters are explained. Next, in §12.4, the insight gained from the academic- and industry-level cases, Cases II, III and IV, are contrasted and compared according to the CIMO-logic structure. Next, in §12.5, a conceptual framework is derived from the process mechanisms identified and 12.5.2. implications for innovation managers are derived. Finally, in § 12.6, suggestions for the South African AM industry are derived based on the insights and dynamics gained from the conceptual framework and Cases II, III and IV. Hypotheses are also derived to be tested in the subsequent chapter's industry survey.

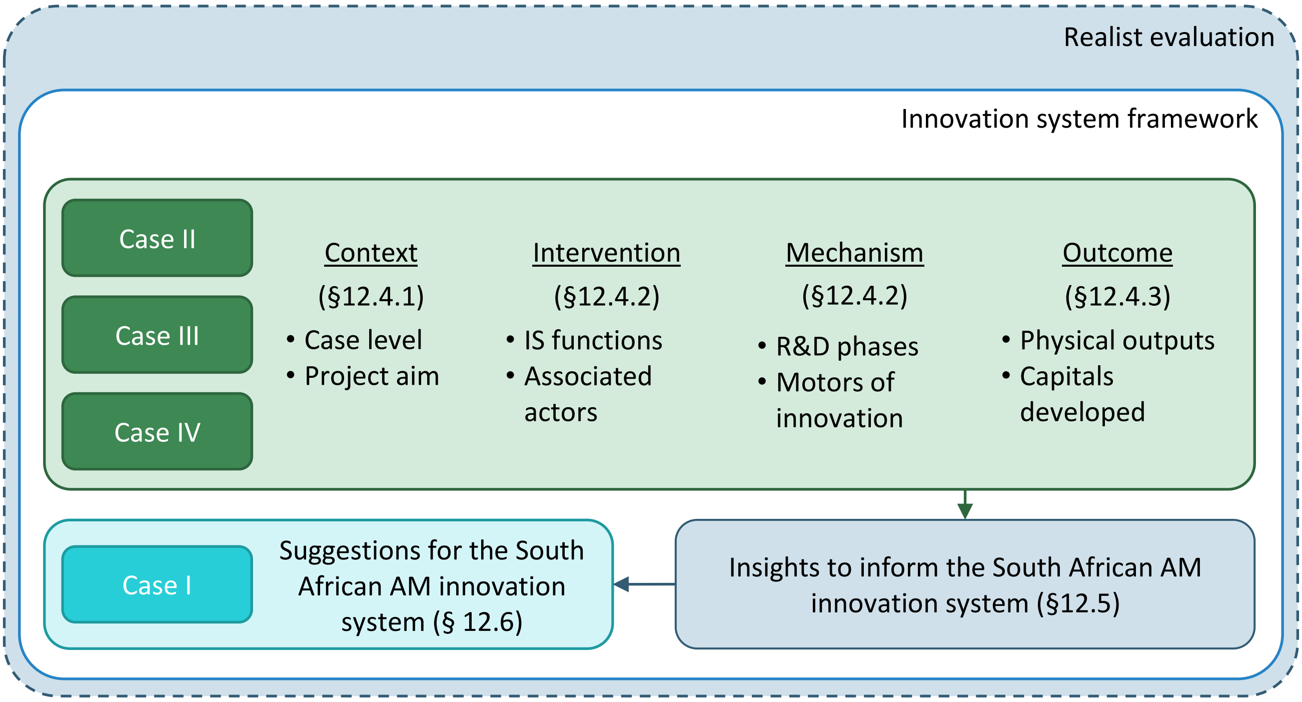


Figure 12.2: Chapter 4 sections, approach and logic flow

12.2. Reflection of the studied cases

This section reflects on the four cases studied and elucidates why each case was selected for study. Table 12.1 summarises the four cases studied along with their level, objectives, progress history and motors of innovation.

12.2.1. Case I: The South African additive manufacturing industry

In Case I, the establishment of the South African AM industry was studied to gain an understanding of the initial context in which the industry that exists today was developed. The case shed light on how AM systems were imported and implemented into various organisations, centres, universities, and companies and how research studies were conducted in various application fields. Furthermore, insight was provided into the governmental support provided to the industry and how networks of actors were established to create awareness of the technology and stimulate the adoption thereof. Finally, upon the case's conclusion at the end of 2020, an overview of the industry's establishment is obtained, accompanying how they evolved.

Following Case I, insights were sought to identify the necessary IS functions and dynamics on an academic and industry level. As no single case existed that could provide insights on manufactured hardmetal products with AM technology on both an academic and industry level with academic, knowledge institute, government, and industry actors in a single geographical area, three more case studies were selected to study a diverse range of actors and context. Therefore, the cases studied covered the actors, countries and maturity levels as presented in the cube framework of Figure 11.1.

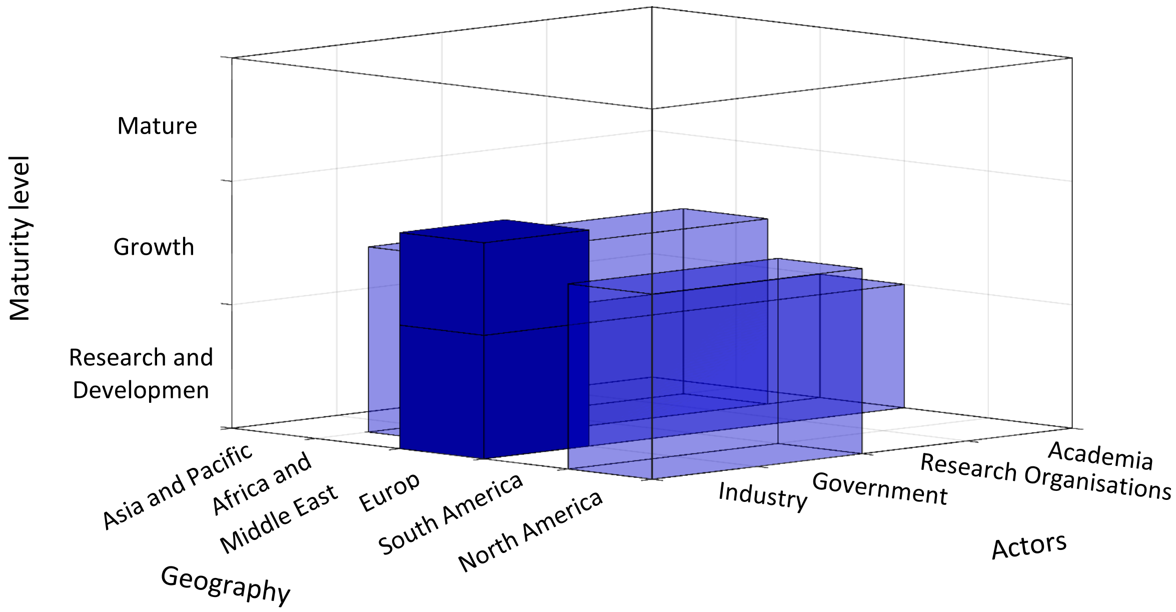


Figure 12.3: Cube framework of four cases studied

12.2.2. Case II: The Additive Manufacturing of Machining Tools out of WC-Co

For the academic-level case, a Fraunhofer ILT research group conducting AM research on hardmetals was selected as Fraunhofer is the world's leading applied research organisation [410]. Additionally, the research project included actors from a knowledge institute, a university, a governmental funding organisation and members from different SMEs. Additionally, unexpected market conditions, such as the hazardous classification of the manufacturing material and the COVID-19 pandemic, influenced the project. The case thus provided insight into the context within which world-leading applied research is conducted, the collaboration and institutions between different innovation actors and the effect of external market conditions. Consequently, the projects deemed warranted to be studied.

12.2.3. Case III: Dyze Design's Hardmetal Nozzle

As the South African AM industry is still relatively young and new enterprises are still entering the market, a start-up industry-level case was sought. Therefore, for Case III, Dyze Design was selected for study as they demonstrated how an innovative start-up company with minimal resources and business expertise utilised governmental and end-user support to develop and commercialise hardmetal AM products. Since its establishment in 2015, Dyze Design has won four innovation awards for being one of Canada's most innovative technology-oriented start-up companies [351], [399], [400].

12.2.4. Case IV: Varel's high-precision nozzles

To gain insight on how more established enterprises may be supported (and if support is necessary), an established enterprise industry-level case was sought. In Case IV, the collaborative R&D project between Sandvik and Varel was studied. Sandvik is a Swedish multinational engineering company specialising in metal cutting, digital and additive manufacturing, mining and construction, stainless and special steel alloys, and industrial heating [406]. As such, Sandvik is a role model for South African manufacturing enterprises, especially hardmetal enterprises. Furthermore, in the selected AM project, Sandvik had almost unlimited R&D resources and aimed to establish themselves as a competitor in the global AM market. Therefore, this case provides insight into the dynamics established manufacturing enterprises use to commercialise their products and gain market share.

Table 12.1: Summary of the case studies studied

Case	I	II	III	IV
Level	Industry	Academic	Industry: SME	Industry: Large enterprise
Country	South Africa	Germany	Canada	Sweden
Objective	To establish the South Africa AM industry	To develop an AM technique to manufacture WC-Co machining tools	To develop and commercialise hardmetal 3D printer nozzles	To gain market share and develop an AM technique to manufacture a client's hardmetal drill bit nozzles
Timespan	1991-2020	2019-2022	2015-2021	2013-2021
Progress history	AM is well implemented; the industry is growing annually.	Industry partners are conducting field tests.	The nozzles and subsequent nozzles have been commercialised.	The nozzles have been developed and are subjected to field tests.
Primary actors	Governmental departments, a national research organisation, and universities.	A national research organisation, a university, and a governmental research funding organisation.	The members of an SME, product end-users and the national government.	Two product developers and a product manager from the involved enterprises.
Motors of innovation	Technology Push (with an additional `guidance' loop)	Research collaboration motor	Development motor with additional Entrepreneurial loop	Research and Development motor
Impact of motors	By 2018, more than 6000 AM systems were installed in the country, and AM was used by academia and industry. Several demonstration centres and research projects were also established, and an AM national strategy was released to guide AM research.	A working technique to manufacture hardmetal products was developed. The motor enabled the continuation of the research project despite the fluctuating market conditions influencing the project.	Hardmetal 3D printer nozzles were developed with end-user funding, after which it was commercialised. Subsequent nozzles were also developed and marketed.	Hardmetal drill bit nozzles were developed with AM. As a result, the nozzles' production lead time was reduced by more than 50%, and the quality of the nozzles enabled faster, more efficient drilling for more extended continuous periods.

12.3. Method of synthesis of findings from three AM projects

This section reflects on the method and research approach utilised to gain insight from the individual case studies and synthesise the findings into suggestions for the South African AM innovation system.

12.3.1. Event history analysis and innovation systems

Whilst there is much interest in developing systemic instruments to support innovation systems (ISs) to perform more optimally, most IS authors have adopted a variance approach rather than a process approach.

Where variance approaches to the IS studies seek understanding based on the relationships between functions, structures and systemic problems, process studies seek understanding based on the development of functions and structures over time.

As mentioned in Chapter 6, due to the existing variance approaches utilised in IS studies, Broekel and Boschma [349] and Hekkert *et al.* [33] have argued for an evolutionary method that traces the development of IS functions and components over time to determine how systemic problems are developed or mitigated throughout an IS's development. In this regard, Hekkert *et al.* [33], Suurs [23], [24] and Negro [34], [36] adopted a processual approach, the evolutionary analysis method of event history analysis (EHA), to study the development of innovation systems over time. Therefore, similar to Hekkert et al. [7],

12.3.2. Realist evaluation and CIMO-logic

A realist evaluation approach [411] was adopted to guide the IS analysis of the individual case studies through EHA and synthesise the findings. The approach, described in §2.2 and §4.1, was utilised as it is a well-established approach for evaluating programmes and projects [163], [246]. As previously mentioned, the realist evaluation approach seeks to uncover why particular interventions triggered mechanisms that led to valuable outcomes. Realist evaluation authors Rogers [248], Mathison [249], and Pawson *et al.* [246] have argued that realist evaluations are best suited to complex systems where several social processes may be functioning. Due to the complexity of the innovation dynamics known in Valley of Death literature to operate during the development stages of a technology, a realist synthesis of the case findings was deemed suitable.

As mentioned in §4.3.1, realist evaluation starts with a programme theory about how a programme is intended to operate [256]. In this study, the programme theory refers to how technology projects cross the Valley of Death. To guide the search for data and guide the evaluation logic, Pawson and Tilley [411] and later Denyer [253] developed the CIMO-logic structure. The structure combines a problematic innovation *context* (C) with specific innovation actions or *intervention* (I) types to develop *mechanisms* (M) to deliver specific *outcomes* (O). The structure comprises four elements that express the logic underpinning the programme theory aimed to be developed, namely how technology projects cross the Valley of Death.

12.3.3. CIMO-based EHA framework

To guide the IS analysis of the individual case studies through the method of EHA and synthesise the findings, a realist evaluation approach [411] and the CIMO-logic structure [253], [411] were adopted. These four elements of the CIMO-logic structure provided a set of generic headings that were used to guide the pattern analysis phase of the EHA method, to form the CIMO-based EHA framework (Chapter 6). Therefore, in the previous four chapters, after each case's narrative was constructed following the EHA method and the innovation actors and the events they performed were identified, the CIMO-logic structure provided generic headings to organise and guide the case insights. First, each case's context was identified regarding its project objectives, and key IS structures. Thereafter, the IS functions (interventions) and their associated actors were recorded. Next, the patterns in which the IS functions were performed were traced to identify cumulative causation and thus motors of innovation (mechanisms). Finally, the physical and capital outputs developed by these motors of innovation were recorded for each case.

In this chapter, the CIMO-logic structure once again provided generic headings to organise and synthesise the findings from the individual case studies. First, the data from the individual case studies gathered in the previous four chapters were ordered in terms of their specific context. This included their level (academic, SME or established enterprise) and aim (product or technology). They were also ordered in terms of their interventions, the IS functions performed. The motors of innovation (mechanisms) from each case study were then contrasted to identify similarities and grouped in an analytical routine similar to the clustering of categories performed by Ellwood *et al.* [163]. Finally, from this clustering routine, the findings from the three cases were synthesised, leading to the identification of seven motors of innovation or innovation mechanisms operating during the Valley of Death.

This synthesis was consistent with the realism philosophy that a theory does not seek to be generalised in terms of the relationships between variables but rather the role and impact of the innovation mechanisms that developed over time [253]. In the subsequent sections, the motors of innovation or innovation mechanisms operating during the Valley of Death are elucidated through the CIMO-logic structure and combined in a conceptual framework.

12.4. Contrasting and comparing: a cross-case analysis

From Figure 12.3 and the case descriptions mentioned above, it is evident that the cases differ in level and country and thus context. However, insight may still be gained from the contrasts and comparisons among the R&D processes, functions performed, motors of innovation and the involved actors. Therefore, this section presents an overview of the cases where they are compared to identify high-level contexts and phase contrasts and comparisons. The subsequent sections dive into more detail about the cases and compare their functions, motors of innovation and actors.

12.4.1. Context

The process phases and context summaries of Figure 9.11, Figure 10.22, Figure 10.23, and Figure 11.13 were combined into Figure 12.4 to present the R&D phases of Cases II, III and IV alongside each other. Figure 12.4 shows that, as expected, the initial contexts of the cases differed as the case studies had different triggers and were located in different geographical areas. For example, the research design process of Case I was triggered by the common German culture that academic research projects usually only obtain funding when identified projects address an industry need. Case III, however, was initiated when Dyze Design saw an opportunity in the products available in the global printing market. Finally, in Case IV, the research project was initiated as Sandvik wanted to establish itself in the global AM market and identified a market opportunity to develop nozzles for Varel.

However, the context of the R&D projects presents similarities in the projects' aims. For example, cases II and IV both focused on extending AM research as they aimed to develop new AM techniques or processes. Case IV's enterprise also aimed to enhance its end-user's product value by including product features that could not be manufactured with traditional manufacturing techniques. Similarly, Case III improved the AM printer nozzles available in the global market and successfully commercialised them. Consequently, the context of the three cases may be summarised as "extension of AM research", "enhancement of product value", and "commercialisation of high-value value-offering", as presented in Table 12.2.

Table 12.2: Grouping contexts of Cases II, III and IV

Context	Case study
Extension of AM research	• Case II (Academic) • Case IV (Established enterprise)
Enhancement of product value	• Case III (SME) • Case IV (Established enterprise)
Commercialisation of high-value value-offering	• Case III (SME)

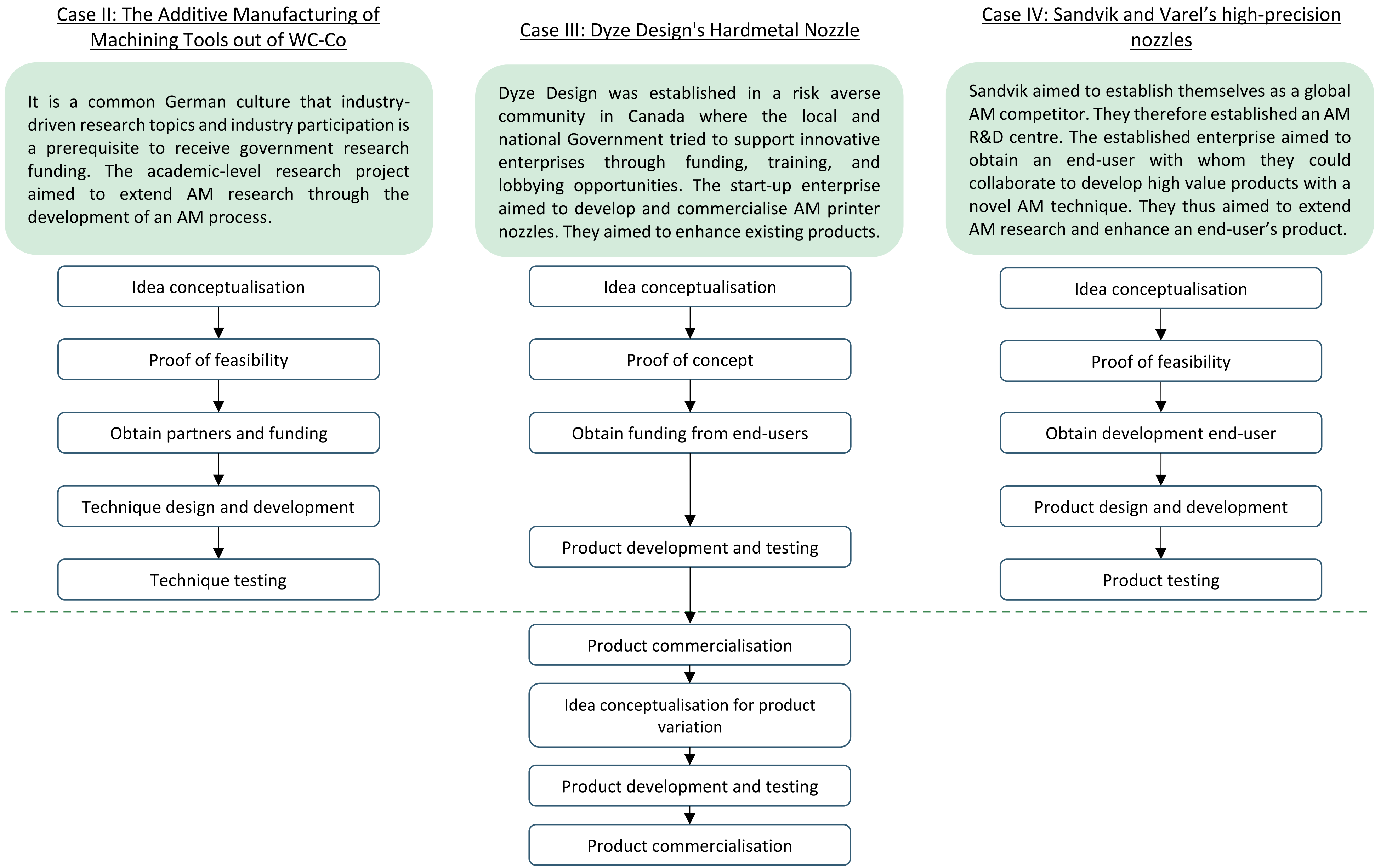


Figure 12.4: Matching of similar project steps or phases across case studies I, II and III

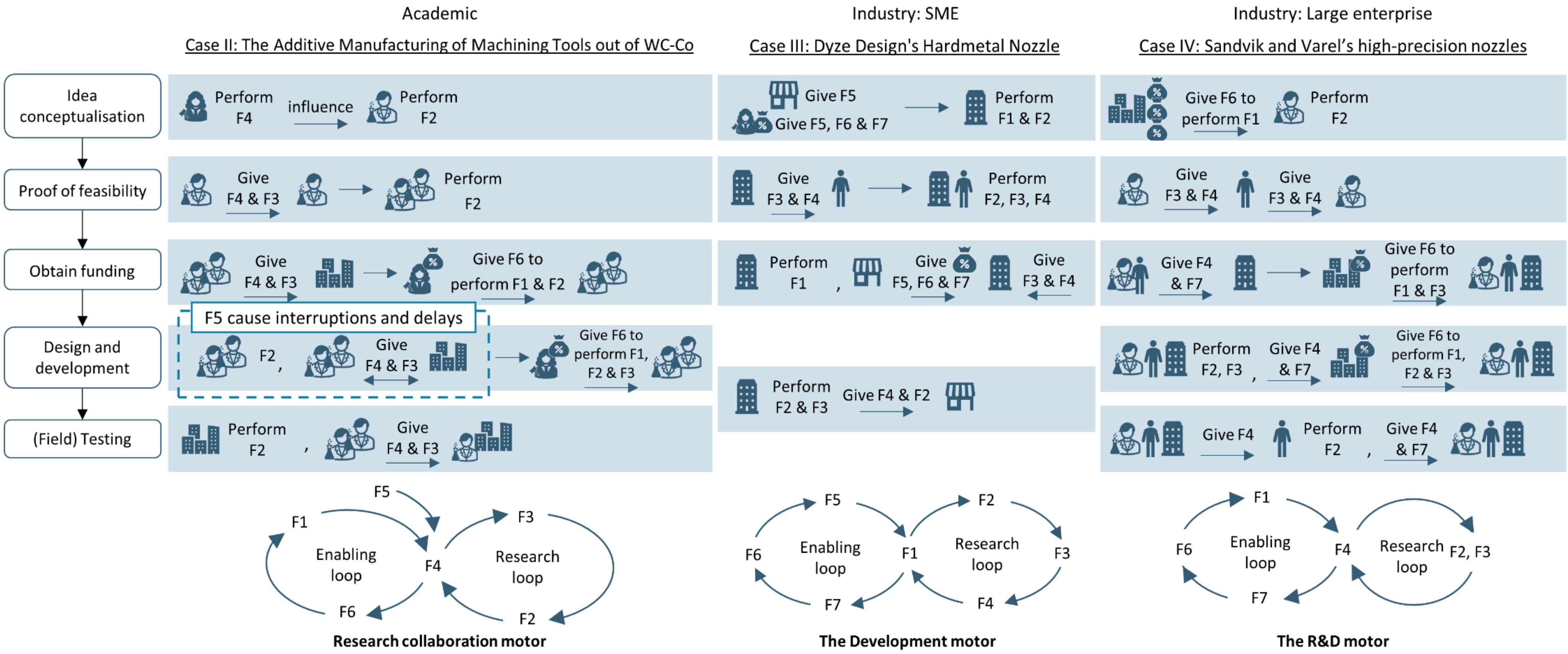


Figure 12.5: The fulfilment of the project phases in terms of the cases' motors of innovation and corresponding actors

Function key: F1: Entrepreneurial Activity, F2: Knowledge Development, F3: Knowledge Diffusion, F4: Guidance of Search, F5: Market Formation, F6: Resource Mobilisation, F7: Creation of Legitimacy

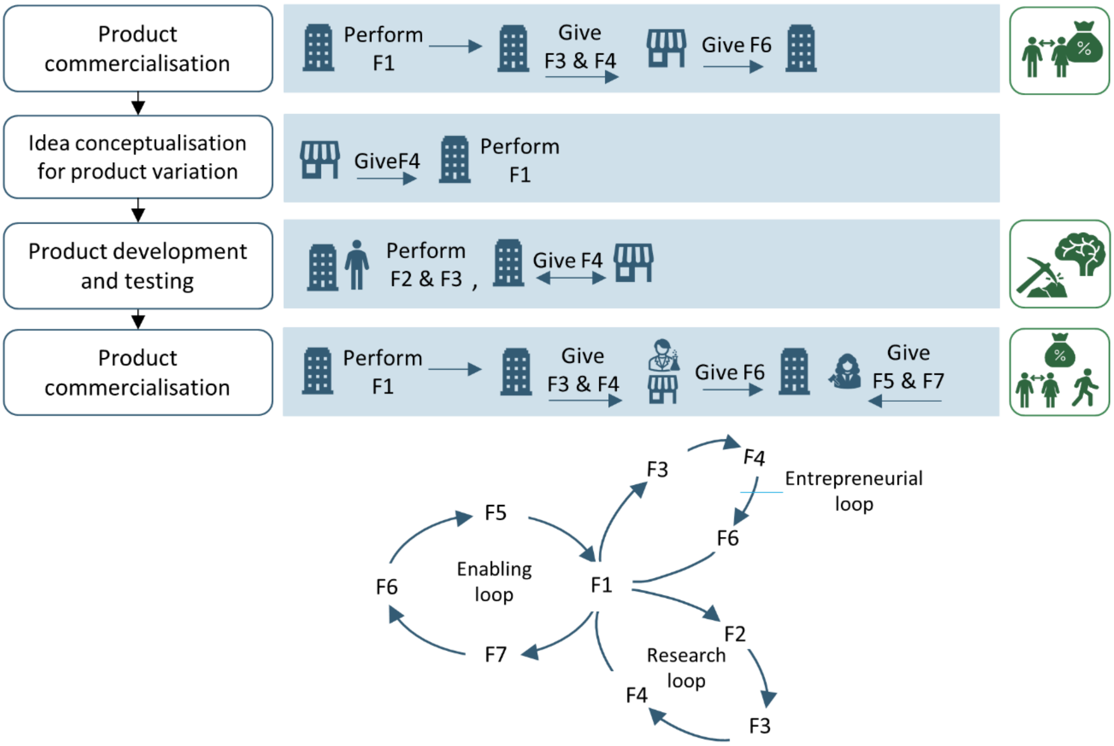


Figure 12.6: The fulfilment of Case III's product commercialisation phase, along with the Entrepreneurial motor and the corresponding actors

Function key: F1: Entrepreneurial Activity, F2: Knowledge Development, F3: Knowledge Diffusion, F4: Guidance of Search, F5: Market Formation, F6: Resource Mobilisation, F7: Creation of Legitimacy

12.4.2. Mechanisms and interventions

In Figure 12.4 and Figure 12.5, it is evident that the cases followed the same initial five phases to develop their AM products or techniques. The *idea conceptualisation phase* of each case involved knowledge development **[F2]**. It may thus be concluded that the idea conceptualisation phase of any R&D project, no matter the level, requires research and knowledge development. However, as the context of the cases differed, the functions and actors initiating knowledge development differed. These initiating functions form part of the *enabling loops* of the motors of innovation and include interventions such as goals for company expansion **[F1]**, guidance from external funders **[F4]**, and market opportunities **[F5]**.

The *proof of feasibility phase* of each case involves knowledge diffusion **[F3]** and guidance of search **[F4]**, thus completing the *research loop* of the motors initiated in the *idea conceptualisation phase*. During this phase, researchers of each case invited their collaborative partners **[F4]** with whom they would conduct the rest of the R&D activities **[F3]**, as these actors were more knowledgeable in certain facets of the R&D projects than the researchers. For example, in Case IV, the collaborative partner was a market expert on the manufacturing material utilised, while Case III's collaborative partners were the enterprise's suppliers.

During the *funding obtainment phase*, the *enabling loops* of the motors of innovation are present. In cases II and III, financial resources **[F6]** were required to continue with the R&D project **[F1, F2]**. However, as case IV had sufficient financial resources, they required a collaborative end-user **[F3]** for whom a product could be developed while an AM technique was perfected. Forms of feedback **[F4]** and lobbying **[F7]** supported the obtainment of the resource. Upon the obtainment of an end-user collaborative partner, development funding was mobilised to stimulate the continuation of the *research loop.* Thus, whether it be the obtainment of funding (cases II and III) or collaboration partners (case IV), the *enabling loop* enables the obtainment of the necessary resources to support the continuation of the *research loop*.

In the *design and development phase*, the *research loops* of the motors of innovation are repeated. Thus, knowledge development **[F2]**, knowledge diffusion **[F3]** and guidance of search **[F4]** is fulfilled. In cases II and IV, the research loop is followed by the *enabling loop,* where funding **[F6]** is provided for the continuation of the project **[F1]**. Thereafter, the *research loop* is reiterated. However, in case II, this phase is severely delayed by external market conditions **[F5]**, indicating that external market conditions may influence or delay any research project and, typically, any project phase.

The product *testing phase concludes* the first five phases of the R&D process. In this phase, the *research loops* of the motors of innovation **[F2, F3, F4]** are again fulfilled. As with the other phases, the actors performing the research loop's functions differ, indicating that field tests may be conducted by the product, process developers, or external actors. From the three cases, industry enterprises typically perform product testing.

Cases II and IV's documentation ends after the fifth R&D phase, while Case III evolved through to the *commercialisation phase* and the development and *commercialisation of product variants* (Figure 12.6). In both the *commercialisation phases*, entrepreneurial activities **[F1]** are followed by awareness creation **[F3],** and feedback from end-users **[F4]** before money **[F6]** from product sales is obtained. The first product commercialisation phase is followed by another *idea conceptualisation* phase, after which the product development and commercialisation phases repeat. Therefore, the product commercialisation phase may be viewed as the final R&D project phase before the R&D cycle is repeated for new product variants.

The six R&D phases, from *idea conceptualisation* to *product commercialisation*, thus repeated throughout all the cases and led to the development of commercially feasible or commercialised products. Therefore, the six R&D phases may be classified as CIMO mechanisms operating during the development phase of innovations.

Table 12.3: Summary of the observed innovation process mechanisms and their associated innovation interventions

<table>
<tr><th colspan="2">Mechanisms</th><th rowspan="2">Interventions
(IS functions)</th></tr>
<tr><th>Motors of innovation</th><th>R&D project</th></tr>
<tr><td rowspan="2">Research loop</td><td>Idea conceptualisation</td><td>• F4 – Funding requirements trigger specific research projects (II)
• F5 – Market conditions trigger product ideas (III)
• F2 – Research conducted to conceptualise the product idea (II, III, IV)</td></tr>
<tr><td>Proof of feasibility</td><td>• F3 – Obtain a development partner (II, III, IV)
• F4 – Communicate project vision and provide feedback (II, III, IV)
• F2 – Feasibility tests (II, III)</td></tr>
<tr><td>Enabling loop</td><td>Obtain funding or collaborative partner</td><td>• F6 – Obtained research or development funding (II, III)
• F1 – Start of a project with a commercial aim
• F4 – Communicate project vision and provide feedback (II, III, IV)
• F7 – Lobbying and trust in the enterprise's brand (III, IV)</td></tr>
<tr><td rowspan="2">Research loop</td><td>Design and development</td><td>• F2 – Product development activities (II, III, IV)
• F3 – Collaboration with development partners during R&D (II, IV)
• F4 – Communicating feedback and progress to collaborating partners (II, III, IV)</td></tr>
<tr><td>Field Testing</td><td>• F2 – Product testing activities (II, III, IV)
• F4 – Communicating feedback to collaborating partners (II, III, IV)</td></tr>
<tr><td>Entrepreneurial loop</td><td>Product commercialisation</td><td>• F1 – Entrepreneurial activities
• F3 – Collaborations with distribution channels
• F4 – Feedback from end-users
• F6 – Money received from end-users from product purchases.</td></tr>
</table>

12.4.3. Outcome

Similar physical outputs were delivered as the cases followed the same five mechanisms to conceptualise, develop and field test their products and AM techniques. Furthermore, the development capitals delivered across the six process mechanisms slightly differed per case. Therefore, the capitals delivered by at least two cases were selected as the capital outcomes of the process mechanisms. These physical and capital outcomes are presented in Table 12.4.

Table 12.4: Groupings of the physical outcome delivered by the process mechanisms

R&D process Mechanisms	Context	Outcome	
		Physical	Development capitals
Idea conceptualisation	Extension of AM research	Validated product or process concept	Human
Proof of feasibility			
Obtain funding or collaborative partner	Enhancement of product value	Sufficient resources for product development	Social Financial
Design and development		Commercially ready value-offering	Human Produced
Field Testing			
Product commercialisation	Commercialisation of high-value value-offering	Commercialisation of value-offering	Social Financial

To describe the outcomes delivered more fully, they are related to the innovation process mechanisms and contexts in which they developed. The analysis summarised in Table 12.4 suggests that the innovation processes for developing a product or technique and crossing the Valley of Death in the AM-focused cases operate within three contexts. As mentioned in §12.4.1, they include “extension of AM research”, after which sufficient resources are obtained to facilitate the “enhancement of product value” to enable the “commercialisation of high-value value-offering”.

Extension of AM research comprised interventions to test the feasibility of a conceptualised product or process idea. These two mechanisms were led by researchers or product developers and delivered validated product or process concepts and human capital (knowledge and skills on how to develop their conceptualised idea). The enhancement of product value is achieved by interventions to obtain sufficient resources to conduct the project and the designing and developing prototypes that may be tested in field application. The dominant actors contributing to these interventions were the researchers or product developers, resource suppliers (financial, human, and physical) and industry end-users testing the prototypes. The delivered outcomes included sufficient resources for product development through relationships established with actors (social capital), R&D funding obtained (Financial capital), and commercially ready value-offering produced. Finally, the commercialisation of high-value value offerings was achieved through product commercialisation interventions and delivered both financial and social capital through the relationships established with end-users and distributors.

12.5. Synthesis of case findings

The final stage of the CIMO-based analysis is to combine the preceding analysis into a single conceptual framework so that insight might be derived for the South African AM innovation system. This section combines the analysis insights into a conceptual framework, after which indications for innovation managers are derived.

12.5.1. Conceptual framework of the R&D process mechanism

As all three cases followed the same innovation process mechanism, the mechanisms may be developed into a conceptual framework for R&D projects operating in the Valley of Death. In addition, specific insight from the cases may also refine the framework.

In Case IV, after the feasibility of several AM project concepts was verified for feasibility by a market expert, only one project, the project studied, was deemed feasible. The other project concepts had to be reworked. Thus, a double-pointed arrow may be included between the *idea conceptualisation* and *proof of feasibility* mechanisms to indicate that conceptualised ideas deemed infeasible require reworking.

In Case II, unexpected market conditions led to the requirement of additional R&D funding to enable the continuation of the project. Similarly, in Case IV, when the prototypes of conceptualised ideas were rejected due to infeasibility, more funds were required to design and develop new conceptual ideas. Thus, a double-pointed arrow may be included between the *obtain funding or collaborative partner* and the *design and development* mechanism. Similarly, a double-pointed arrow may be included between the *design and development* mechanism and the *field-testing* mechanism. Following the successful completion of the prototype field testing, the high-value value offering may be manufactured and commercialised.

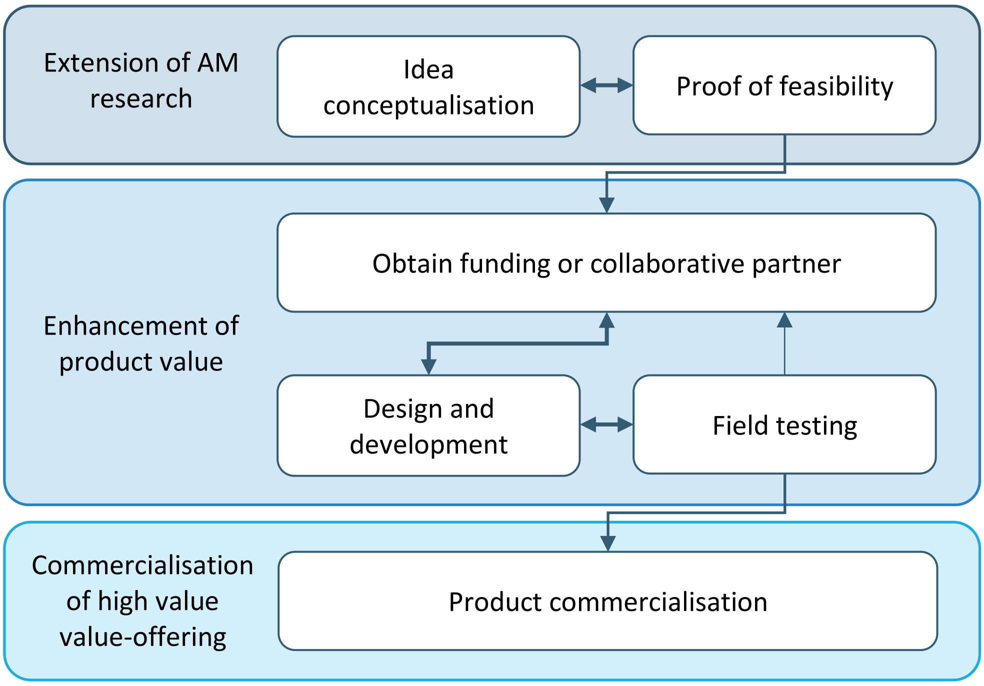


Figure 12.7: Conceptual framework of the R&D process mechanism

Figure 12.7 presents the conceptualise framework of the R&D process mechanisms derived from the case insights. To extend AM research, product or process ideas may be conceptualised. Depending on the contingencies of the surrounding market, researchers and product developers may alternate between the interventions of the *idea conceptualisation* and *proof of feasibility* mechanisms. Once feasibility has been proven, product value enhancement may be created through the obtainment of resources and the design and development of prototypes to be field-tested. The interventions of the product value enhancement phase may be repeated until a point when high-value value offerings become available for commercialisation.

12.5.2. Implications for innovation managers via the Intervention actors

Additional insights may be gained on the actors who performed the earn the process mechanisms' interventions. As presented in Figure 12.5 and Figure 12.6, different innovation actors were included in the four cases: the government, industry enterprises, academia and research organisations, suppliers and end-users or customers. Therefore, this section compares the roles of the innovation actors throughout the innovation process mechanism.

12.5.2.1 Academia

As Case II is an academic research-level case, the researchers are the product and technology developers. To gain access to the financial support provided by governmental research funding organisations, the researchers identify research project opportunities for the application areas identified by the research funding organisations. Subsequently, they have to obtain the required SME participation, share their progress and findings with the participating SMEs throughout the research process and publish their research findings in the public domain upon completion of project phases to allow non-participating enterprises to also benefit from the research conducted.

In Case III, academia acts as end-users of the industry-developed products (nozzles) and observers of industry practices. For example, Canadian and European universities are end-users of the enterprise's nozzles when they bought and used them in their research projects and provided feedback on the type of nozzles they require. Furthermore, the Canadian university students located near the enterprise are observers of industry practices when they complete their practical year at the enterprise and gain paid, practical experience in AM technology.

Figure 12.8: Academia's role in Case II and III

12.5.2.2 Government

In Case II, the governmental actors stimulate industry-specific research that requires industry participation through their prerequisites for research funding. Through their prerequisites, they stimulated practical research that can be further developed for commercialisation in industry. The governmental actors act as a bridge between academia and industry by requiring the academic research process to be shared with the collaborating industry partners throughout the research project and in the public domain upon the conclusion of the research project. The governmental actors do not require the industry enterprises to conceptualise research project ideas but require academia to conceptualise project ideas and invite industry to observe their research process. The governmental actors also do not require the academic actors to find industry partners that would provide funding for their research projects as it could delay the academic research projects. In this way, both industry and academia benefit from the research project as academia may conduct founded research projects, while industry receives free R&D insight without having to invest in any technology or products.

In case III, the governmental actors played a tremendous supporting role during the start-up's initial development. In case III, the governmental actors support innovative companies by hosting numerous events and competitions where grants and advocacy may be obtained. Companies are also offered the opportunity to win business development training. As the start-up had minimal resources, the grants offered by their government support competitions were extremely valuable to the enterprise as they enabled the R&D project. Additionally, the business development training obtained from winning the competitions enabled the start-up to structure their enterprise and distribution channels to match the profiles of their customer base and find opportunities to obtain production funding when external investors were not interested in investing in their enterprise.

In addition to the grants and business development training, the enterprise gained advocacy from winning the competitions held by these initiatives. This sponsorship supported the start-up to build trust in their enterprise's brand and supported the hosting of the crowdfunding campaign as the competitions the enterprise had won could be advertised on the enterprise's website.

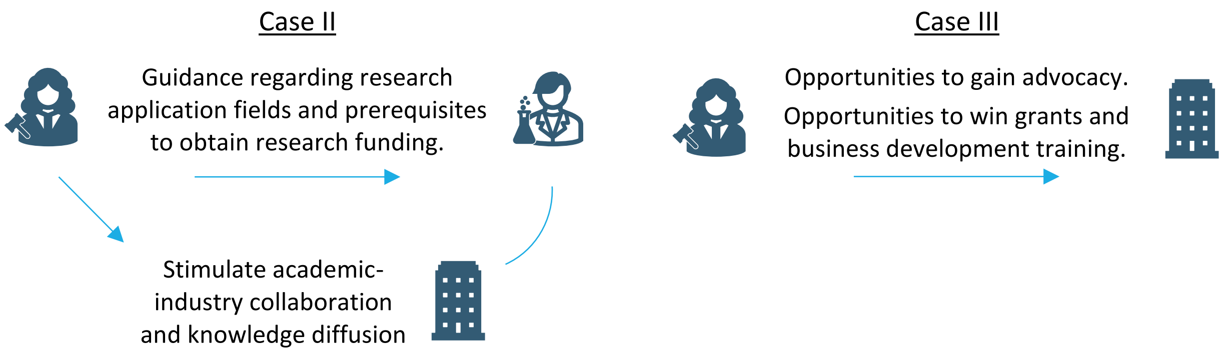


Figure 12.9: Governmental actors' role in Case II and III

12.5.2.3 Industry

In Case II, the industry actors are the observers of the research process who occasionally provide guidance and practical feedback to the researchers when they request it. They are also the product testers upon request of the researchers. According to the research funding agreement, they do not have to contribute any financial or physical resources (only during product testing, which is also not compulsory), only knowledge resources in the form of expertise and guidance. The enterprises also do not have to provide a product or project idea but only observe the research process of the researchers as the research agreement is initiated by the projects suggested by the academics or researchers. In this way, participating (for 'free') in the research process is highly beneficial to the enterprises as they gain a competitive advantage over non-participating enterprises by learning from the researchers throughout the research process before it is documented in the public domain. Their only obligation is to provide practical guidance ad feedback upon request of the academic researchers.

In Case III, the start-up enterprise is the product developer. To gain access to grants, advocacy and business development training, the enterprise participates in all the supporting initiatives hosted in their area. With the grant funding obtained, the enterprise conceptualised a project idea and collaborated with its suppliers throughout the R&D project. Upon completion of the business development training and the feasibility phase of the R&D project, the enterprise utilised its training and found a creative manner to raise production funding. Building on the advocacy gained from the supporting initiatives, the enterprise asked its end-users to pre-order their product. Once the product was developed, the enterprise utilised different distribution channels to expand its client base and sell its product. Through these channels, they discover that a product variant may be developed to reach a new customer market. Once a prototype of the new product variant is available, the enterprise asks for market feedback before the product is manufactured and released into the product market. Additionally, the enterprise adjusts its company structure to suit the profiles of its newfound clients. Although the enterprise's brand had already been established and an international client base had been established, the enterprise continued to participate in the supporting initiatives to gain further advocacy and opportunities to learn from market experts and other enterprises. The start-up also collaborated with nearby universities to share their knowledge with students while gaining access to potential employees.

In Case IV, the enterprises act as the researchers, product developers and end-users. They also do not collaborate with academia as they conduct their own research nor utilise any form of help from the government as the primary enterprise has sufficient physical, financial and knowledge resources. The primary enterprise aims to establish itself in the global AM market. Therefore, once a potential idea to develop a novel AM process and technique was conceptualised, the enterprise utilised a market expert to evaluate the idea's feasibility. Instead, as the primary enterprise has sufficient resources, their challenge is identifying an end-user to utilise or buy their products and services. From experience, the enterprise has learned that it is best to develop novel techniques alongside the products of end users who would purchase the products upon completion of the project. In that way, the products may be examples for future end-users of what the technology or technique may achieve, and the processing technique may be perfected. Once an end-user is identified, the primary enterprise provides all the resources for the R&D project and only expects the end-user to purchase the products upon completion of the project. Due to the relationships established with the end-users throughout the R&D project, the enterprises continued to collaborate on more projects upon the project's conclusion.

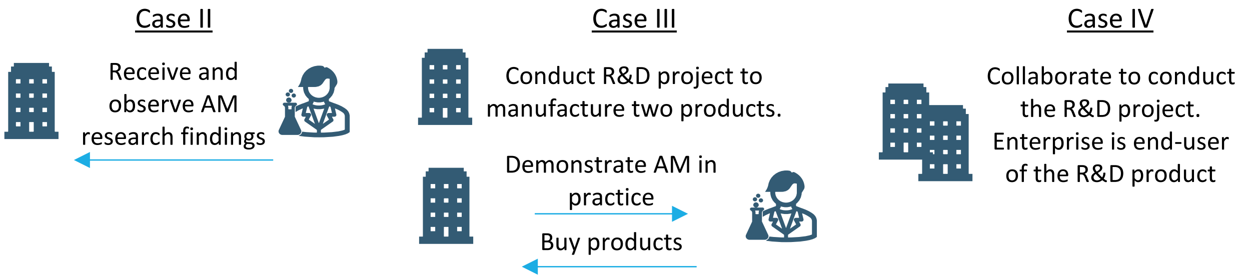


Figure 12.10: Industry's role in Case II, III and IV

Table 12.5: Summary of the Development stage's innovation process mechanisms, associated functional interventions, and outcomes delivered. The cases relevant to the functions, actors, or outcomes are indicated in brackets

R&D mechanisms		Interventions (IS functions)	Actors	Academia requires	Industry requires
Research	**Idea conceptualisation**	• F4 – Funding requirements trigger specific research projects (II) • F5 – Market conditions trigger product ideas (III) • F2 – Research conducted to conceptualise the product idea (II, III, IV)	• Academic researchers (II) • Research funding providers to trigger research (II) • Industry product developers (III, IV) • Market with opportunities (III, IV)	• Prerequisites to research funding, e.g., Industry-based research with industry collaboration (II)	• Market opportunity (II, III, IV)
Research	**Proof of feasibility**	• F3 – Obtain a development partner (II, III, IV) • F4 – Communicate project vision and provide feedback (II, III, IV) • F2 - Feasibility tests (II, III)	• Academic researchers (II) • Industry enterprises (III, IV) • Suppliers (III)	• Expertise in project focus areas or technology (II)	• Expert on proposed project's application or end-users (III, IV)
Enabling	**Obtain funding or collaborative partner**	• F6 – Obtained research or development funding (II, III) • F1 – Start of a project with a commercial aim • F4 – Communicate project vision and provide feedback (II, III, IV) • F7 – Lobbying and trust in the enterprise's brand (III, IV)	• Academic researchers (II) • External funders (II, III) • Industry enterprises (III, IV) • End-users (III, IV)	• Fulfilment of funding prerequisites (II) • Funding from an external funder to conduct research (II)	• Funding to conduct the project (III, IV) • End-user with and form whom the product may be developed (IV) • Lobbying for the enterprise's brand
Research	**Design and development**	• F2 - Product development activities (II, III, IV) • F3 - Collaboration with development partners during R&D (II, IV) • F4 – Communicating feedback and progress to collaborating partners	• Academic researchers (II) • Industry product developers (III, IV)	• Funding and resources to develop the product or technique (II)	• Funding and resources to develop the product or technique (III, IV)
Research	**Field Testing**	• F2 – Product testing activities (II, III, IV) • F4 – Communicating feedback to collaborating partners	• Product testers (II, III, IV) • Academic researchers (II) • Industry product developers (III, IV)	• Industry partner to test the prototypes developed (II)	• Time and resources to conduct field testing (III, IV)
Entrepreneur	**Product commercialisation**	• F1 – Entrepreneurial activities • F3 – Collaborations with different distribution channels • F4 – Feedback from end-users • F6 – Money received from end-users from product purchases	• Industry • Distribution channels • End-users	-	• Distribution channels • End-users purchasing the products

12.6. Suggestions for the South African AM industry based on Cases II, III and IV

From the conceptual framework of the R&D process mechanism and the insights derived for innovation managers, suggestions may be derived for the South African AM innovation system.

12.6.1. Context and outcome suggestions

In the context of *extending AM research*, lessons may be learned from Case II, where a pre-requite was implemented to guide research. In Case II, the German government required research groups to conduct research that addressed industry problems so that more research has the potential to be further developed for adoption in industry as high-value value offerings.

Therefore, in addition to the research focus areas set out by the government in the National AM Strategy, governmental actors may require researchers to conduct industry-specific research that addresses industry needs, particularly SMEs' needs. In this way, enterprises are supported through academic research, and academics have the opportunity to develop products and techniques that can be further developed for commercialisation in industry.

In the context of *enhancing product value*, lessons may be learned from Case IV. In Case IV, the enterprise conceptualised an AM manufacturing technique. Following the *feasibility phase*, they sought an end-user for whom they could develop a new, enhanced product while perfecting their AM technique. In this regard, when the enterprise had perfected its technique, the end-user had an advanced, high-value product that the enterprise could use as an example to advertise its technique. Additionally, the enterprise established a relationship (social capital) with the end-user and continued collaborating with them on new projects.

In the context of the South African AM innovation system, enterprises are encouraged to follow the example of Case IV's enterprise and to obtain end-user participation in developing new value offerings to ensure the practicality and need for the value offering. Additionally, they will have an end-user to purchase the first value offerings and product examples to use as marketing material. Additionally, the enterprises will have the opportunity to establish relationships with the end-users to collaborate on future projects.

12.6.2. Intervention and mechanism suggestions

During the *idea conceptualisation* mechanism, Case II's governmental actors had funding requirements to trigger specific research projects. These included industry-based research topics and industry collaboration (Table 12.5). In Case II, the industry collaboration requirement supported the diffusion of academic, fundamental AM knowledge to SMEs, and academia received practical, industry-based feedback throughout the research process. The industry collaboration also facilitated the *field-testing* phases of the developed prototypes.

In the South African AM context, in addition to the THRIP cost-sharing programme initiated by industry, governmental actors may require researchers to conceptualise research projects and obtain several industry enterprises to participate in their research studies as observers and feedback providers, not financial contributors. In this way, academia is not required to identify enterprises willing to fund research projects as it could delay academic research projects. The participating enterprises also receive free R&D insight without investing in technology or products. As in Case III, the enterprises may also gain access to potential future employees knowledgeable of AM technologies and techniques.

During the *proof of feasibility* mechanism, Case IV consulted a market expert knowledgeable of the application materials and end-users of the proposed AM technique. The expert sheds light on which conceptualised ideas were feasible in the market conditions and identified potential end-users with whom the enterprise could collaborate to develop products and perfect the conceptualised AM technique.

In the South African AM context, industry enterprises are encouraged to consult market experts or conduct extensive market research on the potential application areas, materials and end-users of conceptualised ideas. In this sense, feasible projects without feasible materials or end-users may be stored for future market opportunities, while feasible projects with feasible market conditions may be pursued first.

For the *obtain funding or collaborative partner* mechanism, two lessons may be learned from Case III. First, in Case III, the Canadian government supported enterprises by financially supporting several competitions and initiatives where innovative enterprises could win business training and grants and receive advocacy. For example, the start-up enterprise won business development training and grants from four competitions, which they utilised during *idea conceptualisation* and *feasibility mechanisms*.

Secondly, during the *obtain funding or collaborative partner* mechanism, the enterprise asked end-users to pre-order their products as they did not have the required R&D funding. This was enabled through the brand awareness and advocacy they obtained from the support competitions and initiatives. Similar to Case IV, Case III's product developers thus collaborated with their end-users to ensure a customer segment for their products.

In the South African AM context, several government-funded research projects and AM demonstration centres exist. In addition, however, the innovation system may benefit from government-supported initiatives or competitions such as those of Case III, where AM enterprises, particularly start-ups and SMEs, may gain business skills, guidance, grants for their R&D endeavours and particularly, brand awareness and advocacy. With the advocacy, enterprises may be supported to increase their brand awareness and perhaps find external investors or new application industries and establish (new) collaborations or knowledge networks. Such initiatives or competitions may be hosted by actors such as the CSIR or AM-related technology stations.

Secondly, South African enterprises are encouraged to identify creative channels through which knowledge, guidance and capital may be gained. Similar to Case III's start-up, who established knowledge networks with the enterprises from the support initiative, enterprises are encouraged to establish such networks. Start-ups or SMEs are also encouraged to identify creative channels through which capital may be gained, such as Case III's crowdfunding pre-order campaign.

Finally, several lessons may be learned from Case III for the *product commercialisation* mechanism. In Case III, the start-up used international conferences and exhibitions as a distribution channel for their products and a marketing platform to gain brand awareness. The conferences and exhibitions were explicitly aimed at the public or non-academic actors of society to provide enterprises with a platform to gain brand and product awareness and sell their products. The conferences were also inclusive for various end-users as the start-up researched both end-users who utilised the nozzles manufactured for AM hobbyists and industrial nozzles utilised by manufacturing enterprises and academic institutions.

Within the South African context, the RAPDASA organisation brings academic, knowledge institute and industry actors together through their annual conference. The conference presents academic actors with the opportunity to share their research with other researchers and attend industry enterprises. Knowledge of AM technologies is thus annually shared between academic actors and enterprises who choose to participate in the conference. The South African AM innovation system may thus benefit from industry- and public-based conferences, exhibitions, and trade shows, where the South African public, academic and industry actors may purchase or view the South African enterprises' value offerings. Such conferences, exhibitions and trade shows are encouraged to be inclusive for various end-users to ensure that both hobbyist and industrial users are reached. Such conferences, exhibitions and trade shows may then be advertised to a vast range of enterprises to ensure that different application industries are exposed to the technology, enabling the potential development of novel AM applications and products.

12.6.3. Hypotheses to be tested in South African AM industry survey

Based on the insight derived from the conceptualised framework and the suggestions for the South African AM industry based on Cases II, III and IV, hypotheses may be derived to be tested in the South African AM industry survey presented in Chapter 13.

To test whether South African AM enterprises follow Case IV's example of obtaining end-user participation in the development of new value offerings, especially when new techniques are developed, the following hypothesis may be derived.

CH1: The surveyed AM enterprises often collaborate with end-users to develop new AM techniques or products to ensure the commercialisation of the products and AM techniques.

The following hypothesis may be derived to test whether South African AM enterprises prefer collaborating with end-users to academic actors, as in Case IV.

CH2: Established AM enterprises prefer to collaborate with end-users rather than academia.

The following hypothesis may be derived to test whether, as in Case II, a culture or programme exists where South African enterprises may collaborate in academic research projects as observers and not as financial contributors, such as in the THRIP programme.

CH3: The South African AM enterprises are unaware of any AM research culture or programme where industry may participate in academic research studies as research observers.

Additionally, the following hypothesis may be derived to identify whether enterprises are willing to collaborate with academia and present them with industry-based needs as concepts for research projects, as in Case II.

CH4: The South African AM enterprises share their industry needs or needs for fundamental AM research with academia to stimulate industry-focused research projects and gain access to academic R&D projects.

The following hypothesis may be derived to test whether South African enterprises consult market experts or conduct extensive market research during the proof of feasibility mechanism.

CH5: South African AM enterprises conduct feasibility studies on conceptualised project ideas and consult market research to ensure the feasibility of their ideas.

To test whether innovation support opportunities, such as those that supported Case III's start-up, or AM supporting regulations exist in South Africa, CH6 was derived.

CH6: There are regulations or innovation support opportunities that support start-up enterprises within the AM industry.

The following hypothesis may be derived to test whether South African enterprises use end-user pre-order campaigns such as Case III during the *obtain funding or collaborative partner* mechanism.

CH7: To gain access to funding, South African AM enterprises utilise end-user funding campaigns rather than traditional money lending channels, such as those from banks or external investors.

The following hypothesis may be derived to test whether enterprises collaborate to share resources and knowledge, as in Cases II and IV.

CH8: The South African AM enterprises form strategic alliances or collaborations to access more resources.

To test whether government support initiatives or competitions exit where enterprises may win or gain training, grants and or advocacy, as in Case III, CH9 is derived.

CH9: Support initiatives or competitions are available to South African enterprises to obtain AM or business training, grants and brand awareness.

To test whether industry-based conferences and exhibitions exist, such as in Case III, to sell and advertise their value offerings to the South African public, hypothesis CH10 may be derived as follows.

CH10: The South African AM conference is primarily an academic research conference.

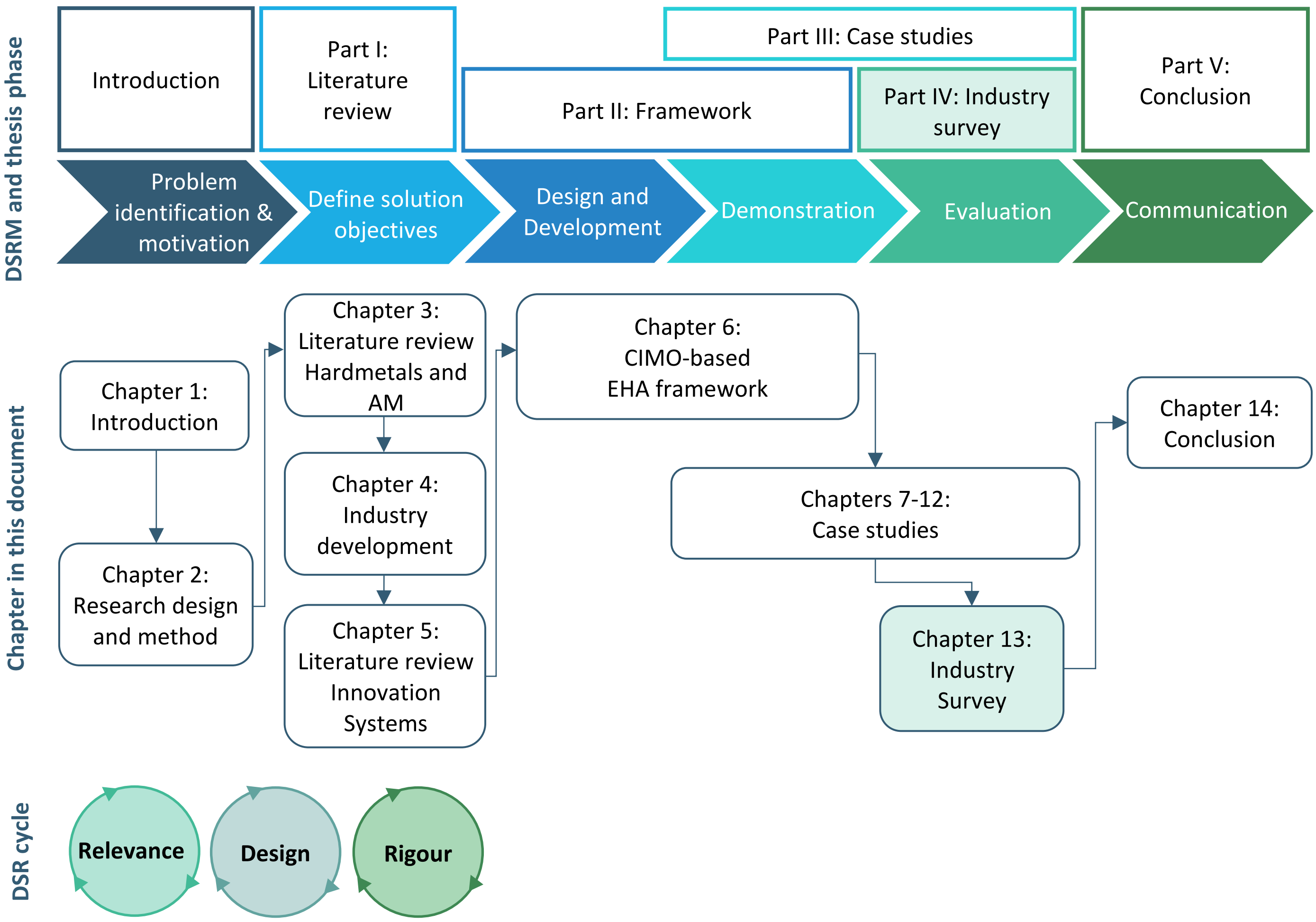
12.7. Chapter 12 summary

In this chapter, the insights derived from cases II, III and IV were compared to identify the contexts, interventions, and mechanisms required to cross the valley of death and achieve desired outcomes. From these insights, this study suggests that crossing the Valley of Death implies successfully completing six distinct R&D innovation process mechanisms. Additionally, from these insights and mechanisms, hypotheses were derived to be tested in the South African-based industry survey. This chapter satisfies objective VI, as mentioned in §1.4.

This chapter concludes Part III. Part IV presents the development of a survey instrument and its application to South African AM enterprises.

Part IV

Industry survey



Chapter 13

Industry survey

The previous five chapters presented the application of the CIMO-based EHA framework to the four `AM for hardmetal' case studies and the case synthesis chapter. This chapter aims to gain insights into the South African manufacturing industry by applying the framework functional indicators in the form of a survey instrument. This chapter satisfies Objective VII, as mentioned in §1.4.

Chapter 13 contribution:

- A novel methodology to measure innovation system functions.
- A functional framework from which a survey instrument may be derived.
- An application of the survey instrument to the South African AM enterprises.
- Analysis of survey data of approximately 80% of the South African AM enterprises.
- Derivation of policy support suggestions based on the survey response data.

Chapter 13 objectives:

- Present an introduction to surveys (§13.1).
- Demonstrate the survey validation process (§13.2).
- Define survey candidate inclusion criteria (§13.3).
- Present an overview of the data analysis methodology (§13.3.3).
- Analyse survey responses (§13.4).

This chapter starts with an introduction to survey studies and their benefits and drawbacks. Then, the survey construction and expert review process, describing the survey development and validation process, is detailed. Finally, the survey response data is presented along with statistical analysis and data visualisation.

13.1. Introduction to surveys

Fuller, Warren and Argyle [81] define a survey as a list of questions aimed at extracting specific data from a particular group of people. The design of surveys depends on a researcher's objective [82]. For example, it may include collecting exploratory information such as qualitative information to understand an artefact better or the generation of hypotheses on a subject. It may also include collecting quantitative information to test specific hypotheses generated previously [82], [83].

Formal standardised surveys are used when researchers want to test and quantify hypotheses and statistically analyse the obtained data. According to Crawford [82], they are typically characterised by:

- prescribed wording and order of questions to ensure that each respondent receives the same stimuli,
- prescribed definitions or explanations for each question to ensure interviewers handle questions consistently and may answer respondents' requests for clarification, and
- prescribed response format to enable rapid completion of the questionnaire during the interviewing process.

As humans differ and perform tasks differently, Crawford [82] suggests four points be kept in mind during survey development.

- *A well-designed questionnaire should meet the research objectives*. Often, essential survey questions are omitted due to inadequate preparation and inadequately probing of issues due to poor understanding. However, all surveys are bound to leave some questions unanswered and provide a need for further research, but well-designed surveys aim to minimise these problems.
- *Obtain complete and accurate information*. Survey designers should ensure that respondents comprehend the questions and reduce the likeliness of respondents refusing answers, lying, or concealing their attitudes. Well-designed surveys are organised and worded to encourage respondents to provide accurate, unbiased, and complete information.
- *Well-designed surveys are easy to complete and record feedback*. Therefore, a survey should enable respondents to provide the necessary information as seamlessly as possible and interviewers to record the answers quickly. Consequently, it should be arranged to enable sound analysis and interpretation.
- *Short interviews are essential*. Hosting short and to-the-point interviews with survey respondents is essential to ensure that the survey is answered, and respondents remain interested throughout the interview.

The benefits of survey studies include that they are relatively easy to administer, may be administered online, and advanced statistical techniques can be utilised to analyse the qualitative and quantitative aspects of the survey responses. However, survey instruments also have several drawbacks. They include, amongst others, a low response rate, respondents feeling surveys are too time-consuming to complete, and biased questions that influence responses. Additionally, if the survey questions are too closed-ended, extra insights may not be gained from the framework. The following sections discuss how these drawbacks were overcome.

13.2. Survey expert review process

As the framework of innovation system functional indicators (Figure 6.6) presents TIS scholars with the innovation activities required for conceptualising, developing, and diffusing innovations, a survey instrument could be derived from the indicators to determine how well TISs fulfil their innovation activities. Therefore, the frameworks' functional indicators informed survey statements to analyse a TIS's challenges and opportunities. The survey development underwent several iterations to ensure that the survey was comprehensive and unambiguous and that all essential questions were included. Cassim's [83] seven-step survey design process (Table 13.1) was used.

Table 13.1: Survey design

Steps	Description
1. Specify the required information	Specify the purpose and the aim of the survey.
2. Specify the content of questions	Specify the aim of each question.
3. Specify the structure of questions	Specify whether closed-ended, open-ended, or both types of questions will be asked - state whether multiple-choice, Yes-No, or explanatory answers will be required.
4. The careful wording of questions	Use specific words such as "once or twice" instead of "occasionally" or "sometimes."
5. Determining the sequence of questions	The most important questions must be placed at the start of the survey and less essential questions towards the end.
6. Determining the layout of the survey	State the scope of the survey and divide the survey into theme-based sections.
7. Pilot testing of the survey	Test whether similar individuals to those who will be surveyed understand the contents of the survey in the manner intended.

As established by Fuller, Warren and Argyle [81], the normative value of research may be tested by the extent to which relevant individuals deem the artefact and ideas behind it to be of value. The validation of the survey questions was therefore tested via expert analysis. In this study, the expert analysis took the form of semi-structured interviews (*process followed documented §6.2*) with experts who were asked their perspectives on the rationality and applicability of the survey questions to achieve the survey's above-mentioned goal.

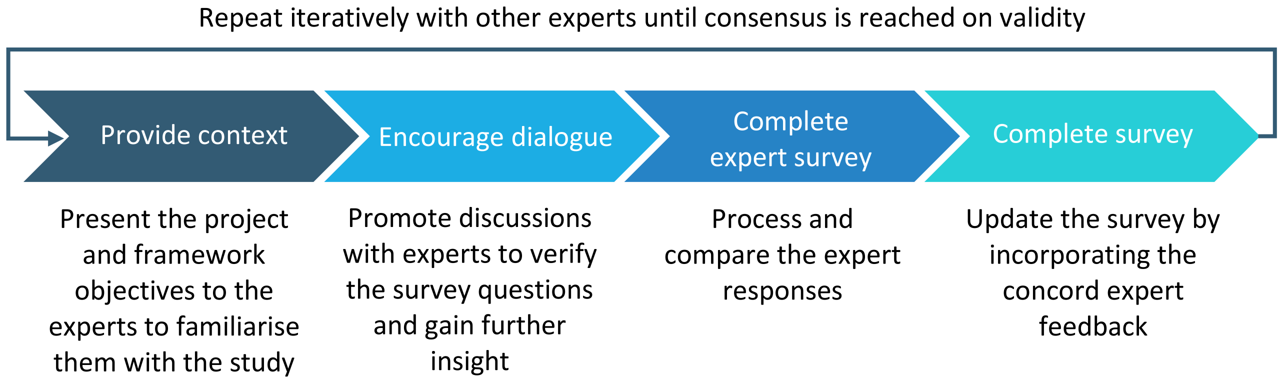


Figure 13.1: The expert interview validation process

As presented in Figure 13.1, the expert review process was initiated with a presentation of the project and framework objectives to minimise ambiguity regarding the survey questions, how they were arrived at, or how they were presented in the survey. Next, a discussion was held to address aspects of concern, after which validation questions on the survey were answered. Finally, the expert responses were summarised and compared before the necessary amendments were made. The data capturing was regulated by the Stellenbosch REC's ethical guidelines.

13.2.1. Survey expert reviewers

Nine expert reviewers were interviewed. The expert consisted of two industry practitioners, three innovation system researchers, three experts active in both industry and the innovation system research environments and one statistics expert (Table 13.2 and Figure 13.2). In addition, each expert (E#) reviewer was assigned a unique identifier for reporting purposes to maintain their anonymity.

Table 13.2: Characteristics of the survey's expert reviewers

Expert	Domain: Research or industry	Years of experience	Validated the framework, indicators, or the survey	Field of expertise
E1	Both	25+	All three	Innovation management and sustainable development
E2	Research	12	All three	Innovation systems and management
E3	Research	8	All three	Innovation and industrial systems, industrial policy
E4	Both	22	All three	Technology and innovation management
E5	Both	20	All three	Innovation management, business development
E6	Research	23	All three	Innovation systems and management
E7	Industry	12	Survey	Additive manufacturing and tungsten carbides
E8	Industry	6	Survey	Additive manufacturing
E9	Research	31	Survey	Statistics

Six of the nine experts were part of the group who validated the CIMO-based EHA framework as they were very knowledgeable of the IS framework and the functional indicators. However, three additional experts were consulted. Two experts were knowledgeable in additive manufacturing (AM) and the South African AM

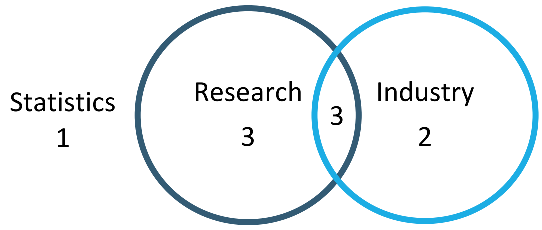


Figure 13.2: Domains of interviewed experts

industry. Furthermore, the final expert is knowledgeable in statistics and the analysis of survey data. The selection of the experts was based on their expertise, years of experience, and ability to provide credible and accurate information.

- Innovation systems: Experts with many years of experience, a thorough understanding and practical application experience of the innovation system framework were selected for consultation. These experts provided valuable insight into the framework structure, the framework indicators, and the indicators' application to an enterprise-level survey. In addition, these experts provided practical insight on the utilisation of the framework by innovation scholars and policy developers and on the innovation insight that may be gathered from the industry survey.
- Additive manufacturing: Experts with practical knowledge of the South African additive manufacturing (AM) industry at the forefront of best practices and independent research with several AM technologies and materials were selected for consultation. These experts also have first-hand experience in the South African AM industry's development and provided practical insight and understanding into the dynamics of the AM industry and its enterprises. Finally, they provided insight into the application of the indicators to an industry-level survey.
- Statistics: An expert with over thirty years of expertise in statistics, data analysis, and data modelling in the research and industry domains was selected for consultation. The expert reviewed the statistical analysis capability of the survey before it was released to the survey respondents and assisted in analysing the survey responses. On the survey responses, the expert reviewer guided the identification of the appropriate data analysis utilised based on the (formative) data gathered. Furthermore, they provided insight into the statistical tests that could be performed on the continuous and categorical data of the demographic and functional sections.

In this way, the collective knowledge of the experts provided validation of the survey from both the innovation system and additive manufacturing focus. Convergence was found early in the screening interview process, with the positive feedback indicating that the experts generally deemed the survey questions valid.

13.2.2. Expert reviewer suggestions

The expert reviewers suggested that

- E6: "*The survey should be more industry-friendly. Theoretical questions should be simplified to be more user-friendly.*"
- E7: "*The survey should be shortened to include only the most important questions and remove "interesting-to know" questions.*"
- E5 and E8: In the demographic section, the survey should classify respondents according to the level to which AM technology has been implemented. The reviewers suggested the following categories: 'Not

interested in implementing the technology,' 'Currently investigating implementing an AM technology,' 'Have implemented AM technology' and 'Our business is solely based around additive manufacturing.'

- E1 and E3: For function *F1 - Entrepreneurial Activity*, the expert reviewers suggested questions that assess whether South African enterprises seek to compete with international AM enterprises or primarily South African-based enterprises. They suggested that it would support the identification of external AM industry competitors.
- E1, E2, E5: For function *F4 - Guidance of Search*, the reviewers suggested that a ranking question be included that prompts the respondents to rank blocking mechanisms in order of their hindrance. E5: "*All blocking mechanisms are relevant. Rather, ask respondents to rank them according to their level of hindrance.*"
- E2: "*For F6 – resource mobilisation, an additional availability and accessibility question should be added to determine the root cause of insufficient resources. If, for example, a resources type is asked, ask the respondent to rank the resources' availability from one to x and their accessibility from one to x.*"
- E4: "*Data resources are becoming increasingly more important to enterprises, especially to manufacturing enterprises which implement AM systems, as data sharing is essential to the printing of a component. I think you should test the respondents' opinions on data resources and how important they are compared to physical, financial and knowledge resources.*"

After the interviews, the expert's suggestions were incorporated into the survey. The survey was updated with the additional questions and new forms of asking questions. The survey was also shortened as proposed by the experts, after which the survey questions were once again validated. Figure 13.3 presents the verified and validated final framework of IS functional indicators from which the survey questions were derived. The addition of the data resources to the F6: Resource Mobilisation function is indicated in blue.

13.3. Survey construction

The following sections reflect on the surveyed enterprises and the captured data. The succeeding section details the survey results obtained.

13.3.1. Sample selection

A good sample selection is fundamental as it allows one to generalise the findings from the sample to the population, which is the whole purpose of survey research. Therefore, to ensure the findings could be generalised.

Owners and managers of South African additive manufacturing (AM) enterprises were surveyed. This includes enterprises offering AM value-added services and those selling AM systems as sales representatives for international AM system manufacturers. The majority of the AM survey sample was constructed from the service provider directory of the RAPDASA organisation, globally the oldest AM association and the official mouthpiece of the South Africa AM industry, as well as the CAMASA (Commercial Aerospace Manufacturing Association of South Africa) membership directory, an aerospace association promoting advanced manufacturing in South Africa. Other respondents were found via an ad hoc approach of scouring the internet for AM services. Survey responses were also asked for referrals to other AM enterprises. As most of the respondents came from the RAPDASA and CAMASA databases, the credibility of the respondents was ensured.

From the RAPDASA and CAMASA databases, it was found that approximately fifty AM enterprises are operational in South Africa. Thus, approximately fifty enterprises in South Africa offer AM value-added

Entrepreneurial Activity

- Projects with commercial aims
- Technology demonstrations
- Portfolio expansions
- Entry of firms
- Manufacturing, constructing, or installing technology

Knowledge Diffusion

- Alliances between actors
- Joint ventures
- Training activities
- Setting up branch organisations
- Awareness campaigns
- Conferences, workshops, seminars, and meetings
- Demonstrations

Market Formation

- Market regulations
- Regulations supporting niche markets
- Reforming regulations
- Setting tax incentives and tax exemptions
- "Obligatory use"
- Subsidies (the cost-sharing of investment)
- Public procurement
- Expectations

Creation of Legitimacy

- Lobbying activities
- Advice
- Advocacy coalitions actors

Knowledge Development

- (Academic) Research studies
- Feasibility studies
- Pilot projects
- Developing prototypes
- Testing of model performance
- Adapting model
- Assessing the availability of raw materials
- Conducting impact analysis
- Market surveys
- Technology literacy of entrepreneurs
- Learning by doing and using

Guidance of Search

- Setting policy targets and standards
- Research outcomes
- Designing favourable regulations and policies
- Defining expectations and communicating vision
- Promises
- Providing directions or showing interest
- Communicate research outcomes to the public

Resource Mobilisation

- Financial resources
  - Financial incentives
  - Subsidies
  - Investments
- Physical resources
  - Infrastructure development
  - Providing equipment
- Knowledge resources
  - Recruiting human resources
- Data resources
  - Databases and data sharing

Figure 13.3: Innovation system functional indicators framework

services or sell AM systems. A RAPDASA management committee member and the two AM survey expert reviewers verified this number.

13.3.2. Survey instrument design

An invitation email was sent to forty-nine potential respondents, which, over 45 days, produced 40 enterprises willing to participate in the study. Thus, approximately 80% of the South African AM enterprises were surveyed. The forty enterprises delivered thirty-five complete survey responses from South African AM enterprises. The survey instrument can be found in Appendix C. Unfortunately, five incomplete responses were removed from the online survey tools' database (SurveyMonkey) due to the respondents abandoning the survey after only addressing the demographic section. From the demographic data captured prior to their impromptu abandoning of the survey, the incomplete responders were young micro-enterprises that offered ad hoc AM printing services of plastic parts. However, when these respondents were contacted, it became apparent that the survey was abandoned due to the limited number of functionalities the micro-enterprise respondents were performing and fulfilling.

13.3.3. Appropriate data capture

This section presents the data analysis applied to the survey data. The type of data gathered is also discussed.

13.3.3.1 Reflective and Formative measurement models

Measures or indicators can be distinguished as either one that is influenced by (reflect) or influence (form) latent variables [412]. Measurement model misspecification occurs when researchers ignore the directional relationship between indicators and constructs of phenomena [412]. Reflective latent variables show that changes in the indicators reflect changes in the underlying latent construct. For example, as shown in Figure 13.4, a diet is indicated by a person's food choice. In addition, the indicators are subjected to measurement errors in the reflective model. Therefore, reflective measurement models validate the indicators influenced by their latent variables [412]. Subsequently, indicators should possess internal consistency.

In contrast, in formative composite variables, the indicators influence the construct. Therefore, the indicators of formative latent variables are often referred to as *causal* indicators, and the construct is often termed a *combination or composite* variable, indicating that the indicators cause the construct [412]. For example, as shown in Figure 13.4, a balanced diet, regular exercise, and sufficient sleep contribute to a healthy lifestyle. Subsequently, internal consistency is not implied.

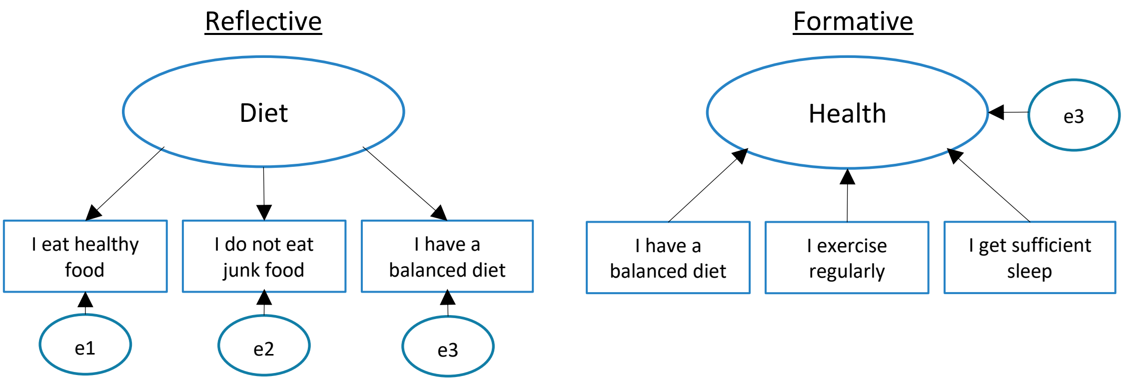


Figure 13.4: Example of relative and formative composite variables

As mentioned above, the survey aimed to gain insight into the dynamics of the South African AM enterprises and investigate whether the programmes and support documented in Case I on the South African AM industry were still operational and which additional programmes had developed. The survey's aim was thus not to validate the indicators of the IS functions as it was already verified and validated by the expert reviewers of the CIMO-based EHA framework and the survey indicators and questions. Therefore, the survey did not assess whether the IS indicators were relevant or applicable to IS functions but instead to what extent activities related to the indicators are performed (extent), how they are viewed (importance), and what effort is put into them (difficulty). For example, for the F1: Entrepreneurial activity indicator *projects with commercial aims*, the survey assessed through which channels or sources projects with commercial aims were identified and the amount of effort each channel or source requires.

The survey thus presented formative data on the functions rather than reflective data. As internal consistency is not implied in formative data, the Cronbach reliability analysis, which assesses the internal consistency of indicators, does not apply to the survey data. Furthermore, as the survey delivered thirty-five complete responses, the sample size of the data was too small for a structural equation model, which typically comprises sample sizes of 150 responses or more, to be developed. However, variance and regression analysis were applied to the survey data, as shown in Figure 13.5. The statistics software, STATISTICA [413], was utilised for all data analysis.

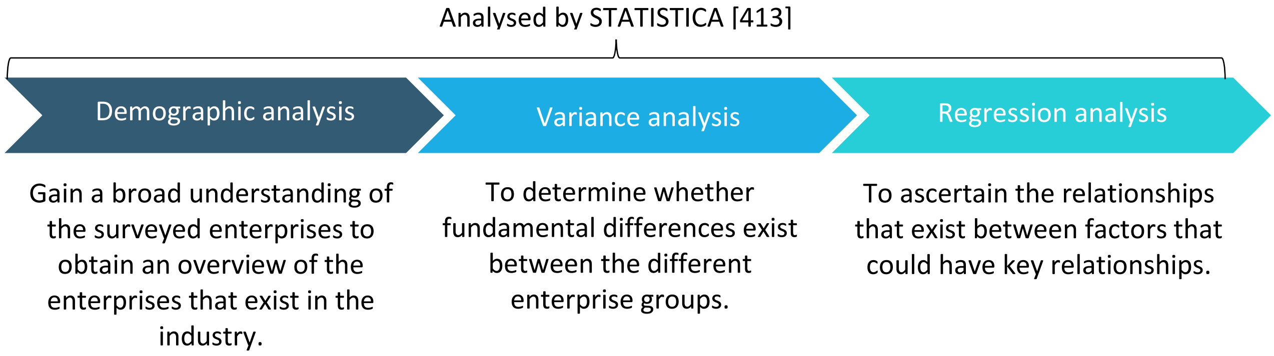


Figure 13.5: Survey data analysis

13.3.3.2 Demographic analysis

Categorical data analysis is used to organise observations into groups that share a common trait. Demographic data may be defined as categorical data. Demographic data was captured to gain insight into the types of AM enterprises operational in South Africa, their age, size, number of employees, materials they specialise in, and the industries to whom they usually provide services or sell AM systems.

13.3.3.3 Variance analysis

Ordinal data were captured using Likert scale ratings on the indicator activities of the IS functions to gather insight into the operational dynamics of the South African AM enterprises. Five-point Likert scale ratings (Table 13.3) were used to ask the respondents to rate their perception of the importance of the activities to the enterprise and how difficult they are to perform. Finally, the respondents were asked to rate their perception of the extent to which their enterprise performs the activities.

Table 13.3: Likert scale ratings utilised in the survey

	Likert scale ratings	1	2	3	4	5
Indicators	Level of Importance	Very low importance	Low importance	Moderate importance	High importance	Highest importance
	Level of difficulty	Very easy	Easy	Moderate	Difficult	Extremely difficult
	Extent performed	Not at all	To a small extent	To some extent	Moderate extent	Large extent

Figure 13.6 presents the mappings approaches considered for the Likert scale data. The mappings of the Likert scale data gathered on the functional indicator activities (Figure 6.6) allow the identification of improvement opportunities and functions that require specific attention. Thus, the mappings allow a form of *gap analysis.*

Figure 13.7, based on the Importance-Performance Analysis work of Martilla and James [414], focuses on identifying improvement priorities and provides the guideline followed in this study to identify improvement opportunities and functions that require specific attention. First, an indication of priority is placed on high-importance indicator activities that are either easy to perform or currently performed to a small extent. For maximised results, strategic improvement actions should be, in particular, applied to the activities in this

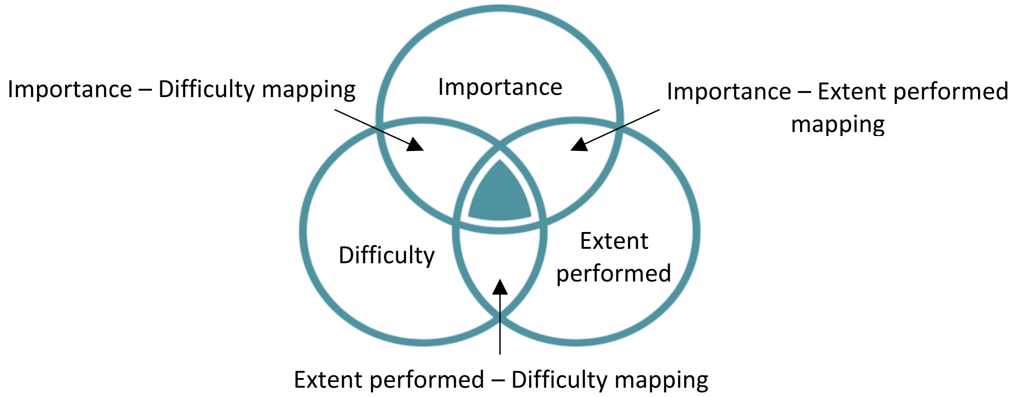


Figure 13.6: Functional analysis approach

quadrant [414]. Thereafter, priority should be placed on low-importance activities performed less but are easy to perform [414]. The third priority should be given to activities of high impact and difficulty that are also performed to a large extent. Finally, low-importance activities that are difficult to perform and performed primarily should be prioritised [414]. In this study, Martilla and James' [414] importance-performance Analysis approach will be applied to the functional analysis approach presented in Figure 13.6.

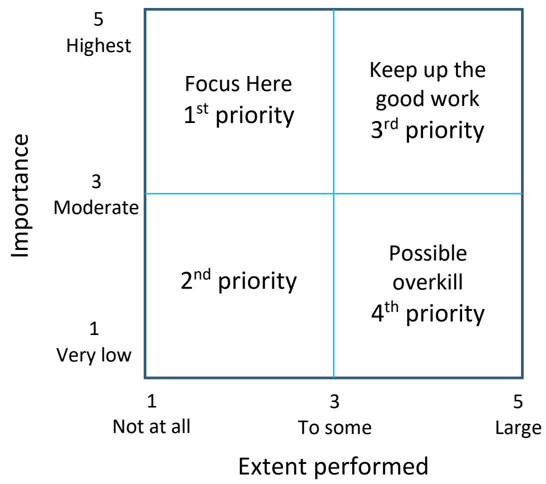


Figure 13.7: Functional analysis mapping and priority focus areas

To analyse the ordinal data, the ANOVA F-test was used. The analysis of variance (ANOVA) test allows a comparison of more than two groups to determine whether a relationship exists between them [415]. The ANOVA F-test was used to compare categorical data with ordinal data (Likert scale data). The F-test tests the equality of the two population variances. It is designed to compare the dispersion (variance) of two normally distributed and independent datasets with the null hypothesis that no difference exists. The F-test also incorporates the p-value factor. As the dataset is relatively small, the statistics expert reviewer suggested utilising a significance level of 10% to assess null hypotheses. Therefore, a p-value of $p < 0.1$ represented statistical significance between datasets.

Cross tabulation tests were used to compare two categorical variables, for example, the materials enterprises use against the economic sector in which they operate. The Fisher's exact test was used to assess the independence between two variables when the comparing groups were independent and not correlated. The chi-squared test was also considered for analysis. However, it was not selected as it applies an approximation assuming large samples, while the Fisher's exact test runs an exact procedure, especially for small samples [415]. The Fisher's exact test assesses the independence of two groups with the null hypothesis that the groups are equal or not different. It incorporates the p-value factor, which is the probability that measures the evidence against the null hypothesis. A p-value of $p < 0.1$ indicated statistical significance between datasets.

13.3.3.4 Regression analysis

Regression analysis is a statistical process that estimates the relationships among variables, generally focusing on the relationship between a dependent variable and one or more independent variables. The dependent variable is denoted by X and is known as the explanatory variable, while the independent variables are denoted by Y and are known as the response variable or predictors.

Two correlation types are associated with regression analysis. First, Pearson's correlation is used for parametric statistics (when data is assumed to follow a normal distribution) to assess the strength and direction of the linear relationship between two continuous variables [415]. The non-parametric equivalent to Pearson's correlation is Spearman's rank correlation and is appropriate when at least one of the variables is measured on an ordinal scale. It determines the strength and direction of the monotonic relationship between two variables. The Pearson and Spearman correlation coefficients range from -1 to +1 [415].

As the survey data gathered is predominantly ordinal with few outliers, representing monotonic relationships, Spearman's rank correlation is most often utilised to report the strength and direction of the association between two variables. Table 13.4 presents Montgomery and Runger's [415] guideline range of Rho (ρ) values utilised in this thesis, which relate to the strength of the correlation between variables (the guidelines apply to both positive and negative correlations). A zero value indicates no association or correlation between the two variables. Values above zero indicate a positive association, indicating that when one variable's values increase, the other variable's value also increases. A negative value indicates a negative association, indicating that when one variable's value increases, the other variable's value decreases [415].

Table 13.4: Correlation strength guidelines [415]

Intermediate	Very weak	Weak	Moderate	Strong	Very strong
$\rho = 0$	$\rho < 0.2$	$\rho < 0.4$	$\rho < 0.6$	$\rho < 0.8$	$\rho < 1.0$

13.3.3.5 Hypothesis derived to be assessed

Along with estimating the relationships among the data, regression and variance analysis will also be used to test the hypothesis formulated in the previous case synthesis chapter and the new hypothesis formulated for the demographic and functional survey data.

<u>Case study hypothesis:</u>

CH1: The surveyed AM enterprises often collaborate with end-users to develop new AM techniques or products to ensure the commercialisation of the products and AM techniques.

CH2: Established AM enterprises prefer to collaborate with end-users rather than academia.

CH3: The South African AM enterprises are unaware of any AM research culture or programme where industry may participate in academic research studies as research observers.

CH4: The South African AM enterprises share their industry needs or needs for fundamental AM research with academia to stimulate industry-focused research projects and gain access to academic R&D projects.

CH5: South African AM enterprises conduct feasibility studies on conceptualised project ideas and consult market research to ensure the feasibility of their ideas.

CH6: South African AM enterprises strive to identify regulations or innovation support opportunities that support start-up enterprises within the AM industry.

CH7: To gain access to funding, South African AM enterprises utilise end-user funding campaigns rather than traditional money lending channels, such as those from banks or external investors.

CH8: The South African AM enterprises form strategic alliances or collaborations to access more resources.

CH9: Support initiatives or competitions are available to South African enterprises to obtain AM or business training, grants, and brand awareness.

CH10: The South African AM conference is primarily an academic research conference.

<u>Demographic hypothesis</u>

To determine whether statistically significant differences exist between the sectors, ages, sizes, and stances on AM of the surveyed enterprises, the following null hypotheses were formulated:

H1: The enterprises' stance on AM is similar for manufacturing enterprises and retailers.

H2: The enterprises' ages are similar for manufacturing enterprises and retailers.

H3: The enterprises' stance on AM is similar for the different ages of the enterprises.

H4: The size of the enterprises is similar for manufacturing enterprises and retailers.

H5: The size of the enterprises is similar for the different ages of the enterprises.

H6: The size of the enterprises is similar for the different stances on AM.

<u>Functional hypothesis</u>

To determine whether statistically significant differences and correlations exist between the activities of the functional indicators and different demographical indicators, the following null hypotheses were formulated:

H7: There is a strong positive correlation between the indicator activities the enterprises deem important (or unimportant) and the activities they perform to a large extent (or to a small extent).

H8: There is a statistically significant difference between the sector of the enterprises and the constraints that hinder them from developing innovative solutions.

H9: There will be a statistically significant difference in the resources the manufacturing and retailing enterprises deem essential.

H10: There is a strong positive correlation between the ages of enterprises and the availability of financial resources and technology infrastructure.

H11: There is a positive correlation between the ages of the enterprises and the availability and accessibility of financial, physical and knowledge resources.

H12: There is a positive correlation between the size of the enterprises and the availability and accessibility of financial, physical and knowledge resources.

H13: The availability of resources is positively correlated to the strength of the knowledge network.

13.4. Data analysis

This section discusses and analyses the feedback of the thirty-five complete survey respondents. A demographic analysis of the survey responses is presented first. Thereafter, the data gathered on each IS function is presented. Finally, the section concludes with insight gathered from all the functions combined. Statistica [413] was used to process the data.

13.4.1. Demographic analysis

This section aims to outline the AM enterprises included in this study. The distribution of the enterprises according to the economic sector they are operating in is presented in Figure 13.8. The secondary sector enterprises are those that use AM technology to provide value-added or manufacturing services. These enterprises made up 63% of the surveyed sample. The enterprises in the third economic sector, presenting 37% of the surveyed sample, represent the enterprises selling AM systems as sales representatives for international AM system manufacturers. These enterprises shed light on the South African end users who acquire AM systems. The surveyed sample thus included more enterprises providing AM services than enterprises selling AM systems. The AM value-added services enterprises included industry companies, technology stations and national centres.

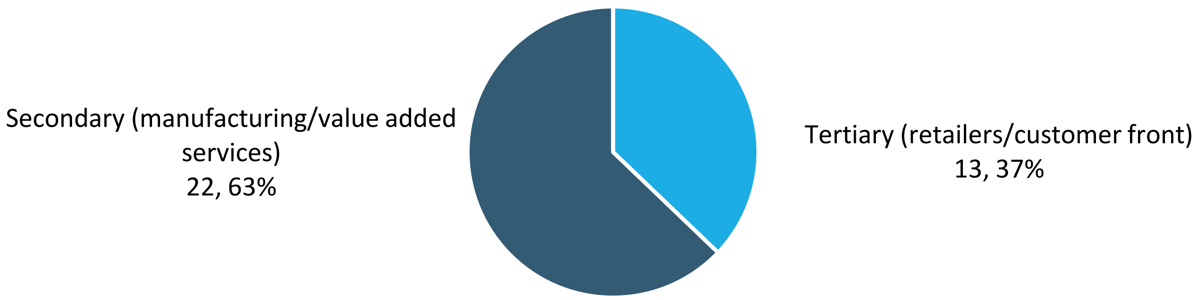


Figure 13.8: The distribution of the surveyed enterprises according to the economic sector they are operating in

When asked their stance on AM technology, AM manufacturing enterprises indicated that 59% are solely based on AM, while 41% use AM technology as an additional manufacturing technology (Figure 13.9). The AM retailers indicated that 62% are solely based on AM, while 38% sell AM systems as an additional manufacturing technology. Sixty percent of the surveyed AM enterprises are solely based on AM systems, while 40% use or sell AM technology as part of their offered manufacturing services or products.

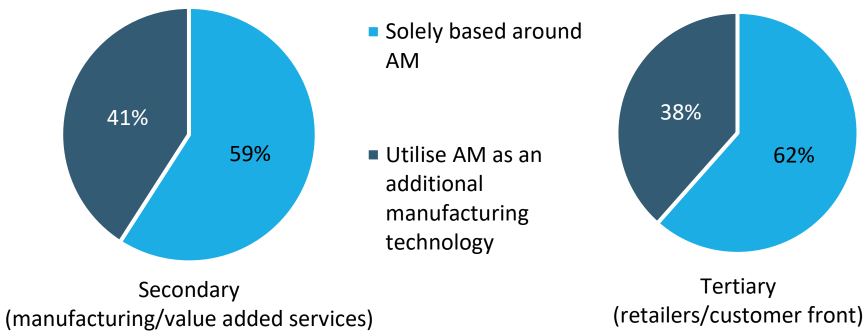


Figure 13.9: Surveyed enterprises' stance on AM

Most South African AM manufacturing enterprises and AM retailers are six to ten years old (59% and 46%, respectively), as presented in Figure 13.10. However, only five surveyed enterprises are older than ten years (9% and 23%), while eleven are five years or younger. This indicates that the industry primarily comprises enterprises established after the 2012 South African AM adoption boom (Case I) that are now well established, while a few new companies have also been established in the past five years.

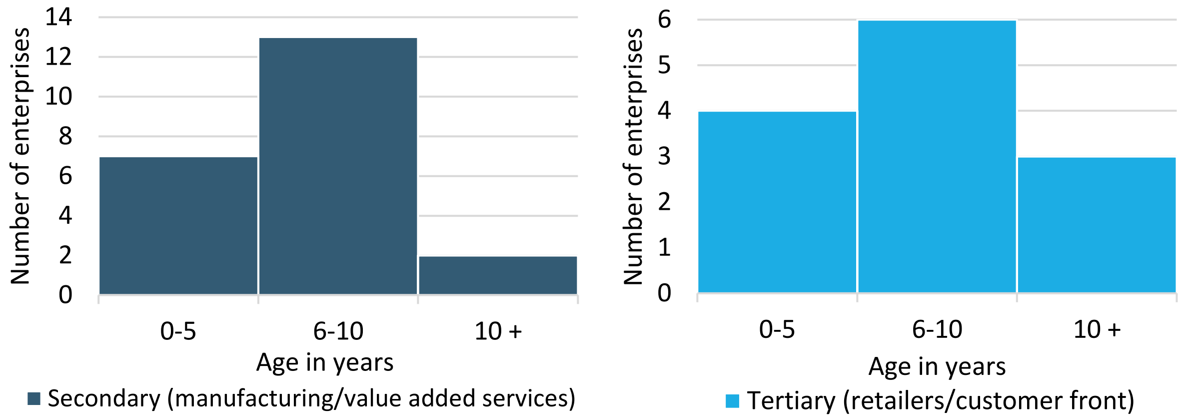


Figure 13.10: Age of the surveyed enterprises

The South African National Small Business (NSB) Act 102 of 1996 defines a small business as a separate entity operating within any economic sector or sub-sector. A small business can be classified as a micro-enterprise, a very small enterprise, a small enterprise, or a medium enterprise [416]. Table 13.5 presents the SMMEs definitions defined by the NSB Act of South Africa.

Table 13.5: Definitions of small, medium, and micro enterprises (SMMEs) given in the National Small Business Act [416]

Enterprise Size	Number of Employees	Annual Turnover in South African Rand	Gross Assets, Excluding Fixed Property
Micro	Fewer than 5	Less than R150,000	Less than R100,000
Very Small	Fewer than 10 to 20, depending on the industry	Less than R200,000 to R500,000, depending on the industry	Less than R150,000 to R500,000, depending on the industry
Small	Fewer than 50	Less than R2 million to R25 million, depending on the industry	Less than R2m to R4.5 million, depending on the industry
Medium	Fewer than 100 to 200, depending on the industry	Less than R4 million to R50 million, depending on the industry	Less than R2 m to R18 million, depending on the industry

The South African AM manufacturers and retailers are predominantly micro and very small enterprises, accounting for 43% and 31% of the surveyed sample (Figure 13.11). Only four enterprises employ more than fifty employees. With a p-value of $p = 0.19 > 0.1$, the ANOVA F-test indicate that no statistically significant difference exists between the sizes of the surveyed enterprises and the sectors in which they operate. Therefore, the South African AM manufacturers and retailers are micro or very small enterprises.

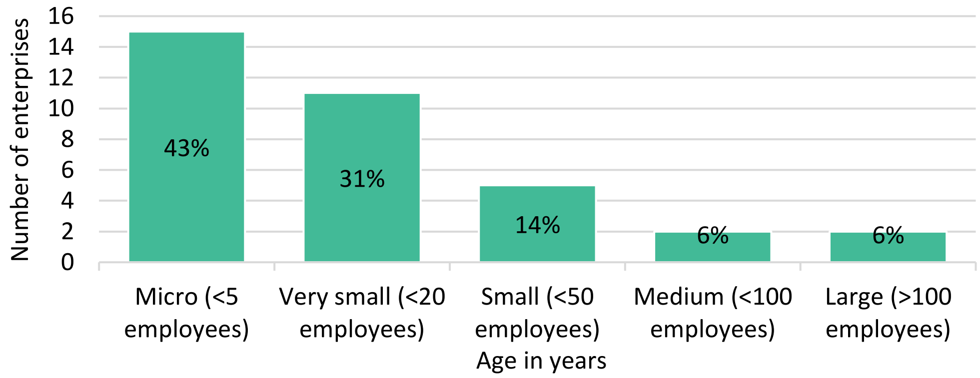


Figure 13.11: Sizes of the surveyed enterprises

The manufacturing materials the AM manufacturing enterprises (secondary) and AM system retailers (tertiary) typically specialise in or utilise are presented in Figure 13.12. Most South African AM enterprises utilise some form of plastic material. During the survey introduction interviews, the AM manufacturing enterprises mentioned that plastic AM systems are typically used for prototyping before final parts are manufactured. Furthermore, AM system retailers mentioned the benefit of selling fused deposition modelling (FDM) systems as the South African AM hobbyist market is continuously growing. Both ferrous and non-ferrous metals were very popular amongst AM retailers and service providers, while composites and non-ferrous metals were less prevalent among AM system retailers. It is thus evident that composite materials such as hardmetal are more common amongst AM manufacturing enterprises than AM systems retailers.

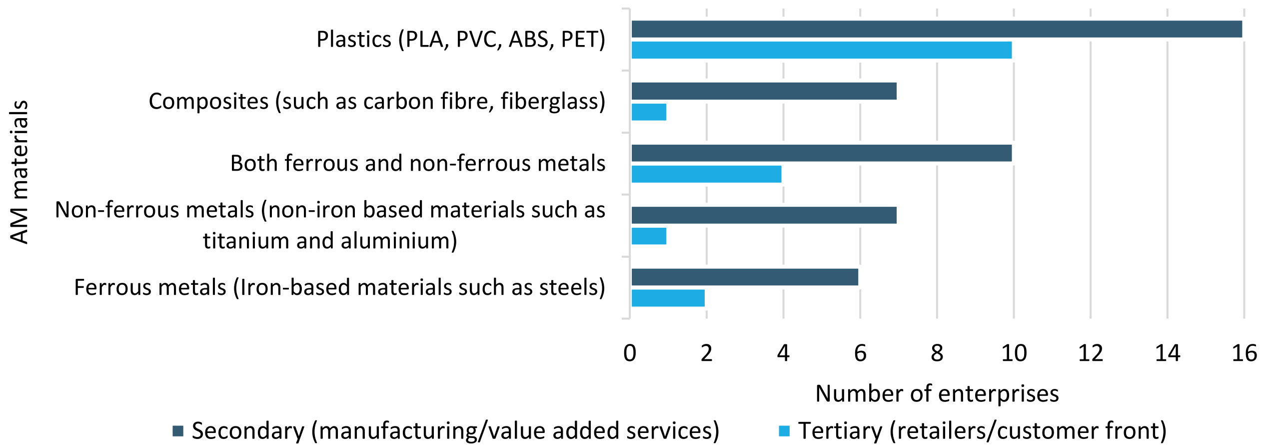


Figure 13.12: The manufacturing materials the surveyed AM enterprises typically specialise in or utilise

Given the utilised materials, the surveyed enterprises were asked to estimate the revenue percentage their enterprises gain from delivering AM services or systems to different application industries. Figure 13.13 presents these application industries. Figure 13.14 indicates that metal AM printing is mainly utilised for research and development (R&D) and the tooling and medical and dental industries. In contrast, composites and plastics materials are mainly utilised for R&D and by AM hobbyists. Additionally, plastics and composites are highly utilised by *others*, including the jewellery, marketing, filming, architecture (3D models of maps and structures), and energy industries. It is thus evident that metals are used to manufacture expensive, highly specialised parts and components such as dental implants, medical devices, and wear-resistant tools, while plastics and composites are used to manufacture less expensive and specialised components such as jewellery, toys, architectural models and film and marketing props and products.

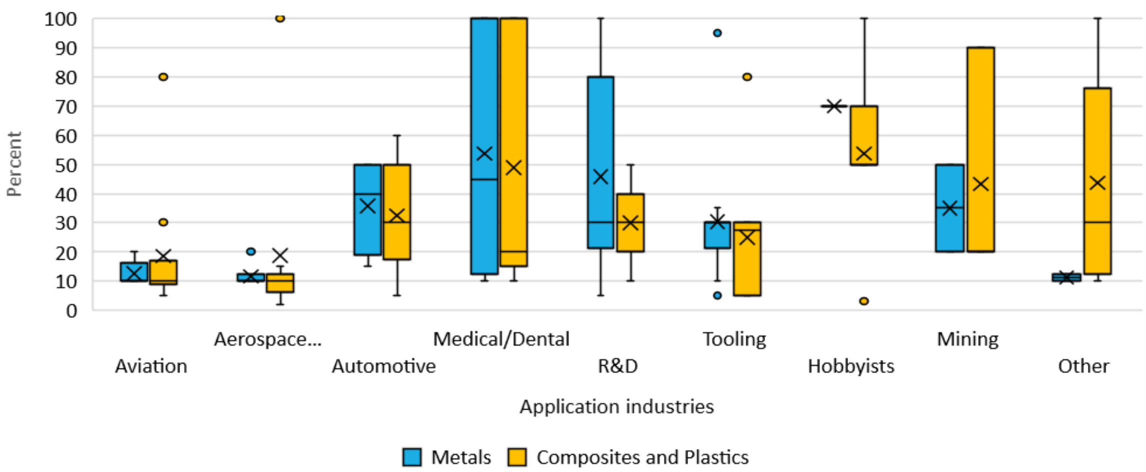


Figure 13.13: Revenue percentages gained from the application industries in terms of the materials utilised

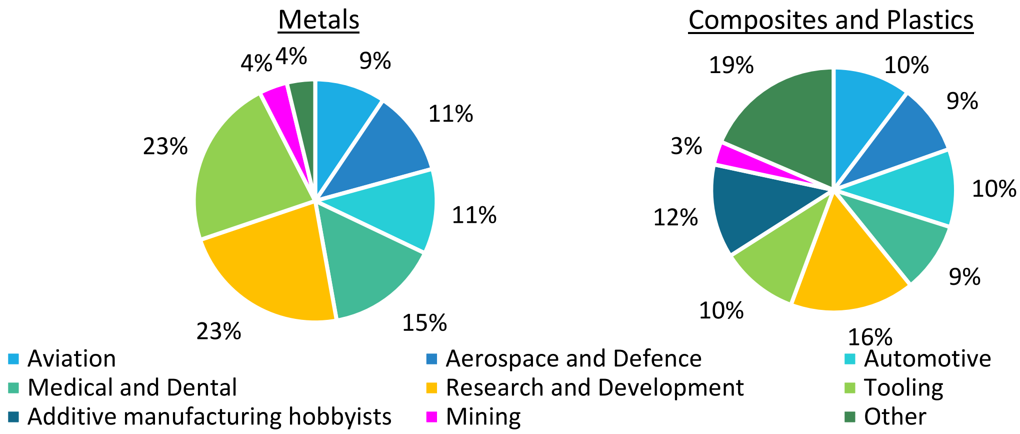


Figure 13.14: Application industries of the surveyed enterprises in terms of the materials utilised

Figure 13.13 presents the percentage revenue gained from these application industries. Overall, the revenue percentages vary significantly amongst the South African enterprises as most of the industries' revenue percentages range over more than 30%. For example, the medical and dental industry varies between 10% to 100% of revenue income, indicating that some AM enterprises focus solely on providing AM services to the medical and dental industry, while others generate very little revenue from the industry. Although the medical and dental industry's plastic and metal revenue range both have an upper limit of 100%, the median of the plastic and composite AM is much lower than the metal AM, indicating that 50% of plastic and composite AM enterprises typically gain lower than 20% revenue from the medical and dental industry, while 50% of the metal AM enterprises gain more than 45% revenue from the medical and dental industry. Thus, metal AM typically gains higher revenue from the medical and dental industry than plastic AM enterprises.

The aviation and aerospace and defence industries have the smallest revenue percentage variation. Furthermore, they are the industries from which AM enterprises least generate revenue, as both typically contribute less than 20% of revenue. However, their outliers indicate that two enterprises utilising plastic and composite materials generate 80% and 100% revenue from the aviation and aerospace and defence industries, respectively.

Although the average revenue percentages gained from metal AM from R&D is 15% higher than the plastic AM, the metal AM has a much more considerable variation, indicating that the revenue plastic AM enterprises gain from R&D are typically similar, ranging between 20% to 40%. In contrast, the revenue metal AM enterprises gain from R&D varies significantly between enterprises, ranging between 20% to 80%. The mining industry indicates the opposite, as the metal AM has much lower variation than the plastic AM although the plastic AM has a higher average revenue.

Finally, the average revenue gained from plastic AM for AM hobbyists and multiple *other* industries is approximately 55% and 45%. As previously mentioned, the *other* industries include the jewellery, marketing, filming, architecture, and energy industries. The variance of the *other* industries is almost double that of the hobbyist as their revenue ranges between 10% to 100% compared to 50% to 100%. This indicates that the income generated from the hobbyist industry is typically similar between AM enterprises, while the revenue plastic AM enterprises gain from *other* industries varies significantly between enterprises.

13.4.2. F1: Entrepreneurial activity

The surveyed enterprises were asked to rate their perception of how important certain activities are to their enterprises, how difficult they are to perform and to what extent they are performed. In Table 13.6 and Table

13.7, dark blue indicates high importance, difficulty, and performance of a large extent, while white indicates very low importance, difficulty, and performance of a non-existent extent. Furthermore, green indicates activities that differ statistically significantly across the two sectors in which the enterprises operate and their age groups.

The AM enterprises offering AM value-added services indicated that to identify projects with commercial aims, they look at international trends (1) and opportunities presented by their end-users (3). Secondary enterprises, however, tend to utilise international trends (1) more than tertiary enterprises (and find it a lot easier) as they differ statistically significantly in their ratings. Although it is typically easy to attend conferences (2), the surveyed enterprises do not attend conferences and exhibitions to identify project ideas as the AM conferences are typically more academic based than industry based. Start-ups typically find it significantly more difficult to identify projects with commercial aims at exhibitions and conferences (2) than established enterprises and attend them significantly less frequently. Start-ups instead find international trends (1) and end-users (3) more important to identify projects with commercial aims. The South African AM industry will thus benefit from industry-based exhibitions and trade shows, such as those attended by Dyze Design in Case III, where the South African public and academic and industry actors may purchase or view the enterprises' product and service offerings.

Table 13.6: The average rantings of the F1 - Entrepreneurial activity related indicator activities in terms of sector and importance, difficulty and extent performed. Statistically significant differences exist when $p < 0.1$.

		Importance			Difficulty			Extend performed		
		Secondary	Tertiary	p	Secondary	Tertiary	p	Secondary	Tertiary	p
1	Commercial projects from international trends	4.3	3.3	**0.07**	2.2	2.9	**0.06**	4.3	3.3	**0.06**
2	Commercial projects from conferences	3.0	2.5	0.3	2.6	2.5	0.7	3.0	2.2	0.1
3	Commercial projects from end-users	4.2	3.9	0.4	2.8	2.2	**0.04**	4.3	4.0	0.4
4	South African customers	4.1	4.6	0.1	3.5	3.2	0.4	4.2	4.5	0.3
5	South African suppliers	2.2	3.5	**0.02**	3.5	2.9	0.4	1.8	3.2	**0.02**
6	South African companies	3.2	3.4	0.6	2.7	3.7	**0.0**	3.3	3.6	0.4
7	International companies	3.3	1.6	**0.09**	4.4	4.8	0.1	2.0	1.4	**0.07**
8	Demonstrating technology	3.4	3.3	0.8	3.3	3.0	0.5	2.9	3.5	0.2

White (1) – Very low importance, very easy, and not performed.
Dark blue (5) - Highest importance, extremely difficult, performed to a large extent

Table 13.7: The average rantings of the F1 - Entrepreneurial activity related indicator activities in terms of age and importance, difficulty and extent performed.

		Importance			Difficulty			Extend performed		
		0-5	6+	p	0-5	6+	p	0-5	6+	p
1	Commercial projects from international trends	4.0	3.9	0.8	2.6	2.5	0.6	4.0	3.9	0.9
2	Commercial projects from conferences	2.4	3.0	0.1	3.4	2.2	**0.0**	1.8	3.0	**0.05**
3	Commercial projects from end-users	4.5	3.9	**0.09**	2.8	2.5	0.4	4.3	4.2	0.8
4	South African customers	3.8	4.5	**0.05**	3.3	3.4	0.5	3.9	4.6	**0.03**
5	South African suppliers	2.9	2.6	0.6	3.2	3.8	**0.09**	2.4	2.4	1.0
6	South African companies	3.0	3.5	0.3	3.1	3.0	0.7	2.8	3.6	0.1
7	International companies	2.6	1.8	0.1	4.0	4.7	**0.04**	2.0	1.6	0.3
8	Demonstrating technology	3.2	3.5	0.6	3.2	3.2	1.0	2.9	3.1	0.7

Established enterprises find it significantly more important to identify South African customers (4) than start-ups and identify them to a larger extent. Both sectors find it very important and moderate to very difficult to identify South African customers (4). However, the sectors differ statistically significantly in their preference to buy AM systems from South African suppliers (5). Established enterprises also find it significantly more difficult than start-ups. At least one South African AM enterprise manufacture AM systems, while several manufactures AM consumables. However, most tertiary enterprises function as sales representatives for international AM system manufacturers. For these enterprises, buying from local AM companies is therefore essential.

A secondary enterprise mentioned that *"…the South African manufactured* (AM) *systems and powders do not deliver the required accuracy and quality of those delivered by international manufacturers. So, we have to import systems from the US and Europe and powder from China, or our clients won't be happy with the quality of our products".*

In contrast, a tertiary enterprise argued that "*because my focus is on selling FDM 3D printers to the hobbyist, I would rate buying from South African suppliers an importance rating of 4/5. Hobbyists don't really import themselves because it is too expensive. They like buying from local suppliers because we can let them test the printers and carry all the risk."* Additionally, another tertiary enterprise mentioned "f*or example*, *I have been a South African agent for EOS for many years, so I have good relations with them. I want South Africans to buy their metal 3D printers from me instead of directly from EOS* (in Germany) *because I know their products like the back of my hind. I can assist my buyers when they struggle. They don't have to request help from EOS; they don't have to YouTube how the printers work. I know how they work."*

Tertiary enterprises find competing with other South African AM enterprises significantly more difficult than secondary enterprises (6). This is due to the tertiary enterprises acting as sales agents for the international AM system manufacturers. However, established enterprises find it of higher importance to compete with other South African AM enterprises than start-ups and therefore perform it to a larger extent. Furthermore, both sectors find it very to extremely difficult to compete with international AM enterprises (7). Established enterprises also find it significantly more difficult than start-up enterprises. Therefore, AM enterprises deem it of low importance and perform it minimally. Finally, both sectors and ages find it moderately important and difficult to demonstrate new technology to potential investors before installation (8) as they rather self-fund the enterprises. It is, therefore, performed to a moderate extent.

13.4.3. F2: Knowledge development

The surveyed enterprises were asked to rank how knowledge is gained from the least utilised (1) source to the most often utilised (5) source. Figure 13.16 presents their responses per sector. The secondary AM enterprises (blue) utilise experimentations as their most utilised information source, followed by information gained from their end-users (similar to Case IV), other enterprises in their value chain, academia and finally, a knowledge network of companies. In contrast, the end-users are the AM system retailers (orange) most utilised sources of information, followed by the extermination, a knowledge network of companies, companies in their value chains and academia as the least utilised source of knowledge and information.

The p-values indicate that the secondary enterprises surveyed value experimentation and collaborating with academia significantly ($p = 0.06$ and $p = 0.04 < 0.1$) more than tertiary enterprises. This is expected from manufacturing enterprises that perform R&D activities. However, both sectors mentioned that collaborating with academia is not preferred as it typically involves a long administrative process before experimental results are obtained. Therefore, niche products or AM processes take too long to develop. Enterprises, therefore, prefer to experiment in their own facilities, collaborate with end-users on projects, and utilise academic journal articles as research sources. Secondary enterprises also very often consult the suppliers in

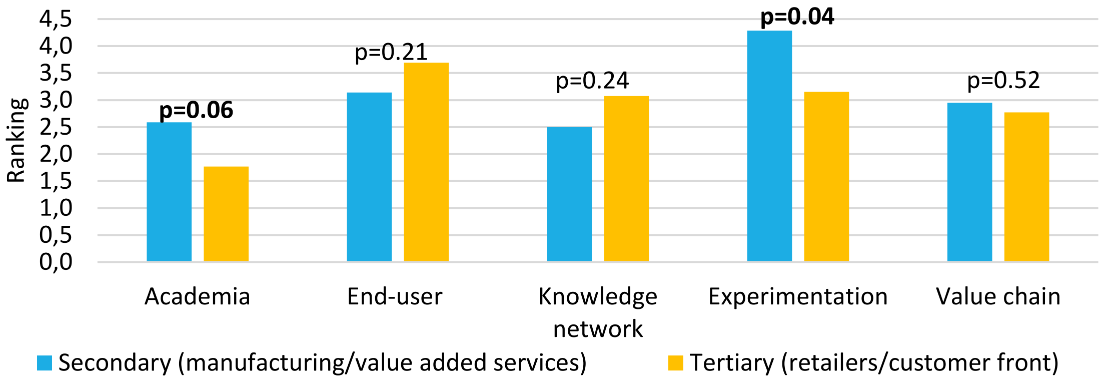


Figure 13.16: The average ranking scores of the knowledge sources utilised by the surveyed enterprises in terms of sector. 5 – Most utilised, 1 - Least utilised. Statistically significant difference exists when p < 0.1

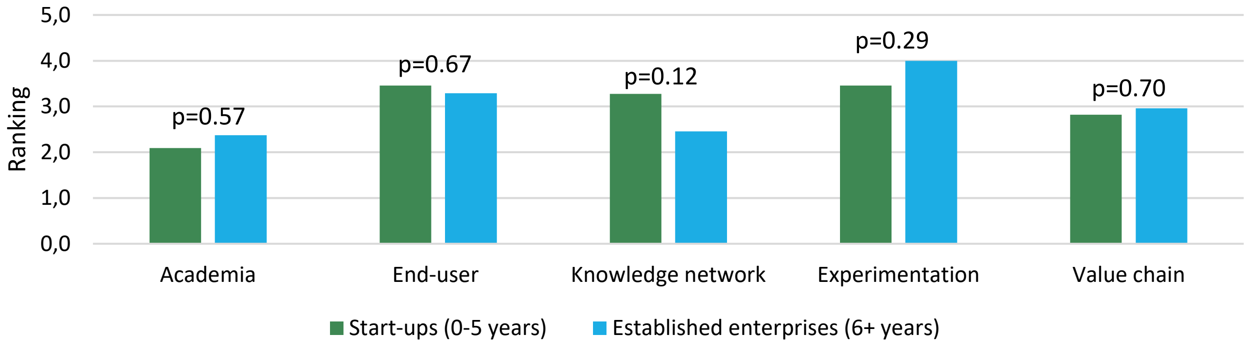


Figure 13.15: The average ranking scores of the knowledge sources utilised by the surveyed enterprises in terms of age. 5 – Most utilised, 1 - Least utilised

their value chain during product development to ask for advice regarding "*material or powder specifications or post-printing heat treatments*."

Figure 13.15 presents the ratings of the knowledge scores in terms of the enterprise age categories. Start-ups (green) rate experimentation and end-users as the most utilised sources of knowledge and academia as the least utilised source. The established enterprises had similar ratings but had a higher utilisation rating for experimentation and a much lower rating for knowledge networks. Therefore, established companies rely less on knowledge networks than start-ups and rely more on experimentation.

As mentioned in §13.4.3, during the introduction interviews with the surveyed enterprises, the enterprises mentioned that they are unaware of any culture or programme where industry may participate in academic research studies as research observers, such as the research culture mentioned in the Fraunhofer case study, Case II. The THRIP programme, mentioned in Case I, requires enterprises to initiate research projects with academia and enterprise funding substituted by governmental funding. The CPAM programme also requires the participating enterprises to conduct research. To stimulate academic-industry collaboration in the AM industry, governmental AM research funding organisations should perhaps consider including industry involvement in academic research projects as a prerequisite to obtaining research funding, similar to Case II. In this way, AM research will be diffused into industry, industry's practical expertise may be diffused into academia, and industry may identify future employees with AM experience (Case III).

13.4.4. F3: Knowledge diffusion

When the surveyed enterprises were asked to rate their perception of how important the following activities are to their enterprises, how difficult they are to perform and to what extent they are performed, they provided the feedback summarised in Table 13.8 and Table 13.9. Maintaining information-sharing networks with other companies (13) is of moderate to high importance to both sectors and relatively easy to maintain to a large extent. However, initiating collaborative projects with other South African companies (14) is of moderate importance and difficulty to start-ups and secondary and established enterprises and, therefore, only performed moderately. Tertiary enterprises, however, differ statistically significantly as they find initiating collaborative projects of very low importance as their primary collaborations are with the international brands they sell.

Table 13.8: The average ratings of the F3 - Knowledge diffusion related indicator activities in terms of sector and importance, difficulty and extent performed. Statistically significant difference exists when p < 0.1.

		Importance			Difficulty			Extend performed		
		Secondary	Tertiary	p	Secondary	Tertiary	p	Secondary	Tertiary	p
13	Maintaining an information-sharing networks	3.6	3.6	1.0	2.7	2.5	0.7	3.9	3.8	0.7
14	Initiating collaborative projects with other companies	3.1	2.2	**0.05**	3.4	3.2	0.6	3.2	2.4	0.2
15	Strategic alliances for resource benefits	2.8	1.8	**0.02**	3.7	4.5	**0.01**	2.6	1.7	**0.04**
16	Collaborate with academia and government	3.3	2.9	0.4	3.2	3.3	0.8	3.1	2.9	0.6
17	Collaborating with end-users	3.9	2.9	**0.02**	2.9	2.7	0.5	3.9	2.9	**0.03**
18	Launching marketing campaigns	3.4	2.9	0.2	2.7	3.0	0.3	3.4	3.0	0.3
19	Attending conferences and exhibitions	3.1	2.9	0.7	2.5	2.4	1.0	2.9	3.2	0.7
20	Attracting customers with the company brand	4.6	4.6	0.9	2.8	2.6	0.5	4.4	4.5	0.6

White (1) – Very low importance, very easy, and not performed.
Dark blue (5) - Highest importance, extremely difficult, performed to a large extent

Furthermore, strategic alliances with companies with similar end goals to obtain resource benefits (15), such as funding and lower costs materials, are of low to moderate importance to secondary AM enterprises and are therefore only utilised moderately. In contrast, tertiary AM enterprise finds it relatively unimportant and seldom utilise it. However, both sectors indicated it is very difficult to form strategic alliances as enterprises find the South African AM industry to be small and very competitive and do not want to collaborate. Start-ups also find it statistically significantly more important and less difficult than established enterprises and perform it to a slightly larger extent.

The secondary enterprises indicated moderate importance of collaborating with academic and governmental actors (16) but relatively high importance of collaborating with end-users (17). These enterprises mentioned the moderately high difficulty of collaborating with academics and governmental actors as collaboration with these actors includes a very timely administrative process. Therefore, these companies only collaborate with these actors to a moderate extent while preferring to collaborate more with their end-users, who are easier to collaborate with. However, tertiary enterprises find it of low importance to collaborate with academic and governmental actors and moderate importance to collaborate with end-users, as collaborating with these actors is moderate to highly challenging. Both age groups also find collaborating with end-users of higher importance than academics and governmental actors and therefore collaborate accordingly.

Table 13.9: The average rantings of the F3 - Knowledge diffusion related indicator activities in terms of age and importance, difficulty and extent performed.

		Importance			Difficulty			Extend performed		
		0-5	6+	p	0-5	6+	p	0-5	6+	p
13	Maintaining an information-sharing networks	3.7	3.6	0.7	2.7	2.6	0.7	3.9	3.8	0.8
14	Initiating collaborative projects with other companies	3.5	3.0	0.3	3.5	3.2	0.6	3.0	3.0	0.2
15	Strategic alliances for resource benefits	3.1	2.1	**0.05**	3.5	4.2	**0.06**	2.6	2.1	0.3
16	Collaborate with academia and government	3.2	2.7	0.3	3.1	3.3	0.3	2.8	2.9	0.9
17	Collaborating with end-users	3.7	3.4	0.5	2.6	2.9	0.3	3.4	3.6	0.6
18	Launching marketing campaigns	3.2	3.2	1.0	2.8	2.9	0.7	3.5	3.2	0.5
19	Attending conferences and exhibitions	3.0	3.0	1.0	2.8	2.4	0.1	2.7	3.3	0.3
20	Attracting customers with the company brand	4.5	4.7	0.7	3.0	2.6	0.2	4.2	4.6	0.2

Finally, both sectors and age groups indicated the moderate importance of attending and marketing their companies at conferences and exhibitions (19). However, although advertising at conferences and exhibitions is relatively easy, the enterprises feel it is too academic based and does not attract enough non-academic end users. Therefore, they tend to focus instead on launching marketing campaigns (18). However, both sectors highlighted the importance of attracting companies with their brands (20) and indicated that they are currently successfully attracting customers through their brands without launching a few marketing campaigns.

13.4.5. F4: Guidance of search

The surveyed enterprises were asked to rank the constraints that block or inhibit the development of innovative solutions from most constraining (1) to least constraining (6) (Figure 13.17 and Figure 13.18). Furthermore, they were asked to rate their perceptions of the importance and difficulty certain activities once again are to their enterprises and the extent to which they are performed (Table 13.10 and Table 13.11).

As Figure 13.17 indicates all p-value factors values above 0.1, the rankings of the two sectors do not differ statistically significantly. The most significant constraint for the secondary or value-adding enterprises is the lack of sufficient resources, as their average ranking is closest to 1. Following the lack of sufficient resources are unsupportive market conditions, lack of sufficient supply chains, customer resistance to change, lack of legislative support, and internal resistance to change. Furthermore, the largest constraint of tertiary enterprises is the unsupportive market conditions. Following unsupportive market conditions are the lack of

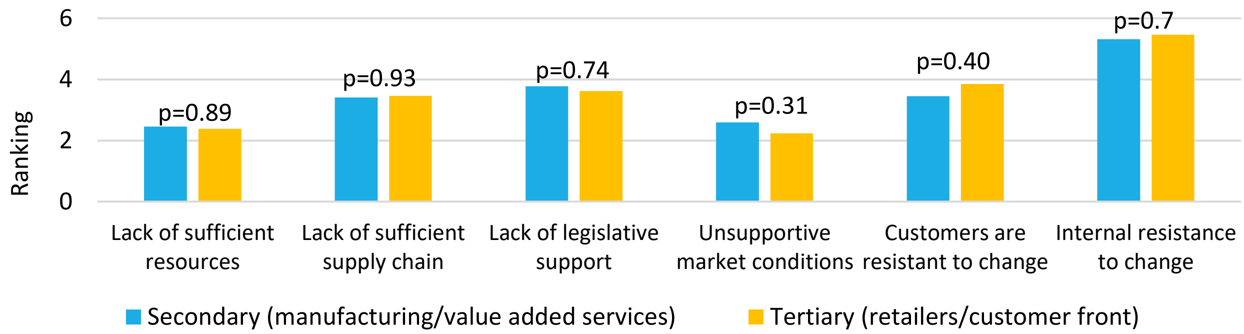


Figure 13.17: The average ranking scores of the constraints that block the development of innovative solutions from most constraining to least constraining. 1 – Most constraining, 6 – Least constraining. Statistically significant difference exists when p < 0.1.

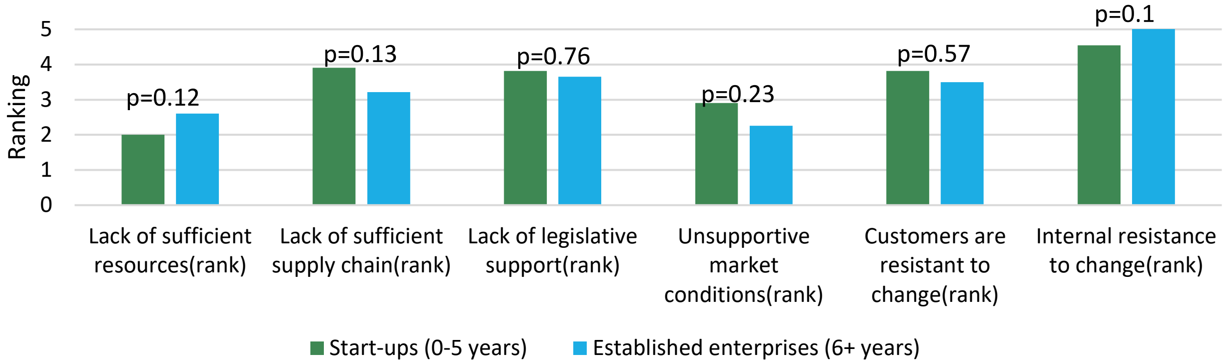


Figure 13.18: The average ranking scores per age group of the constraints that block the development of innovative solutions from most constraining to least constraining. 1 – Most constraining, 6 – Least constraining

sufficient resources, lack of sufficient supply chains, lack of legislative support, customer resistance to change, and finally, internal resistance to change.

The constraint ratings for both start-ups and established enterprises are very similar. Both start-ups and established enterprises find a lack of sufficient resources as the largest constraint, followed by unsupportive market conditions, lack of legislative support, customer resistance to change, lack of sufficient supply chains, and internal resistance to change.

Thus, insufficient resources and unsupportive market conditions are the most constraining mechanisms blocking innovative development for both sectors and age groups. Both constraints include that AM systems and materials must be imported from Europe, the US and China, as it is either not produced in South Africa or the quality of the locally produced products is not of sufficient standard.

Table 13.10: The average rantings of the F4 – Guidance of search-related indicator activities in terms of sector and importance, difficulty and extent performed.

		Importance			Difficulty			Extend performed		
		Secondary	Tertiary	p	Secondary	Tertiary	p	Secondary	Tertiary	p
21	Outlining clear innovation objectives in the company strategy	3.7	2.9	**0.01**	2.8	2.6	**0.01**	3.4	2.9	**0.01**
22	Encouraging a continuous improvement culture	4.1	3.4	**0.02**	3.0	2.4	0.13	3.8	3.2	**0.01**
23	Identifying laws and regulations that support or benefits companies that use AM technologies or offer AM products and services	3.0	2.0	**0.10**	3.7	4.1	0.2	2.5	1.9	**0.04**
24	Improving the company employees' confidence in the abilities of new technologies	4.1	4.3	0.7	3.0	2.3	**0.08**	3.7	4.4	0.5
25	Improving employees' confidence in the company's ability to utilise the abilities of new technologies	4.2	4.3	**0.10**	2.8	2.6	0.9	3.7	4.4	0.3

White (1) – Very low importance, very easy, and not performed.
Dark blue (5) – Highest importance, extremely difficult, performed to a large extent

Table 13.11: The average rantings of the F4 - Guidance of search-related indicator activities in terms of age and importance, difficulty and extent performed.

		Importance			Difficulty			Extend performed		
		0-5	6+	p	0-5	6+	p	0-5	6+	p
21	Outlining clear innovation objectives in the company strategy	3.7	2.9	**0.03**	2.8	2.6	0.6	3.4	2.9	0.3
22	Encouraging a continuous improvement culture	4.1	3.4	0.10	3.0	2.4	**0.07**	3.8	3.2	0.2
23	Identifying laws and regulations that support or benefits companies that use AM technologies or offer AM products and services	3.0	2.0	0.06	3.7	4.1	0.2	2.5	1.9	0.3
24	Improving the company employees' confidence in the abilities of new technologies	4.1	4.3	0.55	3.0	2.3	**0.04**	3.7	4.4	0.1
25	Improving employees' confidence in the company's ability to utilise the abilities of new technologies	4.2	4.3	0.55	2.8	2.6	0.5	3.7	4.4	**0.08**

Both sectors and age groups rate *lack of legislative support* and *customer resistance to change* as the third and fourth most constraining mechanisms to innovative development. In Table 13.10 and Table 13.11, both sectors and age groups indicated that they find it extremely difficult to identify laws and regulations (23) that support or benefit enterprises that use specific AM technologies or offer certain AM products and services. Therefore, if legislative support for South African AM enterprises exists, the associated parties need to increase the visibility of the support offered. Conversely, policymakers may investigate possible support mechanisms if no legislative support exists.

Finally, in Figure 13.17 and Figure 13.18, both sectors indicated *internal resistance to change* as the least concerning blocking mechanism, indicating that South African AM enterprises experience more market constraints than internal constraints. Table 13.10 and Table 13.11 indicates that it is very important and relatively easy to improve employees' confidence in the abilities of new technologies (24), particularly in tertiary and established enterprises, and their enterprise's ability to utilise the abilities of new technologies (25). It may be a consequence of the continuous improvement culture (22) that secondary and start-up enterprises encourage and the innovative objectives outlined in their company strategies (21).

13.4.6. F5: Market formation

When the enterprises were asked to indicate whether they use resources or funding provided by Government agencies when developing innovative technology, 11% (four enterprises) indicated that they did (Figure 13.19). All four were established enterprises delivering AM value-added service, of which three were 10+ years old and the other 6-10 years old.

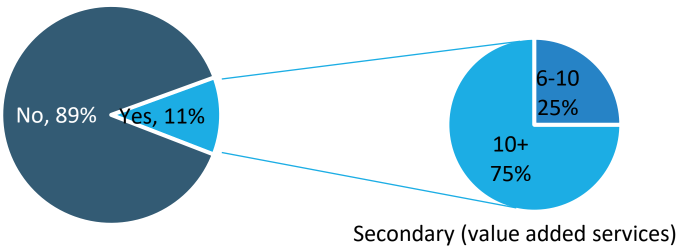


Figure 13.19: Utilisation of Government agencies or schemes when developing technology

The 6-10 years old company (enterprise with <20 employees) specialises in AM of aeronautical parts and components. They received a 12-month grant as part of an aeronautical project funded by the DTI. To obtain the grant, the enterprises collaborated with a handful of non-AM enterprises to form a consortium of companies in a value chain that delivered products together.

The four 10+-year-old enterprises (with 20 to 100 employees) are related to universities or national knowledge institutions established as AM demonstration centres for researchers and manufacturing enterprises. They annually received funding for projects from the Department of Science and Innovation (DSI), Technology Innovation Agency (TIA), the corresponding universities and the Manufacturing, Engineering and Related Services Sector Education and Training Authority (merSETA). In addition to demonstrating the technology, these enterprises offer AM value-added services to the public. However, as they receive financial support from the above-mentioned organisations, several secondary enterprises not receiving financial support mentioned the difficulty of competing with these enterprises as their value-added services are offered at a lower cost.

A secondary enterprise mentioned that "*our services are continuously more expensive than those who receive financial support from the government as our sales costs for printing parts and components must include the purchase costs of my printers, while the financial support helps them to absorb the printers purchase costs. Instead of demonstrating the technology to the public, they compete against us* (other value-added AM enterprises), *and they are pricing us out of the market."* Additionally, another secondary enterprise argued that *"academic and national centres receiving governmental support should not be competing against enterprises who are trying to survive in a very small and competitive market. They should be supporting us and direct clients to us."*

A secondary enterprise receiving funding: *"For us, competing against 3D printing companies is a no-go. We know there are organisations that receive funding that compete with the local companies, but our mandate states that we are only allowed to offer services local 3D printing companies don't offer. We can guide start-ups to set up their companies, but we have to offer niche services, which is hard. So, we rather offer a lot of training to individuals who want to buy printers and help them import them."*

From the enterprises' responses, the centres launched around the time of the AM adoption boom in South Africa in 2012 (Case I) are competing against the South African AM value-adding enterprises. However, the government's intentions have always been to stimulate the industry through financial support [118]. Policymakers, therefore, need to investigate new or additional support mechanisms to support more and younger AM enterprises.

Additionally, when the enterprises were again asked to rank indicator activities in terms of importance, difficulty and extent performed (Table 13.12 and Table 13.13), both sectors and age groups rated surveying for new local customer segments and distribution channels (26) and assisting the creation of niche markets (27) at a high level of importance. However, both sectors and age groups also indicated the difficulty of assisting the creation of niche markets. They attributed the difficulty to a lack of financial resources from the AM enterprises and their South African customer base. Furthermore, identifying regulations that improve market conditions for their enterprises (28) was rated extremely difficult by all enterprises, particularly the tertiary sector and established enterprises. Due to this high difficulty level, South African enterprises deem it unimportant and do not spend much time or effort trying to identify supporting laws and regulations. Therefore, as previously mentioned, if legislative support for South African AM enterprises exists, the associated parties need to increase the visibility of the support offered. Conversely, policymakers may investigate possible support mechanisms if no legislative support exists.

Table 13.12: The average rantings of the F5 - Market formation-related indicator activities in terms of sector and importance, difficulty and extent performed.

		Importance			Difficulty			Extend performed		
		Secondary	Tertiary	p	Secondary	Tertiary	p	Secondary	Tertiary	p
26	Surveying for new local customer segments and distribution channels	3.7	3.9	0.7	3.3	3.2	0.9	3.7	4.0	0.4
27	Assisting the creation of niche markets	4.1	3.7	0.11	4.2	3.8	0.1	3.5	3.9	0.2
28	Identifying regulations that improve market conditions for your enterprise	2.5	1.6	**0.05**	4.2	4.5	0.3	2.0	1.3	**0.05**
29	Testing technology's acceptability, affordability, accessibility	4.0	4.2	0.4	3.1	2.7	0.1	3.9	4.5	0.1
30	Determining the market readiness of a technology	4.2	4.1	0.7	3.1	2.9	0.2	3.9	4.2	0.4
31	Determining the efficiency of employees' knowledge and skills	3.6	2.7	**0.01**	3.1	2.3	**0.03**	4.1	3.0	**0.01**
32	Determining the availability and accessibility of physical infrastructure	3.9	4.0	0.3	3.1	2.5	**0.06**	4.2	4.5	0.2
33	Determining financial resources' availability and accessibility	4.3	3.8	**0.05**	3.6	2.9	**0.05**	4.0	4.5	0.3

White (1) – Very low importance, very easy, and not performed.
Dark blue (5) - Highest importance, extremely difficult, performed to a large extent

Table 13.13: The average rantings of the F5 - Market formation related indicator activities in terms of age and importance, difficulty and extent performed.

		Importance			Difficulty			Extend performed		
		0-5	6+	p	0-5	6+	p	0-5	6+	p
26	Surveying for new local customer segments and distribution channels	3.7	3.9	0.7	3.5	3.1	**0.09**	3.5	4.0	0.3
27	Assisting the creation of niche markets	4.0	4.0	1.0	4.2	3.8	0.2	3.5	3.9	0.2
28	Identifying regulations that improve market conditions for your enterprise	2.8	1.9	**0.08**	3.9	4.5	**0.03**	2.2	1.5	0.1
29	Testing technology's acceptability, affordability, accessibility	3.7	4.3	**0.05**	3.4	2.8	**0.09**	3.5	4.4	**0.06**
30	Determining the market readiness of a technology	3.9	4.3	0.2	3.1	2.9	0.5	3.6	4.1	0.3
31	Determining the efficiency of employees' knowledge and skills	3.5	3.2	0.3	2.9	2.8	0.6	3.6	3.7	0.9
32	Determining the availability and accessibility of physical infrastructure	3.9	4.0	0.7	2.8	2.8	0.8	4.1	4.5	0.1
33	Determining financial resources' availability and accessibility	4.2	4.1	0.7	3.8	3.1	**0.07**	4.0	4.4	0.2

Both sectors and established enterprises indicate the high importance of testing a technology's acceptability, affordability, and accessibility (29) and market readiness (30). However, testing a technology's acceptability, affordability, and accessibility (29) is statistically significant less important and more difficult for start-up enterprises than established enterprises. It is therefore also performed to a significantly less extent. Guidance should thus be provided to AM start-up enterprises regarding how to test a technology's acceptability, affordability, and accessibility to enable them to perform it to a larger extent.

Finally, for both sectors and age groups, determining the availability and accessibility of knowledge and skills (31) are of moderate importance, while the availability and accessibility of physical infrastructure (32) and financial resources (33) are of high importance and performed to a great extent. However, both sectors and age groups identified that determining the availability and accessibility of financial resources is more difficult than determining those of physical infrastructure, as the availability of physical infrastructure and knowledge and skills is often the catalyst of projects with commercial aims.

13.4.7. F6: Resource mobilisation

The surveyed enterprises were asked to rank the four primary innovation resources according to their importance and indicate their obtainment difficulty. The secondary enterprises indicated financial resources as the most important (Figure 13.20 light blue column with its average value closest to 1), followed by physical, human, and data resources. In addition, they indicated that human and physical infrastructure is moderately difficult to obtain, while data resources are easier to obtain, and financial resources are the hardest (navy columns). In contrast, the tertiary enterprises (light orange) indicated physical resources as most important, followed by financial, data, and human resources.

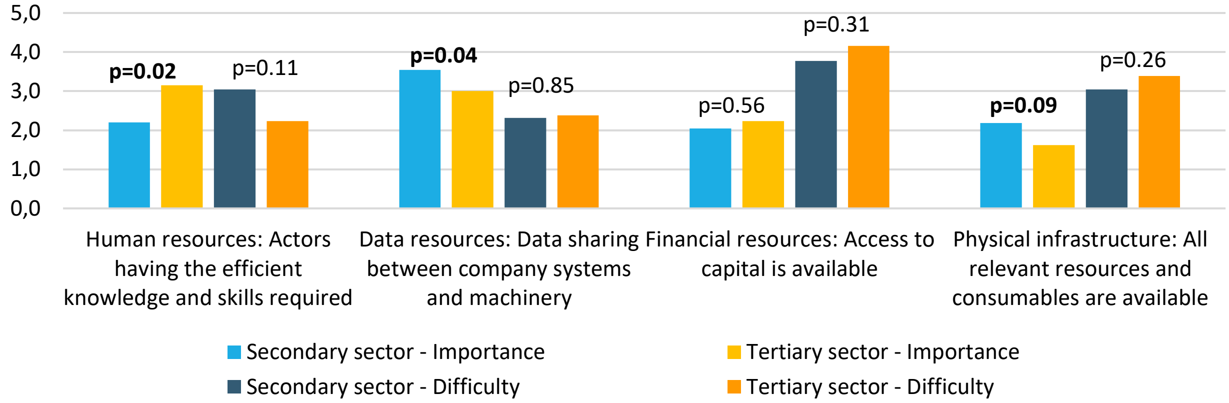


Figure 13.20: The average ranking scores of the innovation resources in order of their importance to the enterprises and the obtainment difficulty. 1 – Most important resource, 4 – Least important resource

1 – Very easy to obtain, 5 - Extremely difficult to obtain

Thus, to both AM value-adding enterprises and AM retailers, materials and consumables, financial and physical resources are the most important, thus capital, cash flow, machinery, AM systems, and equipment. However, physical infrastructure is statistically significantly more important to tertiary enterprises than secondary enterprises as their business is to sell AM systems. However, both sectors are moderate to very difficult to obtain, particularly for tertiary enterprises. This may be due to the AM systems, materials and consumables that must be important. However, human resources are significantly more important to secondary enterprises than tertiary enterprises. This is due to the skills and knowledge value-adding enterprises require to add value to their client's products, while not many employees are necessary to sell AM systems and related materials. Therefore, secondary enterprises also rated human resources obtainment more difficult than tertiary enterprises. Finally, data resources are significantly more important to tertiary enterprises than secondary enterprises, as accurate data sharing is essential to AM system retailers. Both sectors, however, indicate moderate difficulty in obtaining data resources.

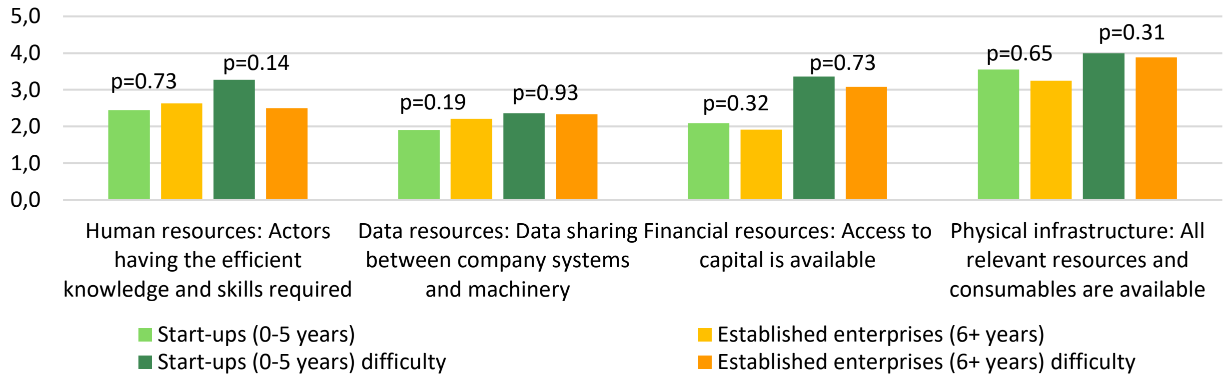


Figure 13.21: The average ranking scores of the innovation resources in order of their importance to start-ups and established enterprises and the obtainment difficulty. 1 – Most important resource, 4 – Least important resource, 1 – Very easy to obtain, 5 - Extremely difficult to obtain

Figure 13.21 present the start-up and established enterprises' rankings of the four primary innovation resources. Start-up enterprises rate data resources as the most important, followed closely by financial, knowledge, and physical resources. Established enterprises rate financial resources most important, followed by data, human and physical resources. Data resources are easily obtained for both age groups, while financial, human, and physical resources are more difficult to obtain. Start-ups and established enterprises thus both find data and financial resources most important, although data is much easier to obtain.

Spearman's rank-order correlation (ρ) was utilised to measure the strength and direction of association between the rankings of the four primary innovation resources and the ages of the surveyed enterprises. Therefore, Table 13.14 presents the Spearman correlation (ρ) of the age of enterprises and the average ranking scores of the innovation resources. As none of the correlations is close to 1 or -1, the correlations between the age of enterprises and the average ranking scores of the innovation resources are weak, indicating no significant correlation or association between the two groups. The importance ranking of the financial resources has a weak positive correlation (0.25) with the age of the enterprises. The other resources all have very weak negative correlations, indicating that when the enterprises' age increases, the importance rating of the resources slightly decreases.

Table 13.14: Spearman correlation (ρ) with the average ranking scores of the innovation resources

Correlation (ρ)	Human Resources	Data resources	Financial resources	Physical infrastructure
Enterprise age	-0.16	-0.03	0.25	-0.01
Maintaining an information-sharing networks	0.27	-0.39	0.09	-0.16
Strategic alliances for resource benefits	-0.11	0.14	-0.11	0.11
Collaborate with academia and government	-0.3	-0.09	0.24	0.13
Collaborating with end-users	-0.35	0.09	0.1	0.18

The correlations of the four innovation resources with the collaboration activities from §13.4.4 and Table 13.8 indicates that the enterprises that maintain an information sharing network have a weak negative correlation with the data resource ranking and a weak positive correlation with the ranking of the human resource. Enterprises collaborating with academia and government also have a weak positive correlation with the ranking of the financial resources, indicating that collaborating with academia and government slightly increases the importance rating of financial resources. The enterprises collaborating with their end-users have a weak negative correlation with the human resources ranking, indicating that the importance rating decreases when enterprises collaborate with their end-users.

Following the ratings of the four innovation resources, the enterprises were asked to rank their sources of financial resources, as presented in Figure 13.23 and Figure 13.22. Both sectors and age groups indicated that acquiring income from end-user sales from selling AM services, products, or AM systems as the most essential source of income. This is followed by loans from banks and external investors and funding from governmental incentives, subsidies, and grants. Funding from governmental incentives also received a significantly lower rating by the tertiary enterprises than the secondary enterprises, confirming once again (§13.4.6) that only secondary enterprises receive government funding. Acquiring funding from governmental incentives, subsidies, and grants was again considered extremely difficult, while obtaining loans and external investments was rated moderate to highly difficult. During their introduction interviews, a few secondary enterprises mentioned that as acquiring governmental support is so difficult, tedious, and rare, enterprises instead utilise small banks to launch their enterprises and then use end-user sales to pay them back. Additionally, external investors tend to invest in established AM enterprises.

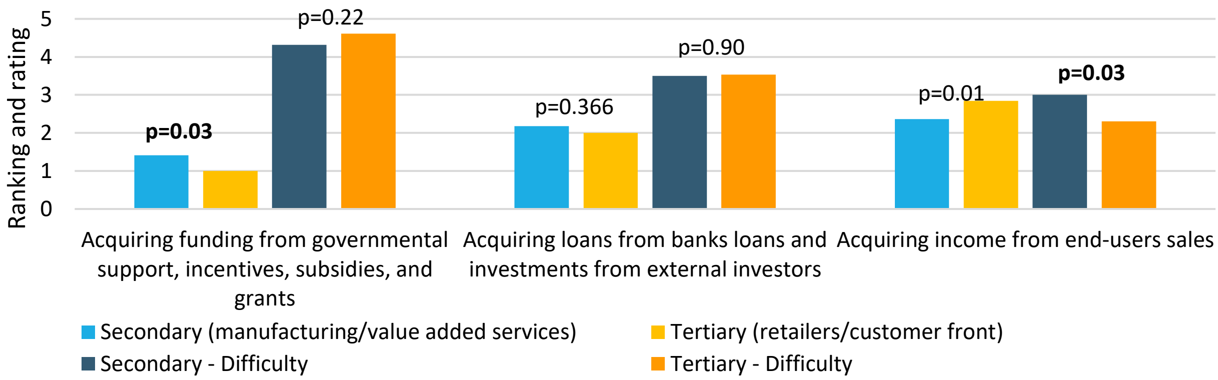


Figure 13.23: The average ranking scores of the sources of capital in order of least essential source of income (1) to the most essential source of income (3) and rate their obtainment difficulty (1 – Very easy to obtain, 5 - Extremely difficult to obtain)

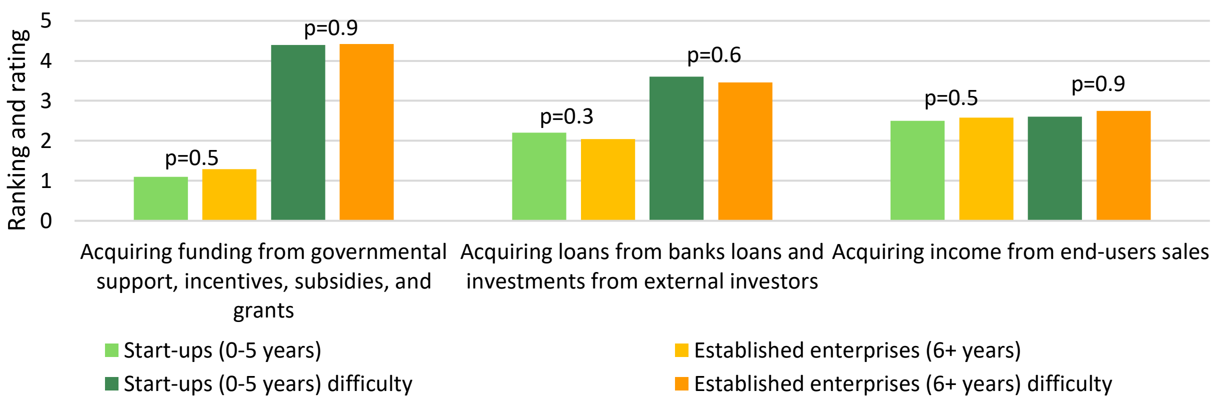


Figure 13.22: The average ranking scores per age group of the sources of capital in order of least essential source of income to most essential source of income and rate their obtainment difficulty

Finally, the surveyed enterprises were asked to rate the availability and accessibility of knowledge, financial and capital resources from 1 - extremely unavailable or inaccessible to 5 – readily available or accessible (Figure 13.25 and Figure 13.24). Both sectors and age groups rated sufficient and sustainable capital for technology acquisition and adoption as moderately available and accessible. This indicates that the AM enterprises believe they have moderate capital available from end-user sales or moderate access to capital from external investors or banks to acquire and develop innovative technology. Furthermore, both sectors and age indicated that sufficient knowledge and skills are highly available and accessible within the knowledge network to adopt new technology successfully. However, the start-ups differed statistically significantly from established enterprises concerning the accessibility of knowledge and skills within the knowledge network, indicating that the knowledge and skills the start-ups have access to are significantly less than those of established enterprises. Start-up enterprises thus require guidance or training from more established enterprises.

Table 13.15: The Spearman correlation between the start-up enterprises' availability of technological infrastructure and accessibility of sufficient knowledge and skills

Variable	Variable	Correlation
Availability - Technological infrastructure that supports the adoption of new technology and the development of new products and services	Accessibility - Sufficient knowledge and skills within the knowledge network to successfully adopt new technology and utilize it to develop innovations	0.6 < **0.67** < 0.8 Strong correlation

Finally, the availability of technological infrastructure that supports the adoption of new technology and product development was rated moderately to highly available by both sectors and moderately available by both age groups. Start-up enterprises, however, find technological infrastructure statistically significantly less available than established enterprises. Table 13.15 indicates, with a strong correlation, that the accessibility of knowledge and skills within the knowledge network of start-up enterprises strongly influences their availability ratings of the technological infrastructure. Therefore, forming alliances with knowledgeable

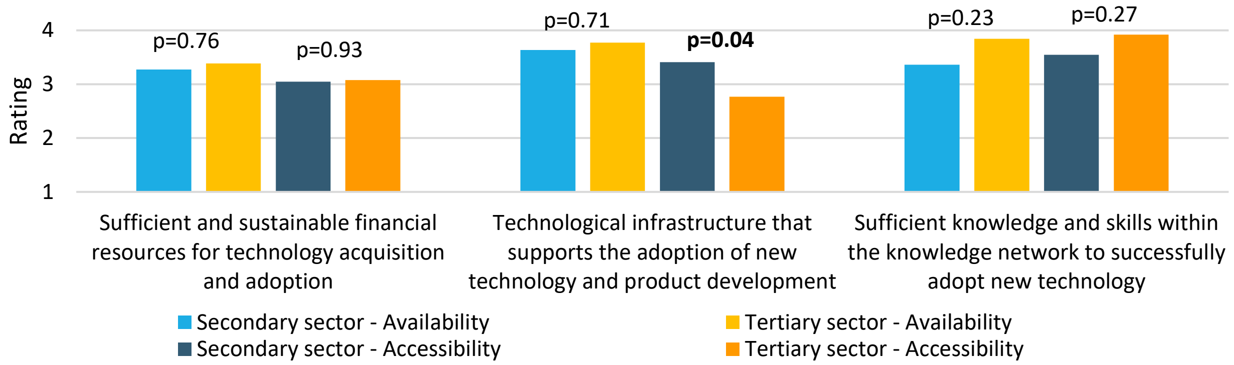


Figure 13.25: The average rating scores of the innovation resources in order of their availability and accessibility to the enterprises and the obtainment difficulty. 1 – Extremely unavailable or inaccessible, 5 – Easily available or accessible

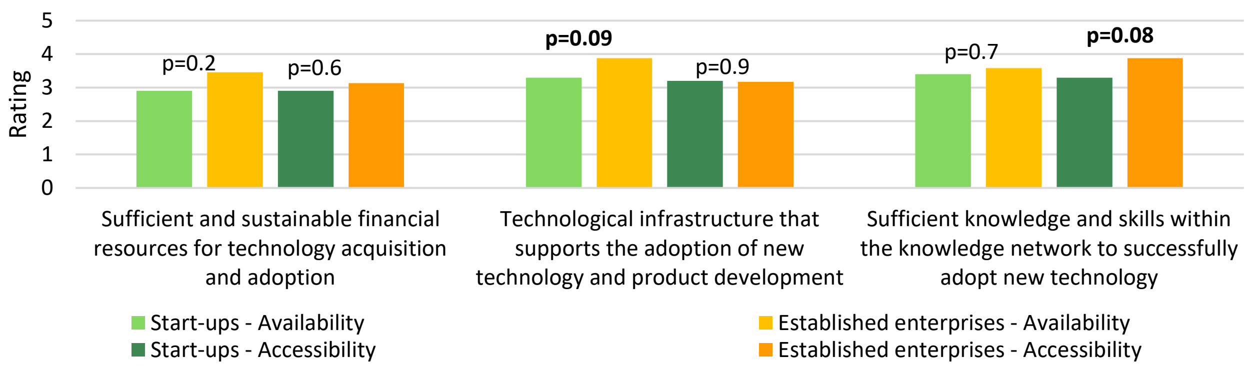


Figure 13.24: The average rating scores of the innovation resources in order of their availability and accessibility to the enterprises and the obtainment difficulty.

enterprises to develop a strong knowledge network will improve the start-up enterprises' availability of technological infrastructure as the network will inform them of more infrastructure opportunities.

Furthermore, the sectors differed statistically significantly concerning the accessibility rating of the technology infrastructure. A secondary enterprise mentioned: *"I would rate technology infrastructure as highly available and highly accessible as several local sales bureaus are selling high-quality systems for different printing materials."* In contrast, a tertiary enterprise mentioned that *"the availability of AM systems is massive globally. Companies such as EOS, Markforged, Artec 3D, 3D Systems, Ultimaker, Formlabs and Zortrax build brilliant AM systems and sell thousands of them. But no one in South Africa manufactures AM systems up to their standards. So, no one wants to buy other brands, they want these well-known brands, so we must import them. So, although they are highly available, they are only moderately accessible because we must import them and buy them in foreign currencies. Weak exchange rates play a massive role in importing these systems."*

13.4.8. F7: Creation of legitimacy

For the creation of legitimacy (Table 13.16 and Table 13.17), the enterprises from both sectors and age groups indicated that establishing trust in their company's brand (38) and ensuring that their products or services live up to the brand's values (39) are highly important and moderately difficult to achieve. Furthermore, both sectors and age groups find it of moderate to high importance and moderate difficulty to effectively advertise their company's products or services (40). Several micro and very small enterprises noted that they do not tend to and do not want to advertise their enterprises as they are too small to manage several orders simultaneously. They, therefore, focus on advertising through word of mouth from existing customers. Additionally, larger enterprises with more employees tend to advertise their products and services through their websites, social media pages and the conferences and exhibitions they attend. Both sectors and age groups, particularly the tertiary enterprises, promote their partnerships with well-known brands (41), typically the large AM system manufacturers such as EOS and Markforged, as it increases trust in their enterprises' products.

Finally, the tertiary or retailer enterprises, start-ups and established enterprises also find it moderate to highly important and easy to offer potential customers the opportunity to try and assess their products or

Table 13.16: The average rantings of the F7: Creation of legitimacy-related indicator activities in terms of sector and importance, difficulty and extent performed.

		Importance			Difficulty			Extend performed		
		Secondary	Tertiary	p	Secondary	Tertiary	p	Secondary	Tertiary	p
38	Establish trust in the company's brand	4.8	4.6	0.3	3.3	2.8	0.4	4.5	4.6	0.4
39	Ensuring products live up to the values of the brand	4.8	4.6	0.3	3.0	2.6	0.2	4.8	4.6	0.2
40	Effectively marketing the company's products	3.5	3.7	0.7	3.1	3.2	0.7	3.7	3.3	0.3
41	Advertising partnerships with well-known brands	3.4	3.6	0.6	2.5	2.4	0.7	3.3	3.7	0.5
42	Offering customers test opportunities before purchase	3.2	3.6	0.3	3.1	2.6	0.1	3.1	3.7	0.2
43	Minimising end-user need for new skill development	3.6	2.8	**0.07**	2.6	2.7	0.7	4.1	3.5	0.2

White (1) – Very low importance, very easy, and not performed.
Dark blue (5) - Highest importance, extremely difficult, performed to a large extent

Table 13.17: The average rantings of the F7: Creation of legitimacy-related indicator activities in terms of age and importance, difficulty and extent performed.

		Importance			Difficulty			Extend performed		
		0-5	6+	p	0-5	6+	p	0-5	6+	p
38	Establish trust in the company's brand	4.9	4.7	0.1	3.3	2.8	0.2	4.5	4.6	0.7
39	Ensuring products live up to the values of the brand	4.7	4.8	0.9	3.3	2.6	**0.02**	4.6	4.7	0.8
40	Effectively marketing the company's products	3.5	3.7	0.7	3.1	3.1	1.0	3.5	3.6	0.8
41	Advertising partnerships with well-known brands	3.4	3.5	0.7	2.7	2.3	0.2	3.2	3.5	0.5
42	Offering customers test opportunities before purchase	3.5	3.2	0.5	3.1	2.8	0.3	3.5	3.2	0.7
43	Minimising end-user need for new skill development	3.6	3.3	0.5	3.1	2.4	**0.07**	3.9	3.9	0.9

services before purchase (42) as it contributes to more sales. The retailers typically have several less expensive AM systems available on the shop floor for potential customers to view and print prototypes for the potential customers. In contrast, the secondary or value-adding enterprises focus on and find it moderate to highly important and easy to minimise the need for new skill development before users can use or benefit from your AM products or services (43) as it contributes to more sales. This is not a focus for AM retailers as the AM system manufacturers provide customers with user manuals and online training videos.

13.4.9. Functional summaries

Following the analysis of the individual functions' indicators, each function's overall importance, difficulty, and extent performed ratings may be compared in terms of sector and age. Figure 13.29 presents the average importance ratings of the indicator activities of each of the IS functions received. Resource mobilisation (F6) is excluded from the list as their activities were ranked and not scored. All the functional means (x) are above 3, indicating that the survey enterprises view the functional indicator activities as moderately to highly important on average. F7 (Creation of legitimacy) has the highest mean and smallest interquartile range (box), indicating that the survey respondents mostly agreed about the activities' high importance. In contrast, the other functions all have relatively long interquartile ranges and whiskers, indicating varied opinions regarding the importance of the indicators.

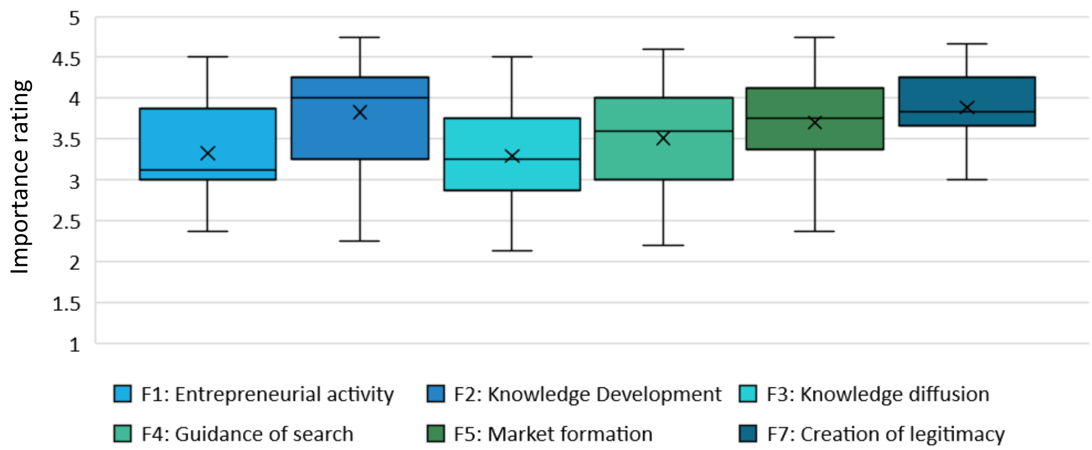


Figure 13.26: Average importance Likert score ratings of the IS functions (excluding F6 – Resource mobilisation)

Table 13.18 presents the regression analyses between the size of the enterprises and the IS activities' importance ratings. From Table 13.4's guidelines, functions F1 to F4 and F7 all have strong positive correlations with the age of the enterprises. This indicates that the age of the enterprises influences how important they view the functions' activities. However, F5 has a weak correlation with the age of the enterprise. Its importance rating is therefore not influenced by the age of the enterprise.

Table 13.18: Regression analyses of the size of the enterprises (dependent variables) and the importance ratings of the IS functions (independent variables)

	F1: Entrepreneurial activity	F2: Knowledge Development	F3: Knowledge diffusion	F4: Guidance of search	F5: Market formation	F7: Creation of legitimacy
Enterprise age	0.76	0.68	0.76	0.65	0.35	0.65

Figure 13.27 presents the average difficulty ratings of the indicator activities of each IS function. All the functions have short interquartile ranges (boxes) around the moderately difficult (3) line. This indicates that the surveyed enterprise was in relative agreement regarding the difficulty levels of the functional activities, particularly regarding the entrepreneurial activities (F1). However, the functions' long whiskers indicate that some of the survey respondents found some functional activities easier or more difficult than most enterprises. As F1 and F7's difficulty rating has outliers, some survey respondents' opinion regarding the function's difficulty varied significantly from the majority's opinion.

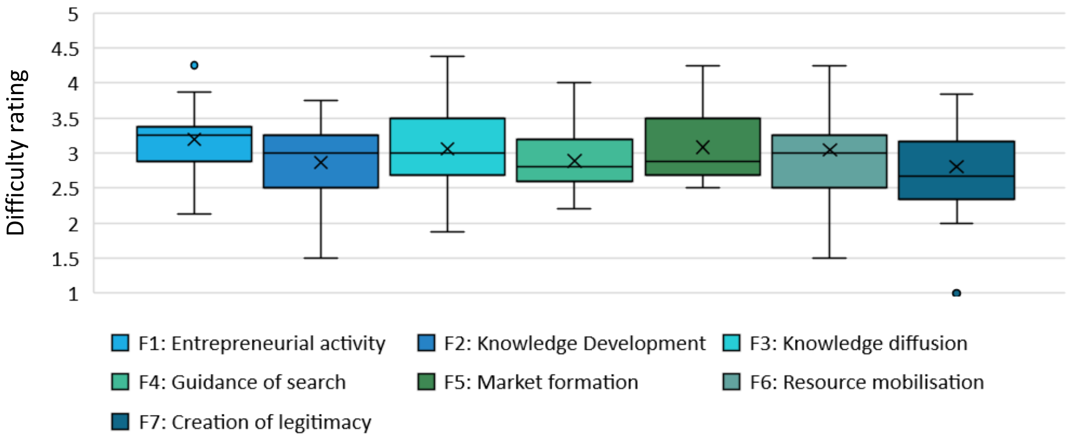


Figure 13.27: Average difficulty Likert score ratings of the IS functions

Table 13.19 indicates that a statistically significant difference exists between the difficulty ratings of the manufacturing and retailer enterprises, and between the start-up and established enterprises in performing the F5 activities. This indicates that the sector (type) and the age of the enterprises affect how difficult the market formation activities are to perform.

Table 13.19: The ANOVA F-test to test whether a statistically significant difference ($p < 0.1$) exists between the difficulty of each IS function and the sectors in which they operate as well as their age

	F1: Entrepreneurial activity	F2: Knowledge Development	F3: Knowledge diffusion	F4: Guidance of search	F5: Market formation	F6: Resource mobilisation	F7: Creation of legitimacy
Sector	0.28	0.78	0.95	0.17	**0.06**	0.64	0.71
Enterprise age	0.43	0.12	0.49	0.16	**0.07**	0.39	0.32

Figure 13.28 presents the average extent performed ratings of the indicator activities of each IS function. Resource mobilisation (F6) is excluded from the list as their indicator activities were ranked and not scored. All the functional means (x) are above 3, indicating that the survey enterprises, on average, perform the indicator activities to a moderate or high extent. F1 and F5 have the smallest interquartile ranges (boxes), indicating that their activities are all performed similarly. In contrast, the other functions' activities are all performed to varying extents, particularly F4 with its long whiskers.

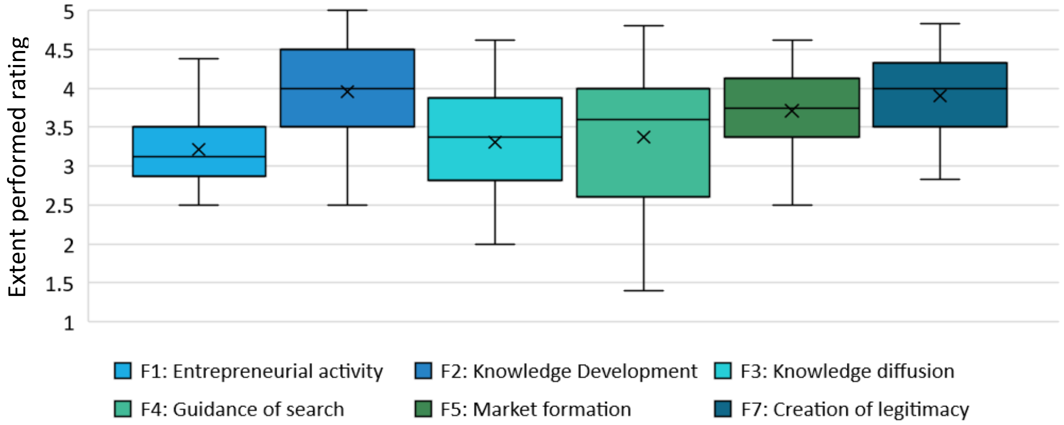


Figure 13.28: Average extent performed Likert score ratings of the IS functions

Table 13.20 indicates that the sector (type) significantly affects the extent to which the surveyed enterprises perform the F4 activities. Furthermore, the age of the enterprises affects the extent to which the F1 activities are performed.

Table 13.20: The ANOVA F-test to test whether a statistically significant difference exists between the extent the IS functions are performed and the sectors in which they operate as well as their size categories (statistically significant difference exists when p < 0.1)

	F1: Entrepreneurial activity	F2: Knowledge Development	F3: Knowledge diffusion	F4: Guidance of search	F5: Market formation	F7: Creation of legitimacy
Sector	0.99	0.92	0.13	**<0.01**	0.97	0.5
Enterprise size	**0.02**	0.23	0.1	0.22	0.39	0.4

13.4.10. Hypothesis assessed

In this section, the hypothesis formulated §13.3.3.5 are tested and discussed. The data analysis methods from §13.3.3 are utilised.

<u>Case study hypothesis:</u>

CH1: The surveyed AM enterprises often collaborate with end-users to develop new AM techniques or products to ensure the commercialisation of the products and AM techniques.

In Table 13.8, secondary enterprises indicated that they find it highly important to collaborate with end-users and that their end-users are relatively easy to collaborate with. However, the retailer (tertiary) enterprises collaborate significantly less with end-users than secondary enterprises as they only sell AM consumables and systems. Furthermore, Table 13.9 indicates that both start-ups and established enterprises find it moderately important to collaborate with end-users and therefore collaborate with them to a moderate extent.

CH2: Established AM enterprises prefer to collaborate with end-users rather than academia.

In Figure 13.15, established enterprises rated collaborating with end-users as a source of knowledge 3.5 out of 5, while collaborating with academia received a 2.2 rating. With $p = 0.013 < 0.1$, a statistically significant difference thus exists between the established enterprises' ratings of collaborating with academia and collaborating with end-users. Additionally, in Table 13.9, established enterprises indicated that they collaborate with end-users more than with academia as they find end-users collaborations more critical.

Collaboration with academia is typically experienced to involve a very timely administrative process before experimental results are obtained.

CH3: The South African AM enterprises are unaware of any AM research culture or programme where industry may participate in academic research studies as research observers.

As mentioned in §13.4.3, during the introduction interviews with the surveyed enterprises, the enterprises mentioned that they are unaware of any culture or programme where industry may participate in academic research studies as research observers. THRIP programme, mentioned in Case I, requires enterprises to initiate research projects with academia and enterprise funding substituted by governmental funding. The CPAM programme also requires the participating enterprises to conduct research. Ch1 may, therefore, not be rejected.

To stimulate academic-industry collaboration in the AM industry, governmental AM research funding organisations should perhaps consider including industry involvement in academic research projects as a prerequisite to obtaining research funding, similar to Case II. In this way, AM research will be diffused into industry, industry's practical expertise may be diffused into academia, and industry may identify future employees with AM experience (Case III).

CH4: The South African AM enterprises share their industry needs or needs for fundamental AM research with academia to stimulate industry-focused research projects and gain access to academic R&D projects.

In Table 13.8, the secondary enterprises indicated the moderately high difficulty of collaborating with academics and governmental actors as collaboration with both actors includes a very timely administrative process. Therefore, these companies only collaborate with these actors to a moderate extent while preferring to collaborate more with their end-users, who are easier to collaborate with. CH4 may thus be rejected.

CH5: South African AM enterprises conduct feasibility studies on conceptualised project ideas and consult market research to ensure the feasibility of their ideas.

Figure 13.16, Table 13.12 and Table 13.13 indicate that secondary and tertiary enterprises find it very important and relatively easy to determine the technology readiness and maturity of innovations they develop. In addition, they, particularly tertiary enterprises, test technology's affordability, accessibility, and market readiness as well as their products' quality and price acceptability to a large extent. Finally, both sectors find it moderately important to set stopping criteria to terminate costly or infeasible projects. CH5 may thus not be rejected as South African enterprises conduct feasibility studies on conceptualised project ideas.

CH6: South African AM enterprises strive to identify regulations or innovation support opportunities that support enterprises within the AM industry.

In Table 13.10 and Table 13.11, both sectors and age groups indicated that they find it extremely difficult to identify laws and regulations that support or benefit enterprises that use specific AM technologies or offer certain AM products and services. They, therefore, search for them only to a small extent. CH6 may thus be rejected. Both sectors and age groups also rated *lack of legislative support* as the third most constraining mechanism to innovative development. Therefore, if legislative support for South African AM enterprises exists, the associated parties need to increase the visibility of the support offered. Conversely, policymakers may investigate possible support mechanisms if no legislative support exists.

CH7: To gain access to funding, South African AM enterprises utilise end-user funding campaigns rather than traditional money lending channels, such as those from banks or external investors.

Figure 13.23 and Figure 13.22 indicate that both sectors and age groups prefer to acquire income from end-user sales from selling AM services, products, or AM systems as the most essential source of income. This is followed by bank loans, investments from external investors, and funding from governmental incentives, subsidies, and grants. CH7 may thus not be rejected.

CH8: The South African AM enterprises form strategic alliances or collaborations to access more resources.

Table 13.8 indicates that forming strategic alliances with companies with similar end goals to obtain resource benefits such as funding and lower costs materials are of low to moderate importance to secondary AM enterprises and are therefore only utilised moderately. In contrast, tertiary AM enterprise finds it relatively unimportant and seldom utilise it. Both sectors indicated it is very difficult to form strategic alliances as the South African AM industry is small and very competitive, and enterprises do not want to collaborate. Start-ups also find it statistically significantly more important and less difficult than established enterprises and perform it to a slightly larger (moderate) extent. CH8 is thus rejected.

CH9: Support initiatives or competitions are available to South African enterprises to obtain AM or business training, grants, and brand awareness.

In Table 13.10 and Table 13.11, both sectors and age groups indicated that they find it extremely difficult to identify laws and regulations (23) that support or benefit enterprises that use specific AM technologies or offer certain AM products and services. Therefore, if legislative support for South African AM enterprises exists, the associated parties need to increase the visibility of the support offered. Conversely, policymakers may investigate possible support mechanisms if no legislative support exists.

CH10: The South African AM conference is primarily an academic research conference.

In Table 13.6 and Table 13.7, the surveyed enterprises indicated that, although it is typically easy to attend conferences (2), they do not attend conferences and exhibitions to identify project ideas, as the AM conferences are typically more academic-based than industry-based. Start-ups typically find it significantly more difficult to identify projects with commercial aims at exhibitions and conferences (2) than established enterprises and attend them significantly less. Start-ups instead find international trends (1) and end-users (3) more important. CH2 is thus not rejected. The South African AM industry will thus benefit from industry-based exhibitions and trade shows, such as those attended by Dyze Design in Case III, where the South African public may view and purchase the enterprises' product and service offerings.

<u>Demographic hypothesis</u>

H1: The enterprises' stance on AM is similar for manufacturing enterprises and retailers.
H2: The enterprises' ages are similar for manufacturing enterprises and retailers.
H3: The enterprises' stance on AM is similar for the different ages of the enterprises.

The Fisher's exact test was utilised to test hypotheses 1 to 3, as presented in Table 13.21. Table 13.21 indicates that hypotheses 1 to 3 may not be rejected. Thus, the type of enterprises (manufacturing or retailer) does not influence their stance on AM or age group. Similarly, the enterprises' stance on AM does not influence their age.

Table 13.21: The Fisher's Exact test to test hypotheses one, two and three (reject is p < 0.1)

Variable	Variable	p-value	Statistically significant difference?	Hypothesis
Sector	Stance on AM	0.32	No, p > 0.1	H1: Do not reject
Sector	Enterprise age	p = 0.76	No, p > 0.1	H2: Do not reject
Stance on AM	Enterprise age	p = 0.56	No, p > 0.1	H3: Do not reject

H4: The size of the enterprises is similar for manufacturing enterprises and retailers.

H5: The size of the enterprises is similar for the different ages of the enterprises.

H6: The size of the enterprises is similar for the different stances on AM.

To test hypotheses 4 to 6 and determine whether statistically significant differences exist between the size of the sampled enterprises, their ages, and stances on AM and sectors, the ANOVA F-test was utilised, as presented in Table 13.22. Table 13.22 indicates that hypotheses 4 to 6 may not be rejected as no statistically significant difference was found. The size of an enterprise is thus not influenced by the sector in which it operates. Furthermore, the size of an enterprise does not influence its age or stance on AM.

Table 13.22: The ANOVA F-test to test hypotheses four, five and six (reject is p < 0.1)

Variable	Variable	p-value	Statistically significant difference?	Hypothesis
Enterprise size	Sector	p = 0.34	No, p > 0.1	H4: Do not reject
Enterprise size	Enterprise age	p = 0.21	No, p > 0.1	H5: Do not reject
Enterprise size	Stance on AM	p = 0.12	No, p > 0.1	H6: Do not reject

<u>Functional hypothesis</u>

H7: There is a strong positive correlation between the indicator activities the enterprises deem important (or unimportant) and the activities they perform to a large extent (or to a small extent).

The result of this hypothesis is presented and discussed in the subsequent section.

H8: There is a statistically significant difference between the sector of the enterprises and the constraints that hinder them from developing innovative solutions.

Figure 13.17 presents the enterprises' average ranking scores of the constraints that block the development of innovative solutions. For each constraint, the two sectors did not differ statistically significantly (all p-values > 0.1), in their rankings of the constraints were similar. Both the manufacturing and the retailing enterprises thus experience a lack of sufficient resources and unsupportive market conditions as the most constraining development blockers, while internal resistance to change is the least constraining development blocker.

H9: There will be a statistically significant difference in the resources the manufacturing enterprises and retailing enterprises deem important.

Figure 13.20 presented the surveyed enterprises' rankings of the four primary innovation resources according to their importance The F-test p-values of the resources were p=0.02 for human resources, p=0.04 for data resources, p=0.54 for financial resources and p=0.09 for physical resources. The secondary and tertiary enterprises differ statistically significantly in their average human, data, and physical resources rankings. H9 is thus rejected as no statistically significant difference exists between the sectors' rankings of the financial resources.

Physical infrastructure is statistically significantly more important to tertiary enterprises, the AM system retailers, than to secondary manufacturing enterprises as their business is to sell AM systems. Human resources are significantly more important to secondary enterprises than tertiary enterprises due to the skills and knowledge value-adding enterprises require to add value to their client's products, while not many employees are necessary to sell AM systems and related materials. Finally, data resources are significantly more important to tertiary enterprises than secondary enterprises as data and accurate data sharing are especially important to AM system retailers.

H10: There is a strong positive correlation between the ages of enterprises and the availability of financial resources and technology infrastructure.

In Table 13.14, Spearman's rank-order correlation (ρ) was utilised to measure the strength and direction of association between the rankings of the availability of financial resources and technology infrastructure and the ages of the surveyed enterprises. Spearman's rank-order correlation (ρ) indicated that the importance ranking of the financial resources has a weak positive correlation (0.25) with the age of the enterprises. Similarly, the importance ranking of the technology infrastructure has an intermediate correlation (-0.01) with the age of the enterprises. This indicates that the age of the enterprise does not influence the ratings of the financial resources and physical infrastructure. H10 is thus rejected.

H11: There is a positive correlation between the ages of the enterprises and the availability and accessibility of financial, physical and knowledge resources.

Table 13.23 presents the Spearman correlations between the age and size of enterprises and the rating scores of the innovation resources. The ages of the enterprises have a weak positive correlation with the availability of financial resources and technology infrastructure and the accessibility of knowledge and skills. Therefore, as the South African AM enterprises become more established, the availability rankings of the financial resources and technology infrastructure and the accessibility of knowledge and skills also tend to increase. H11 may, therefore, not be rejected.

Table 13.23: Spearman correlations (ρ) of the age and size of enterprises and the rating scores of the innovation resources

	Sufficient and sustainable financial resources for technology acquisition and adoption		**Technological infrastructure that supports the adoption of new technology and product development**		**Sufficient knowledge and skills within the knowledge network to successfully adopt new technology**	
	Availability	Accessibility	Availability	Accessibility	Availability	Accessibility
Correlation of enterprise age	0.32	0.29	0.37	0.04	0.17	0.37
Correlation of enterprise size	0.45	0.47	0.07	-0.11	0.00	0.13

H12: There is a positive correlation between the size of the enterprises and the availability and accessibility of financial, physical and knowledge resources.

Moderate positive correlations also exist between the size of the enterprises and the availability and accessibility of financial resources, while very weak correlations exist between the size and the other resources. H12 is thus rejected. Furthermore, the accessibility of technology infrastructure also tends to have a very weak negative correlation with the size of an enterprise. This indicates that as AM enterprises grow larger, they tend to have more financial resources available and accessible, while technology infrastructure tends to become slightly less accessible.

H14: The availability of resources is positively correlated to the strength of the knowledge network.

Table 13.15 indicates, with a strong correlation of 0.67, that the accessibility of knowledge and skills within the knowledge network of start-up enterprises strongly influences their availability ratings of the technological infrastructure. CH13 is thus not rejected. Therefore, forming alliances with knowledgeable enterprises to develop a strong knowledge network will improve the start-up enterprises' availability of technological infrastructure as the network will inform them of more infrastructure opportunities.

13.4.11. Functional analysis

Based on the importance-performance analysis work of Martilla and James [414], focused on identifying improvement priorities, a priority tool could be developed from the functional indicators to identify improvement opportunities and functions that require specific policy attention.

Table 13.24, Figure 13.29 and Figure 13.30 present the tool developed based on the average importance, difficulty, and extent performed ratings the survey respondents rated the Likert scale questions. Those activities whose priorities differ per sector may also be identified and further explored as they may require sector-specific policy support. These indicators are indicated as diamonds in Figure 13.29.

Figure 13.30 indicates a linear relationship, with a goodness of fit level of 94% (R2 = 0.9398), between the indicator activities the survey respondents deem important and those they performed significantly. Thus, both sectors tend to perform the indicator activities they deem important the most while performing the activities they deem less important to a lesser extent. H7 may thus not be rejected.

Table 13.24 and Figure 13.29 indicate that 42% of the indicator activities are deemed first priority by the South African AM enterprises. Due to the linear regression in Figure 13.30, these indicators are performed to a large extent as they are deemed relatively easy to perform. The fourth priority indicator activities represent those activities the enterprises deem difficult, unimportant, and performed to a lesser extent. Consequently, these quadrants do not require policy support suggestions.

Third priority indicators represent the indicators respondents deem important but difficult to perform. All the indicators rated in the second priority quadrant represent diamond indicator activities that differ in priority categorisation. For the third priority and diamond indicators, policy support suggestions may be derived to support enterprises in performing these activities. These suggestions are inspired by the insights derived from the four studied cases and are presented in Table 13.25.

Table 13.24: Mapping key of indicator activities according to their priority quadrants

1st priority							
1.	**[F1]** Commercial projects from international trends	3.	**[F1]** Commercial projects from end-users		9.	**[F2]** Determine technology readiness and maturity	
10.	**[F2]** Testing products' quality and price acceptability	12.	**[F2]** Offer training to employees on new equipment		13.	**[F3]** Maintain an information-sharing networks	
17.	**[F3]** Collaborating with end-users	18.	**[F3]** Launching marketing campaigns		20.	**[F3]** Attract customers with the company brand	
24.	**[F4]** Improve employees' confidence in AM's abilities	25.	**[F4]** Improve employees' confidence in the company's ability to use AM's abilities		31.	**[F5]** Determine the efficiency of staff member's knowledge and skills	
32.	**[F5]** Determine the availability and accessibility of infrastructure	35.	**[F5]** Data resources: Data sharing between company systems and machinery		39.	**[F7]** Ensure products live up to the values of the brand	
40.	**[F7]** Effectively marketing the company's products	41.	**[F7]** Advertising partnerships with well-known brands		43.	**[F7]** Minimise end-users' need for skill development	
3rd priority							
4.	**[F1]** Selling to South African customers	8.	**[F1]** Demonstrate technology to potential investors		26.	**[F5]** Surveying for new local customer segments and distribution channels	
27.	**[F5]** Assisting the creation of niche markets	33.	**[F5]** Determine the availability and accessibility of financial resources				
4th priority							
7.	**[F1]** Competing with international companies	11.	**[F2]** Set stopping criteria for terminating costly or infeasible projects		14.	**[F3]** Initiate collaboration projects with companies	
15.	**[F3]** Strategic alliances for resource benefits	23.	**[F4]** Identify laws and regulations that support the use of AM technology		28.	**[F5]** Identify regulations that improve market conditions for your enterprise	
34.	**[F5]** Human resources: Access to knowledge and skills	36.	**[F5]** Financial resources: Access to capital is available		37.	**[F5]** Physical infrastructure: Access to resources	
Diamond indicators that differ in priority categorisation							
5.	**[F1]** Buying from South African suppliers	6.	**[F1]** Competing with South African companies		16.	**[F3]** Collaborate with academia and government	
19.	**[F3]** Attending conferences and exhibitions	21.	**[F4]** Outline strategic innovation objectives		22.	**[F4]** Encourage a continuous improvement culture	
29.	**[F5]** Testing technology affordability, accessibility	30.	**[F5]** Determining a technology's market readiness		38.	**[F7]** Establish trust in the company's brand	
42.	**[F7]** Offering customers test opportunities before purchase						

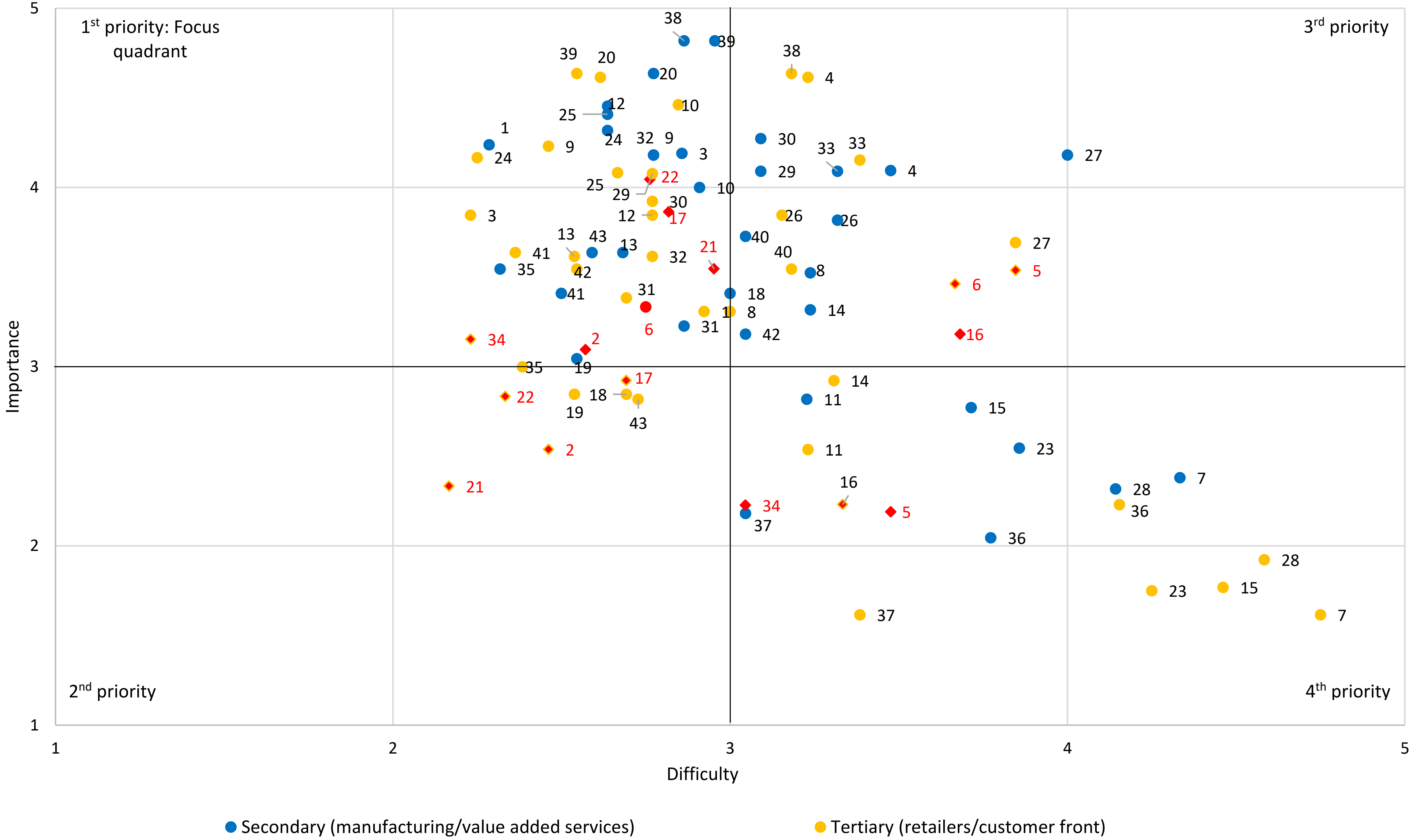


Figure 13.29: Importance-Difficulty mapping. Red diamonds indicate the activities instances whose average rating per sector is rated in different quadrants.

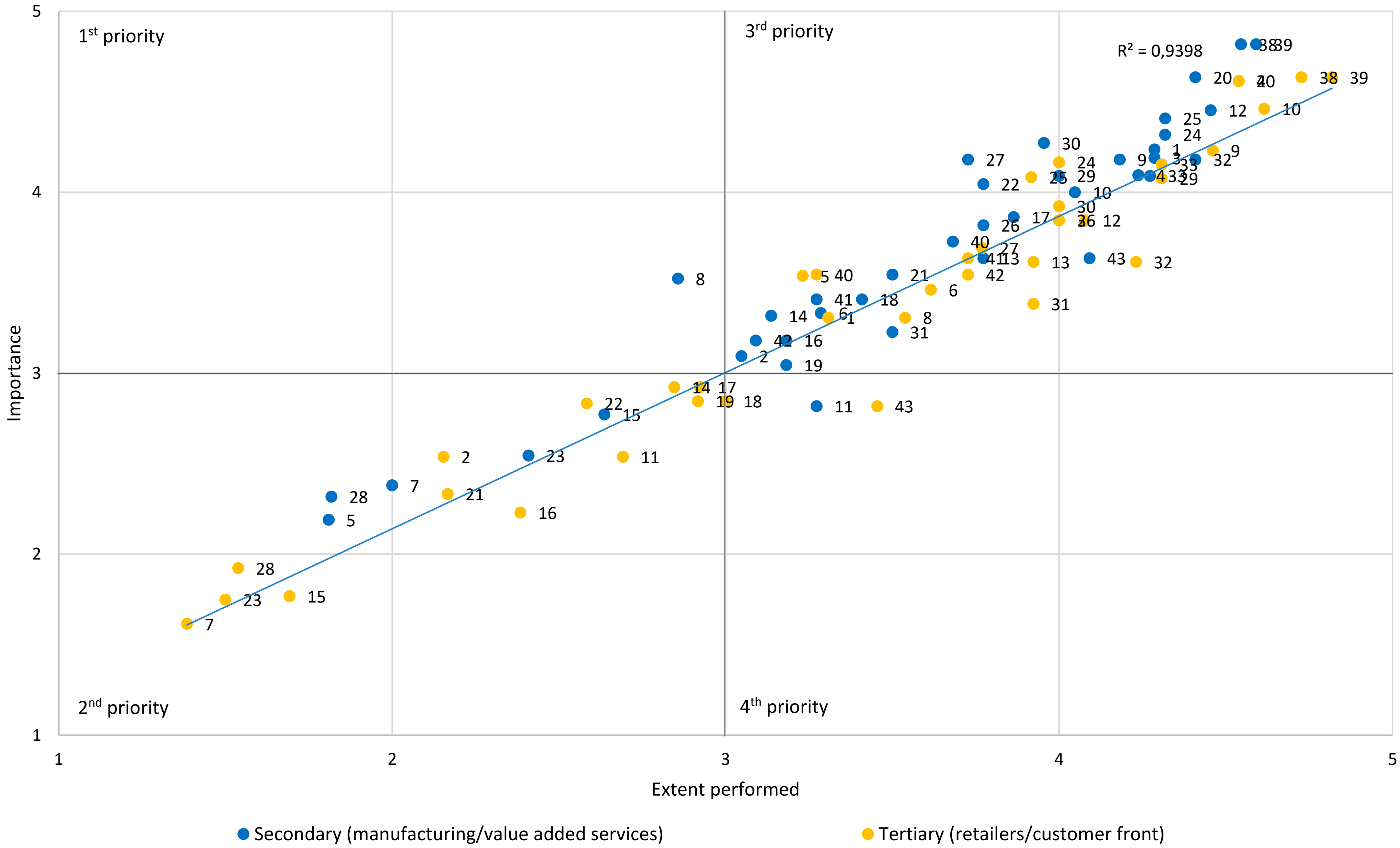


Figure 13.30: Importance-Extent performed mapping

Table 13.25: Policy support suggestions per TIS function

<table>
<tr><th>TIS function</th><th>Policy support suggestions</th></tr>
<tr><td rowspan="2">F1: Entrepreneurial activities
The transformation of knowledge, interaction networks and infrastructure into beneficial business opportunities</td><td>4. Selling to South African customers
8. Demonstrate technology to potential investors
• The South African AM industry will benefit from industry-based exhibitions and trade shows where the South African public, academic, and industry actors may view, test, or purchase the enterprises' hobbyist or industrial product and service offerings. This may support hobbyists and industry practitioners to get more acquainted with the technology, stimulate the adoption of the technology in vast new applications and provide enterprises with the opportunity to demonstrate the technology to potential investors.</td></tr>
<tr><td>5. Buying from South African suppliers
6. Competing with South African companies
• As most AM systems and industrial-grade AM powders are imported, policymakers are encouraged to support local manufacturers producing AM systems, powders, and consumables to achieve sufficient quality and standards. This will support the local economy and innovation and reduce the lead times and costs associated with importing these products.</td></tr>
<tr><td rowspan="2">F2: Knowledge development
All activities associated with learning and the obtainment of information

F3: Knowledge diffusion
All activities, channels and networks through which knowledge is shared among actors</td><td>16. Collaborate with academia and government
• More informal collaborations are suggested to support the diffusion of fundamental AM research and practical AM experience between AM enterprises and academic researchers and address the cumbersome administrative processes associated with formal academic-industry collaborations.
  – An informal academic-industry collaboration comprises academics inviting enterprise actors (particularly SMEs) to act as observers of their research studies. Academics are encouraged to meet with collaborating enterprises periodically to demonstrate progress and communicate challenges. Enterprises are encouraged to provide practical industry feedback and perform field tests of the research findings.
• To support academic-industry collaborations, governmental research funding organisations are encouraged to fund only those projects with clear industry contributions or that address industry needs.</td></tr>
<tr><td>19. Attending conferences and exhibitions
• The South African AM industry will benefit from industry-based exhibitions and trade shows where the South African public, academic, and industry actors may view, test, or purchase the enterprises' hobbyist or industrial product and service offerings.</td></tr>
</table>

<table>
<tr><td>F4: Guidance of search
The direction of people and resources towards appropriate opportunities and the provision of clarity, visibility and understanding</td><td>21. Outline strategic innovation objectives
22. Encourage a continuous improvement culture
• Demonstration centres and AM organisations are encouraged to host business development training to encourage and support enterprises in outlining strategic innovation objectives and encourage a continuous improvement culture.
• To support the use of initiatives, laws and regulations that support AM technologies, associated hosting parties need to increase the visibility of the support offered. Hosting parties are encouraged to communicate these initiatives, laws and regulations at industry-based exhibitions and trade shows through national strategies and AM organisations.</td></tr>
<tr><td rowspan="2">F5: Market formation
All factors influencing the market adoption of an innovation</td><td>26. Surveying for new local customer segments and distribution channels
29. Testing technology’s affordability and accessibility
30. Determining a technology’s market readiness
33. Determine the availability and accessibility of financial resources
• Policymakers and demonstration centres are encouraged to guide startups and SMEs in assessing and testing a novel technology’s acceptability, affordability, and accessibility to enable them to perform it to a more significant extent.
• Demonstration centres and AM organisations are encouraged to host business development training. This will enable AM enterprises of all sizes, sectors, and ages to gain knowledge and skills and form networks with related enterprises.</td></tr>
<tr><td>27. Assisting the creation of niche markets
• To ensure that academic or governmental-supported AM demonstration or training centres do not compete with or undermine industry enterprises, AM policymakers need to encourage demonstrative centres to focus on only offering niche services not offered in the local market and to direct customers towards enterprises that offer mainstream AM services.
• Funding organisations are encouraged to ensure that financial support opportunities are not awarded to recurring enterprises and that startups or established enterprises offering niche products or services also receive support.</td></tr>
<tr><td>F7: Creation of legitimacy
The creation of institutional compliance and support of social acceptance for innovations to overcome the obstacles associated with `newness’ within a market</td><td>38. Establish trust in the company’s brand
42. Offering customers test opportunities before purchase
• To gain advocacy, government innovation agencies, AM organisations and demonstration centres are encouraged to establish innovation support opportunities in the form of innovation competitions (such as for startups or SMEs) or innovation awards where advocacy may be gained.
• Policymakers may consider developing opportunities, such as industry-based exhibitions and trade shows, for AM enterprises to gain exposure and offer customers opportunities to test the technology before purchase.</td></tr>
</table>

13.5. Chapter 13 summary

This chapter studied the dynamics of the South African AM enterprises through a survey. The survey aimed to test to what extent activities related to the indicators are performed (extent), how they are viewed (importance), and what effort is put into them (difficulty). First, the chapter started with constructing the survey and validating feedback from nine expert reviews from academia and industry. Thereafter, the utilised data analysis techniques and methods were discussed, after which the hypothesis tested in the survey was presented. The chapter then concluded with the derivation of a priority tool that identified policy support suggestions. This chapter satisfied Objective VII, as mentioned in §1.4.

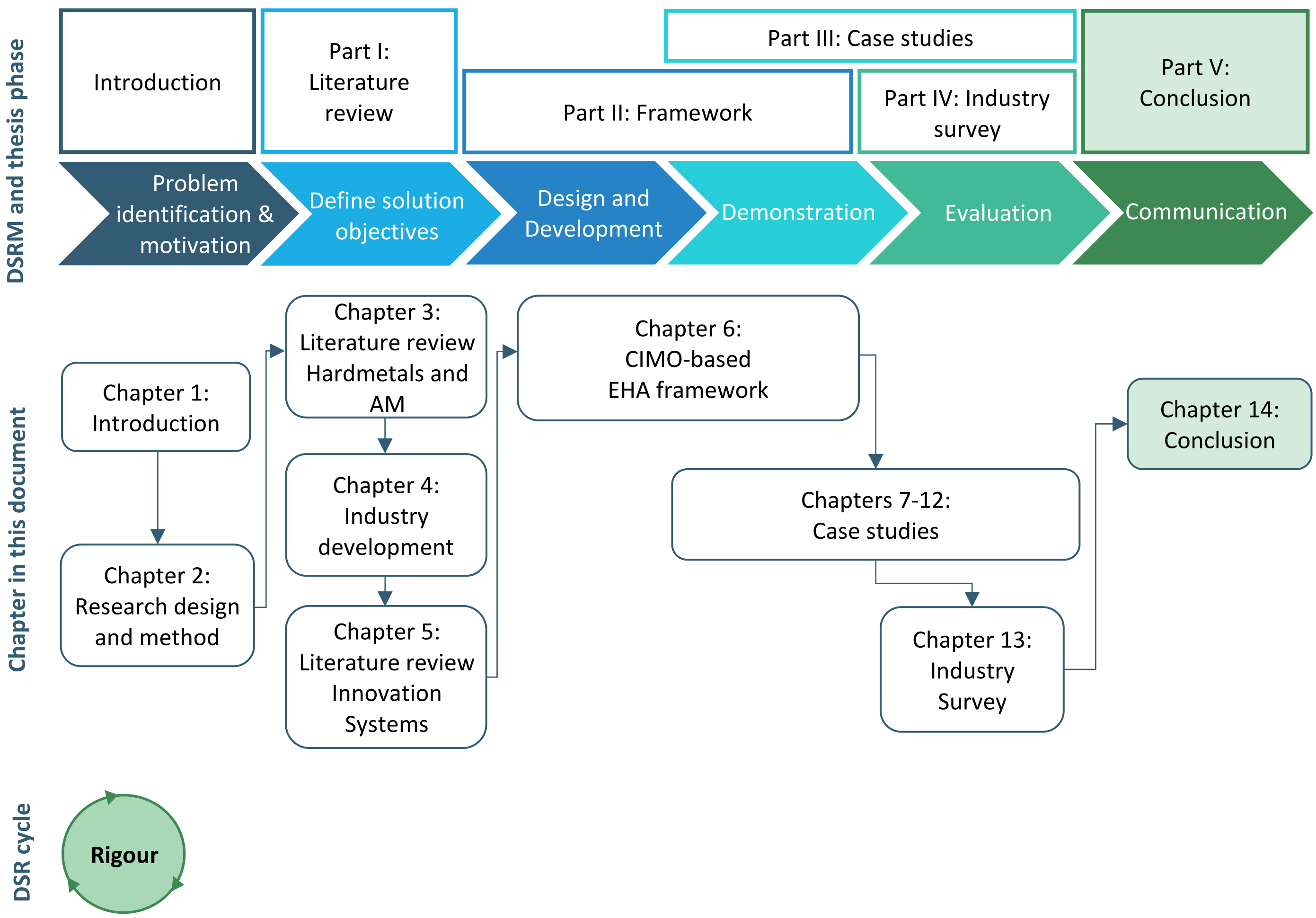
The framework, survey results and policy support suggestions have elucidated managerial implications and contributed to the literature on TISs and the South African AM industry. The framework instrument has elucidated a novel method to derive survey instruments. Developing a framework of the well-established functional indicators presents innovation scholars with a framework to identify and analyse the seven innovation activity types and their related activities performed within TISs. Furthermore, deriving the survey instrument from the framework ensure that TIS analysis comprises the analysis of all relevant innovation activity types and related activities. The derivation of survey statements, based on the functional indicators and the ranking of each statement's importance, difficulty, and extent performed, contributed to a priority tool that enables innovation scholars and managers to visualise response data and identify improvement and policy support opportunities.

Furthermore, this chapter presented a novel application of the TIS framework to the South African AM industry through a functional analysis of the dynamics of the South African AM enterprises. Consequently, insight could be obtained regarding the industry's challenges and opportunities per innovation activities. The priority tool also elucidated policy support opportunities South African innovation managers, and policymakers may address. Additionally, as the framework may be related to any TIS, the functional indicators may be utilised in future surveys to analyse other developing countries' AM industries to compare their dynamics to those of the South African industry.

Applying the survey instrument to the South African AM enterprises also presents innovation scholars and managers with practical results. The survey indicated that although academic-industry collaborations are often motivated in technology diffusion literature, they are associated with cumbersome administrative processes that burden enterprises unnecessarily. Informal collaborations or observation collaborations could benefit industries encouraging academic-industry collaborations as a form of technology and knowledge transfer. Moreover, industry-based knowledge and technology diffusion channels such as workshops, exhibitions, and conferences are encouraged as it supports enterprises, especially startups who struggle to develop networks, to establish knowledge and resource networks. Furthermore, the survey indicated that when enterprises struggle to identify laws and regulations that support the use or development of a specific technology, the effort to identify and use these laws and regulations is significantly reduced. Therefore, policymakers are encouraged to clearly present the laws and regulations to relevant parties and increase awareness thereof. The survey indicated that financial resources are important for all AM enterprises, regardless of age or sector. Therefore, although the South African funding organisations intend to support the growth of the South African AM industry through financial contributions, the demonstration centres receiving the funding compete against the industry's enterprises. The support it also provided to recurring centres. Thus, although governments or funding organisations intend to stimulate and support technology adoption, innovation managers should be mindful of the implications the support could cause for not-supported enterprises.

Part V

Conclusion



Chapter 14

Conclusion and reflections

This chapter presents a summary of the work contained in this study. It reflects on the research conclusions and offers an appraisal of the contributions of the study. Suggestions for possible future follow-up work, building upon the work presented in this study, are also provided. The chapter concludes with the personal reflections of the researcher.

Chapter 14 objectives:

- Present a summary of the work contained in this dissertation.
- Offer an appraisal of the contributions of the dissertation.
- Offer suggestions for future work.

14.1. Dissertation summary

This study aimed to *develop an evaluation framework and tool that support innovation system analysis.* The execution of this study was based on the design science research methodology. Apart from the introductory and methodology chapters, this study comprises twelve chapters, which have been organised into five parts, as presented in Figure 14.1. An overview of the work completed in each part is discussed in the following sections.

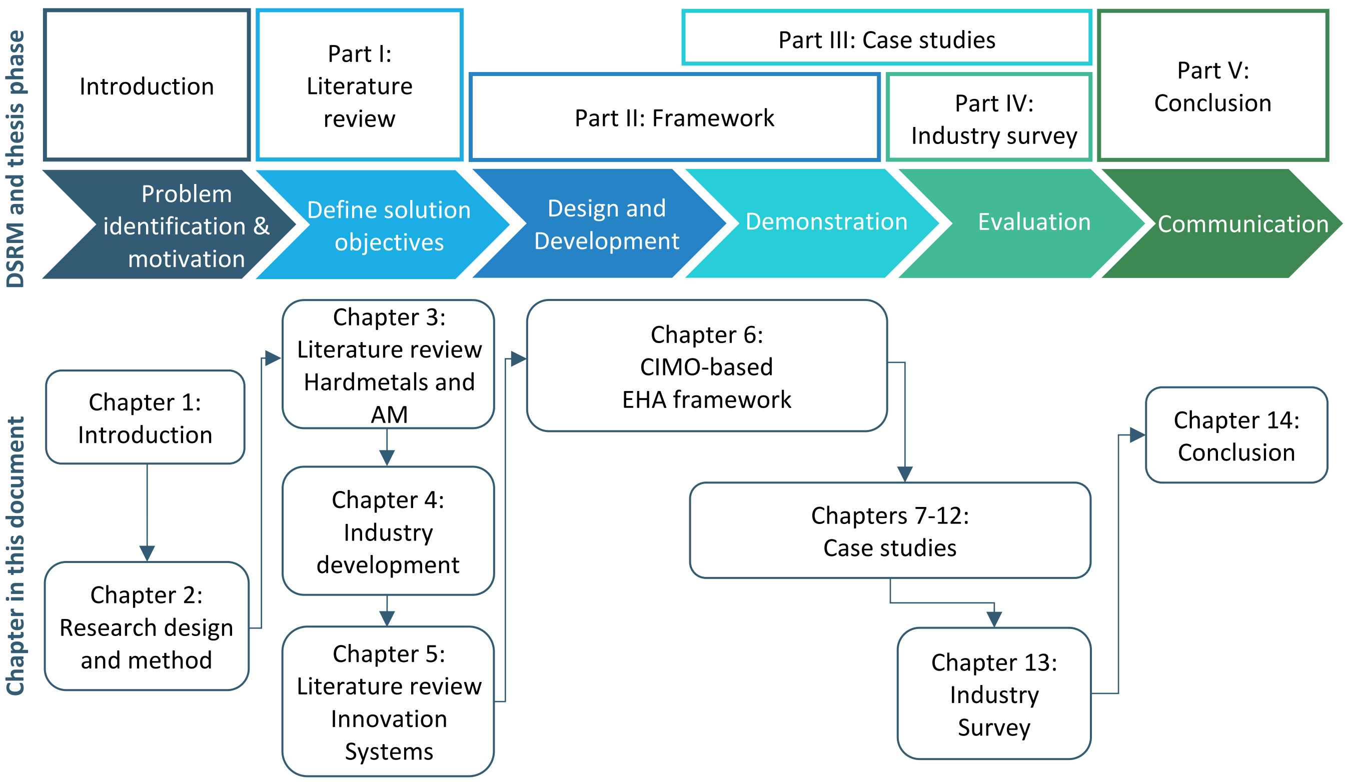


Figure 14.1: Summary of the application of the design science research steps, and the phases and chapters of the study

14.1.1. Phase 1: Literature review

Part I comprised a review of the relevant literature to fulfil Objective I of § 1.4. The first chapter in Part I, Chapter 3, served as a contextual understanding of the application material and technology of the study: hardmetals and additive manufacturing. First, the chapter presented the case for hardmetals and reflected on the hardmetal application fields. Next, an overview of traditional hardmetal manufacturing technologies and the relevant additive manufacturing technologies was presented. The chapter also presented an overview of the South African hardmetal industry. Thereafter, the chapter introduced Industry 4.0 technologies and additive manufacturing. The focus of the chapter shifted to an overview of the additive manufacturing technologies, after which it concluded with an overview of the South African additive manufacturing industry.

Chapter 4 presented an overview of innovation and industry and technology development. The chapter started by introducing the concept of innovation and the four fundamental theories explaining innovation and change processes. Thereafter, industry and technology development dynamics and phases were explored, and the concept of the valley of death was introduced. The chapter then reflected on why the valley of death has been found difficult to cross and presented an overview of the frameworks scholars have used to study the valley. Next, barriers and enablers to advanced manufacturing technology adoption were explored. The literature pertaining to the realist evaluation and the CIMO-logic framework was also studied as a potential lens to guide innovation system analysis. Finally, analysis approaches developed to study industry development were explored, and the innovation system framework was found to be the most appropriate approach.

Chapter 5, the final chapter of Part I, presented a detailed overview of the innovation system framework. The chapter started with an introduction to innovation models and the different innovation system types found in literature. Subsequently, the components and functions of the innovation system framework were explored. Next, the innovation framework was related to the life cycle phases of development and innovation system evaluation approaches explored. The systemic innovation policy framework was identified as a popular framework in innovation literature. Thereafter, the innovation system deliverables were explored, identifying the concept of motors of innovation. Finally, the chapter concluded with the exploration of the Event History Analysis method and previous applications thereof.

14.1.2. Part II: Framework

Part II of this dissertation was dedicated to presenting a newly proposed innovation system analysis framework. In fulfilment of Objectives II, Chapter 6 put forward the design of this generic framework for evaluating the event-based development of innovation systems through the CIMO-logic structure, the CIMO-based EHA framework. In order to place the proposed framework within the context of the current literature, an overview of similar existing frameworks was first presented. These frameworks' shortcomings were highlighted, including a lack of an actor-specific focus, context-specific focus and interventions, guidelines for analysts on designing and implementing new interventions, and focus on cumulative causation of long-term innovative development along with too generalised systemic goals and instruments. Consequently, a generic innovation system paradigm was proposed within which the CIMO-based EHA framework was developed. In this manner, the generic innovation system nature of the framework was ensured. Additionally, it ensured that it contained all the necessary components for analysing the evolutionary development of innovation systems in a structured manner. Finally, the CIMO-based EHA framework itself was described. To this end, a high-level overview of the framework was first presented. The event history analysis and component-function-based CIMO components, the framework's primary functional components, were then described in detail and illustrated by means of component canvases.

After the detailed description of the framework, the chapter's focus shifted to the framework's validation. More specifically, in fulfilment of Objective III, the framework was validated based on the evaluation criteria of the design science research artefact evaluation guidelines. The validation took the form of interviews with review experts who evaluated both the event history analysis and CIMO components of the framework. The implementation of their recommendations into the framework was also presented.

14.1.3. Part III: Case studies

In Part III, four real-world case study was conducted to demonstrate the value of the CIMO-based EHA framework in fulfilment of Objectives IV and V. First, in Chapter 7, the application of the event history analysis component of the framework to real-world case studies is presented in detail. The chapter starts with a detailed description of the case study selection process. Then, the application of the event history analysis steps is detailed. As data analysis and interviews form part of the data collection and verification phase, the interview process and the data analysis methods followed were also presented.

Chapter 8 presented the first real-world case study and contributed a novel writeup of the South African additive manufacturing industry from 1991 to 2020. This case was selected to understand the initial context in which the industry developed. The chapter provided a background of the South African additive manufacturing industry and defined the case study's research design. The case narrative shed light on how AM systems were imported and implemented into various organisations, centres, universities, and companies and how research studies were conducted in various application fields. Furthermore, insight was provided into the governmental support provided to the industry and how networks of actors were established to create awareness of the technology and stimulate the adoption thereof. Through the application of the CIMO-based EHA framework, the context and underlying structural drivers and barriers of the *research collaboration motor of innovation* that led to development within the case was identified. Finally, the influence these innovation structures and the *research collaboration motor* had on the outcomes and outputs of the case were presented. The application of the framework to Case I contributes to the fulfilment of Objectives IV and V.

Chapter 9 presented the second instantiation of the Design Science Research case demonstration and the CIMO-based EHA framework. The chapter presented the academic project level case and contributed a novel writeup of a Fraunhofer ILT research project to additively manufacture hardmetal machining tools (contributing to the fulfilment of Objectives IV and V). The chapter introduced the project's background and aim and presented the case study's research design. Subsequently, the project events were narrated through the event history analysis component of the framework. Then, the CIMO component was applied, and the *research collaboration motor of innovation* was identified. The actors and underlying structural drivers and barriers of the motors were then explored, after which the chapter concluded with a reflection on the outcomes and outputs of the case. This case provided insight into the context within which world-leading applied research is conducted, the collaboration and institutions between different innovation actors and the effect of external market conditions, such as the COVID19 pandemic.

Chapter 10 presented the framework's third real-world case study application and explored the dynamics of a startup company developing and commercialising a new product. Dyze Design, an innovation-award-winning startup, was selected for study. They demonstrated how an innovative startup company with minimal resources and business expertise utilised governmental and end-user support to develop and commercialise hardmetal AM products. The chapter presented the case background and narrated the enterprise's case development as a series of events. Next, the CIMO-based EHA framework's context and underlying structural drivers and barriers of the *development* and *entrepreneurial motors of innovation* that led to development within the case were identified. Finally, the influence these innovation structures and the *motors of innovation* had on the outcomes and outputs of the case were presented. The application of the framework to Case III contributed to the fulfilment of Objectives IV and V.

Chapter 11 presented the last real-world case study and contributed to the fulfilment of Objectives IV and V. The chapter presented a novel writeup of an R&D project conducted by Sandvik, an established multinational engineering enterprise. The project aimed to determine the capabilities of their additive manufacturing processes and to develop a product design that was not manufacturable with traditional manufacturing technologies. The chapter introduced the project's background and aim and presented the case study's research design. Next, the project events were narrated through the event history analysis component of the framework, and the important actors were identified. Then, the CIMO component was applied, and the *R&D motor of innovation* was identified. The actors and underlying structural drivers and barriers of the motors were then explored, after which the chapter concluded with a reflection on the outcomes and outputs of the case. This case provided insight into the dynamics established manufacturing enterprises use to commercialise their products and gain market share.

Chapter 12 comprised the synthesis of the insights and *motors of innovation* identified from each case based on applying the CIMO-based EHA framework. The chapter presented a high-level overview of the four cases and why each was selected. It also reflected on the methods utilised to synthesise the case findings. Subsequently, it compared the insight gained from the four instantiations of the design science research methodology and the CIMO-based EHA framework. From these insights, a conceptualised framework of R&D process mechanisms was derived along with R&D interventions for stimulating the growth and development of the South African AM innovation system. The chapter concluded with hypotheses derived to be tested in the industry survey of Part IV. This chapter fulfilled Objective VI.

14.1.4. Part IV: Industry survey

Part IV and Chapter 13 comprised the development and application of the industry survey instrument in the fulfilment of Objectives VII. The chapter started with the derivation of the survey questions from the CIMO-based EHA framework's functional indicator framework. The validation process of the survey questions by several expert reviewers was also presented along with their feedback. Next, the survey construction was detailed, which comprised a description of the sample selection process, the surveyed sample and the appropriate data capturing methods. It was found that the survey presented formative data, and consequently, demographic, variance and regression analysis methods were determined to be appropriate. Martilla and James' [414] importance-performance analysis work was also utilised to derive a priority tool to support the derivation of policy suggestions.

Over 45 days, the survey was sent to approximately 80% (40) of the South African additive manufacturing enterprises, of which 35 complete surveys were received. The survey response data obtained were presented per function and discussed in detail. Next, the survey results were subjected to the hypothesis derived in Chapter 12. Finally, the survey response data were subjected to the priority tool to identify the innovation initiatives and mechanisms the South African additive manufacturing enterprises need to support their innovation and development activities. The chapter then concluded with the derivation of policy support suggestions based on the priority tool and the hypothesis test results.

14.2. Appraisal of dissertation contributions

The contributions of this dissertation are documented in this thesis as well as in peer-reviewed journals.

14.2.1. Thesis contributions

The main contributions of this thesis are seven-fold. This section contains a summary and appraisal of each of these contributions.

Contribution I. *The proposal of a novel generic innovation system framework paradigm*

Before presenting the CIMO-based EHA framework in Chapter 6, a generic innovation system framework paradigm was first proposed, within which the CIMO-based EHA framework was developed. This paradigm comprises the generic analysis steps typically followed in the innovation system literature, particularly in those frameworks developed after the release of Wieczorek and Hekkert's [27] systemic innovation policy framework. The development of the paradigm extends existing innovation system literature as although the components is implied in the existing framework, it has not yet explicitly been presented as the innovation system framework paradigm. The integration of the tools developed in innovation system literature to support the identification or analyses of the paradigm's steps was also illustrated. It may provide a good starting point for the development of future frameworks aimed at facilitating the analysis of innovation systems. Furthermore, it may provide a structure for comparing similar frameworks.

Contribution II. *The novel relation of the generic innovation system framework paradigm to the components of the CIMO-logic structure*

The relation of the generic innovation system framework paradigm to the components of the CIMO-logic structure extends innovation system research as the innovation system framework has not yet been paired with the CIMO-logic structure, although it has been studied through the realist evaluation perspective. The relation of the generic paradigm to the components of the CIMO-logic structure presents innovation scholars with a novel framework to structure innovation system analysis and document system dynamics. The integration of the generic innovation system paradigm into the CIMO structure was also illustrated. Through utilising the CIMO structure, the innovation system analysts are guided to derive functional insight into the mechanisms that develop in particular contexts and how these contexts influence the outcomes delivered. Consequently, the proposed combination of the generic innovation system framework paradigm and the CIMO structure presents a process methodology through which policymakers may be informed on context-specific, targeted interventions to foster innovation and technology development. The combination thus sheds light on *"what works for which innovation systems, in which contexts, in what respects and how".*

Contribution III. *The development of a novel CIMO-based EHA framework to analyse the evolution of innovation systems.*

The CIMO-based EHA framework, proposed in Chapter 6, presents a novel combination of four existing artefacts, namely the innovation system framework, the EHA method, the development capitals and the CIMO-logic structure. The novel combination of these artefacts addresses the shortcomings of existing frameworks identified in the literature in five primary ways. First, the lack of actor-specific analysis of the event history analysis method is addressed by including the actor identification step during the allocations of events to the innovation system functions. This inclusion ensures that the actors associated with innovation events and their contributions are captured. It also enables a more comprehensive analysis of the innovation system's events and supports the design and development of interventions.

Secondly, the proposed framework's event history analysis component addresses the innovation system literature's lack of cumulative causation focus. It does so by enabling the analysis of how functions developed over time through a series of events, how functions influenced each other and how the innovation structures affected them.

Thirdly, the innovation system framework paradigm and CIMO-logic structures pattern analysis of the event history analysis method. The innovation system framework paradigm presents the event history analysis method with the necessary innovation tools to identify and analyse patterns and the outcomes the systems deliver over time. Furthermore, the CIMO-logic structure presents the event history analysis method with a framework to guide the utilisation of the innovation system tools and to present the finding of these tools in a structured manner. Additionally, it presents guidelines for analysts on designing and implementing new interventions. This supports the generalisability of the framework and the reproducibility of the analysis. The framework, therefore, enables the comparison of the analysis of different innovation systems, as presented in the real-world case studies.

Additionally, the framework addresses the lack of a context-specific focus and interventions by proposing incorporating the innovation system paradigm of the framework into the CIMO-logic structure. As mentioned in contribution II, the CIMO structure ensures that the contexts in which systems exist and develop are captured during innovation system analysis. This enables comparison between the innovation systems based on the context in which they develop, answering *"what works for which innovation systems, in which contexts, in what respects and how".*

Finally, the framework's analysis (CIMO) component was designed to be generic in nature. This was achieved in two manners: by developing the framework's analysis component within the generic innovation system framework paradigm mentioned in Contribution I, and by adopting a modular approach towards the analysis (CIMO) component's design. Any innovation system tools incorporated into the CIMO component of the framework may thus be exchanged, modified, or removed in accordance with innovation system finding in literature and the objectives of the analysis in question without disrupting the correct functioning of other modules of the framework.

The CIMO-based EHA framework was published in the proceedings of the 28th IEEE ICE/ITMC & 31st IAMOT Conference [71].

Contribution IV. *The application of the proposed CIMO-based EHA framework to four novel real-world case studies*

The design of the CIMO-based EHA framework was not limited to a conceptual level. In Chapters 7 to 11, practical implementations of the framework were demonstrated through four real-world case studies. Before the demonstration, in Chapter 7, details were given to describe how the event history analysis component of the framework may be realised. In this manner, the practical usability of the CIMO-based EHA framework was illustrated.

The utility of the CIMO-based EHA framework was illustrated in the context of real-world settings by means of four novel case studies of differing project levels: academic, SME, large enterprise, and industry-level. These cases demonstrated the generality of the framework as the dynamics of all four cases could be analysed. They also demonstrated the comprehensiveness of the framework as case-specific could also be derived from each case. The case synthesis derived in Chapter 12 also indicated how the insights derived and mechanisms identified in three cases studied through the CIMO-based EHA framework could be compared as a standardised framework was followed.

Finally, the four case studies also extend hardmetal and additive manufacturing literature as the cases has not yet previously been documented as case studies. While Chapter 8's case on the South African additive manufacturing industry has only partially been documented previously, Chapter 9, 10 and 11's case studies on the Fraunhofer project, Dyze Design and Sandvik's collaboration with Varel, has not yet been documented as case studies or in-depth examination of real-world contexts.

Contribution V. *The proposal of six novel process mechanisms for crossing the Valley of Death*

This study extends the existing literature on technological developments bridging the valley of death (VoD) by arguing that a technological invention should complete six process mechanisms to bridge the VoD. As prevalent in VoD literature, the cases included in this study experienced a lack of financial and infrastructure support due to the risk associated with investments in untested, unproven, or unknown technologies and a lack of relevant professional competencies. Consequently, the process approach of the six process mechanisms acknowledges the complexity of the VoD dynamics and supports technology developers in managing these challenges. Furthermore, this study draws upon the well-established TIS framework, a conceptually comprehensive systems approach well suited to analyse technological development. By applying the TIS functional analysis, the innovative activities (interventions) performed were identified as TIS functions that inform the six process mechanisms. As the seven functions induce cumulative causation over time, each representing a collection of innovative activities, this study contributes a process approach grounded on cumulative causation to the VoD literature.

Contribution VI. *The development of a novel method to develop a survey instrument and a policy suggestion priority tool.*

The framework instrument has elucidated a novel method to derive survey instruments. Developing a framework of the well-established functional indicators presents innovation scholars with a framework to identify and analyse the seven innovation activity types and their related activities performed within technology innovation systems (TISs). Furthermore, the derivation of the survey instrument from the framework presents a novel contribution to how survey instruments may be derived. Additionally, deriving the survey instrument from the framework ensure that TIS analysis comprises the analysis of all relevant innovation activity types and related activities. Additionally, incorporating the importance, difficulty, and extent performed Likert scale data enables the development of a priority tool that allows innovation scholars and managers to visualise response data and identify opportunities for improvement and policy support.

Contribution VII. *The results obtained from the application of the survey instrument and priority tool to the South African AM enterprises.*

This study contributes a novel application of the TIS framework to the South African AM industry through a functional analysis of the dynamics of the South African AM enterprises. Consequently, insight could be obtained regarding the industry's challenges and opportunities per innovation activities. The application of the survey instrument to the South African AM enterprises presents innovation scholars and managers with practical results. The survey indicated that although academic-industry collaborations are often motivated in technology diffusion literature, they are associated with cumbersome administrative processes that burden enterprises unnecessarily. Informal collaborations or observation collaborations could benefit industries encouraging academic-industry collaborations as a form of technology and knowledge transfer. Moreover, industry-based knowledge and technology diffusion channels such as workshops, exhibitions, and conferences are encouraged as it supports enterprises, especially startups who struggle to develop networks, to establish knowledge and resource networks. Furthermore, the survey indicated that when enterprises struggle to identify laws and regulations that support the use or development of a specific technology, the effort to identify and use these laws and regulations is significantly reduced. Therefore, policymakers are encouraged to clearly present the laws and regulations to the relevant parties and increase the awareness thereof. The survey indicated that financial resources are important for all AM enterprises, regardless of age or sector. Therefore, although the South African funding organisations intend to support the growth of the South African AM industry through financial contributions, the demonstration centres receiving the funding compete against the industry's enterprises. The support it also provided to recurring centres. Thus, although governments or funding organisations intend to stimulate and support technology adoption, innovation managers should be mindful of the implications the support could cause for not-supported enterprises.

The priority tool also elucidated policy support opportunities South African innovation managers and policymakers may address. Additionally, as the framework may be related to any TIS, the functional indicators may be utilised in future surveys to analyse other developing countries' AM industries to compare their dynamics to those of the South African industry.

14.2.2. Publication contributions

The publication contributions of this dissertation are four-fold. This section contains a summary of each of these contributions.

M. McClelland, S. S. Grobbelaar, and N. Sacks, "A scoping review of additive manufacturing policies," in Towards the Digital World and Industry X.0 - Proceedings of the 29th International Conference of the International Association for Management of Technology, IAMOT 2020, 2020, no. 29, pp. 1260–1273, DOI: 9781713818540.

Author contributions: Conceptualization, M.M. and S.S.G.; methodology, M.M. and S.S.G.; validation, M.M. and S.S.G.; formal analysis, M.M.; investigation, M.M.; data curation, M.M.; writing—original draft preparation, M.M. and S.S.G.; writing—review and editing, M.M. and S.S.G.; funding acquisition, S.S.G and N.S.

M. McClelland, S. S. Grobbelaar, and N. Sacks, "Towards an analytical framework to analyse the evolution of manufacturing innovation systems," in IEEE IAMOT ICE conference, Nancy France, IAMOT 2022.

Author contributions: Conceptualization, M.M. and S.S.G.; methodology, M.M. and S.S.G.; validation, M.M. and S.S.G.; formal analysis, M.M.; investigation, M.M.; data curation, M.M.; writing—original draft preparation, M.M. and S.S.G.; writing—review and editing, M.M. and S.S.G.; funding acquisition, S.S.G and N.S.

M. McClelland, S. S. Grobbelaar, and N. Sacks, "Measuring innovation system functions: A survey of additive manufacturing in South Africa," in IEEE Transactions on Engineering Management (under revision).

Author contributions: Conceptualization, M.M. and S.S.G.; methodology, M.M. and S.S.G.; validation, M.M. and S.S.G.; formal analysis, M.M.; investigation, M.M.; data curation, M.M.; writing—original draft preparation, M.M. and S.S.G.; writing—review and editing, M.M. and S.S.G.; funding acquisition, N.S.

M. McClelland, S. S. Grobbelaar, and N. Sacks, "Bridging the Valley of Death: A technology innovation system perspective," in Technovation (in review).

Author contributions: Conceptualization, M.M. and S.S.G.; methodology, M.M. and S.S.G.; validation, M.M. and S.S.G.; formal analysis, M.M.; investigation, M.M.; data curation, M.M.; writing—original draft preparation, M.M. and S.S.G.; writing—review and editing, M.M. and S.S.G.; funding acquisition, N.S.

14.3. Suggestions for future work

This section presents suggestions for possible future follow-up work, building upon the work presented in this study. These suggestions are partitioned into two sections related to the proposed CIMO-based event history analysis framework and the application of the framework to case studies. In each case, the suggestion is stated formally and then briefly motivated and elaborated upon.

14.3.1. Suggestions related to the proposed framework

This section comprises suggestions related to the framework proposed in Chapter 7.

Proposal I. *Exploring additional modules to gain more contextual insight*

The CIMO-based event history analysis framework derived in this dissertation was designed to be modular. Therefore, although the CIMO structure is fundamental to the framework, the insights gained from the structures may be altered to identify context-specific insight. Additional modules may be included in each CIMO structure to gain additional contextual insight into an innovation system's case, or modules may be removed if the required unavailable information. For example, in the case of the outcomes structure, novel modules to inform the identification of systemic problems and the derivation of mitigation strategies may be implemented.

Proposal II. *Exploring new framework perspectives*

The CIMO-based event history analysis framework derived in this dissertation was based on the technology innovation system framework and its definition of the innovation system functions. However, as the framework's components were designed to be modular, the framework components may be changed to better suit other innovation system perspectives. Innovation system scholars are therefore encouraged to apply the framework to the other innovation system frameworks, particularly the regional and inclusive innovation system frameworks. Scholars are encouraged to adopt the innovation structures and functions relevant to these frameworks and to use the CIMO nature of the framework to analyse their regional and inclusive innovation systems. These frameworks' output and outcome measurement tools may also be adapted to inform the identification of systemic problems and the derivation of mitigation strategies.

14.3.2. Suggestions related to case studies

This section comprises suggestions related to the case studies performed in Chapters 8 to 11 and the case synthesis performed in Chapter 12.

Proposal III. *Completing the case study cube*

All the cases studied in this dissertation were relevant to additive manufacturing and hardmetals as it was this study's application focus. To ensure that the cases covered a range of geographical locations, innovation actors and maturity levels, a case study cube (Figure 14.2) was presented in Chapters 7 to 12 to illustrate the cube segments the cases covered. As this dissertation only fulfils a limited number of cube segments, future studies are encouraged to complete the remaining segments. Scholars are encouraged to build on the synthesis derived in Chapter 12, conduct a comparative study of all the dynamics of the cube of cases, and

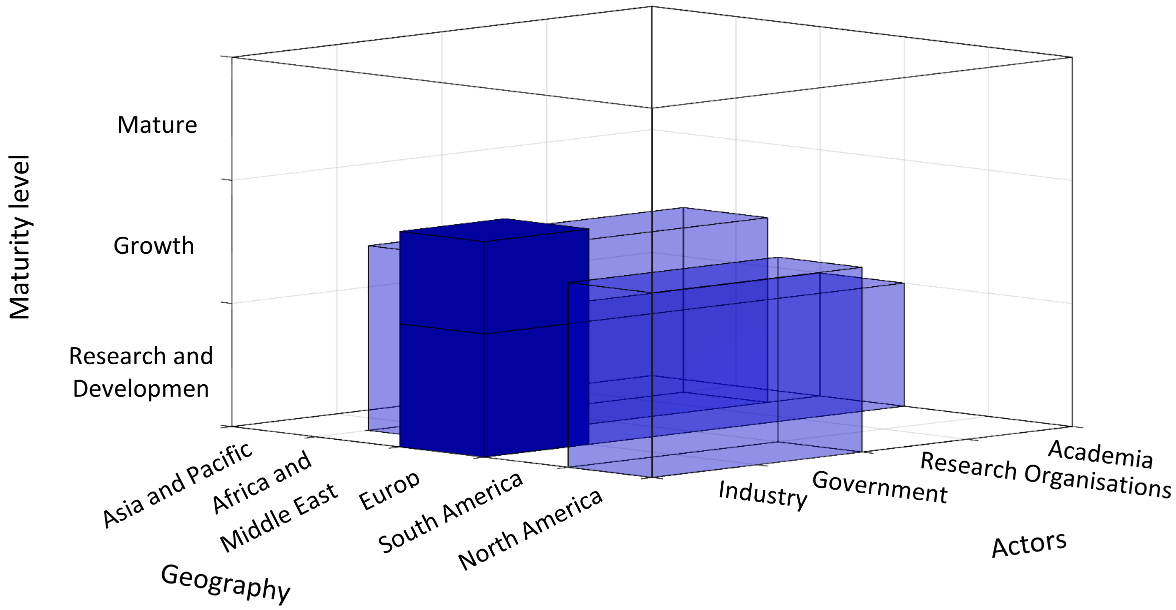


Figure 14.2: Cube framework of four cases studied

compare the insight gained from the cube segments to derive a comprehensive innovation tool to support innovators in developing and commercialising their innovations.

Proposal IV. *Exploring new applications fields*

As a limited number of additive manufacturing and hardmetal cases are available for study, innovation scholars are also encouraged to apply the CIMO-based event history analysis framework to other technologies, materials, and industries. For additive manufacturing cases, scholars may explore cases on metals such as titanium, cobalt chromium, and other alloys, as they are most commonly employed in additive manufacturing applications, particularly in the healthcare field. Additionally, scholars are encouraged to study the development of other Industry 4.0 technologies, such as the evolution of technology innovation systems pertaining to blockchain or artificial intelligent technologies.

14.4. Personal reflection

This research project has helped me grow as an engineer and a person. As an engineer, the project has taught me the value and complexities of qualitative research and data and has presented me with the tools to study and present them quantitatively. I have learned to pursue information with an open mind, critically reflect upon what I have learned, analyse its relevance, and synthesise it in a useful manner. I have also learned the powerful abilities of additive manufacturing and am grateful for the opportunity to have learned about the creative applications thereof from the experts and enterprises interviewed. As a person, this project has enabled me to develop my interviewing skills and ability to extract the necessary information. I have also developed the skills to communicate with people of different professions and geographical locations and to appreciate the contributions every person contributes to a system and project. I will forever be grateful for the privilege of completing this study at the Department of Industrial Engineering, Stellenbosch University, and for all the experiences that came with it.

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Appendix A

Case study event analysis tables

This appendix presents the event analysis tables of Cases I to IV as narrated in Chapters 8 to 11.

14.5. Case I: The South African additive manufacturing industry

Table A.1: Event Analysis Table of Case I

Year	#	Event	Recognisable activity	IS function(s)
1990	1	Through published international case studies and vendor literature, South African researchers learned about the benefits the AM offered.	Research articles	Ex (G), KI (R), Aca F2/KDev
1991	2	Quickly identified application areas relevant to the local context where research opportunities existed.	Communicating vision	KI (P), Aca F4/GoS
		First AM system implemented in South Africa by the South African 3D Systems (Pty) Ltd agent.	Technology implementation	Comp (P) F1/EA
1994	3	Second and third AM system implemented by the CSIR.	Technology implementation	KI (P) F1/EA
1995	4	In the mid-1990s, the introduction rate of new product models into the global market led to the realisation of the enabling power AM offered. In South Africa, it led to the realisation that competitive product development was required to support the local manufacturing industry [28].	Market conditions, advocacy	Ex (G), Gov (R) F4/GoS, F5/MF, F7/CoL
	5	This realisation was fundamental to establishing the CSIR's Product Development Centre in 1995 [28]. Through the Centre, the CSIR intended to demonstrate good, fast, and effective product development technologies that were not well known in the country.	New project with commercial aim, collaboration	KI (P) F1/EA KI (G), CSoc (R) F3/KDif
1996	6	In 1996, three AM systems were implemented at the Product Development Centre.	Technology implementation, advocacy	KI (P) F1/EA, F7/CoL
	7	A partnership between the CSIR and 3D Systems (Pty) Ltd was formed to promote the Centre as an AM service centre for the local manufacturing industry and as a development centre for the CSIR and local universities.	Collaboration, communicating vision and expectations	KI (G), Comp (R), F3/KDif KI (G), Comp (R), Aca (R) F4/GoS
	8	Central University of Technology (CUT) purchased two AM systems, becoming the first South African university to own AM systems [26], [29].	Technology implementation, advocacy	Aca (P) F1/EA, F7/CoL
	9	Purchasing these systems was extremely challenging as some researchers did not understand their application in global or local manufacturing, and single installations had to be imported directly from international manufacturers [34].	Communicating opinions, inhibiting technology installation	Aca (G, R) - F4/GoS Comp (G), Aca (R) -F1/EA

	10	Therefore, funding from partners and the university led to the purchase of two machines.	Resource mobilisation	Aca (G) F6/RM
1997	11	In 1997, CUT and the CSIR established the CRPM to conduct extensive research on AM technologies and expand its application fields within the local manufacturing industry. The CRPM purchased an AM system with support from the NRF.	New firm/project with commercial aim, collaboration, resource mobilisation	KI (G, P), Aca (R, P) F3/KDif, F1/EA, Gov (G), Aca (R) F6/RM
	12	In the same year, a similar centre, known as the Global Competitive Centre (GCC), was established by the Department of Industrial Engineering of Stellenbosch University (SU) [38].	New firm/project with commercial aim	Aca (P) F1/EA
	13	The Product Development Centre became the Time Compression Technologies Centre. This Centre operated as a physical centre and a virtual network of partners, with the CRPM and GCC as the leading academic and knowledge institutions and Rapid Design Technologies (Pty) Ltd as the leading industry partner [28].	New firm/project with commercial aim, collaboration	KI (P) F1/EA, KI (G), Aca (R), Comp (R) F3/KDif
1998	14	South Africa became a founding but interim member of GARPA with the challenge to form a national association to obtain full membership.	Collaboration with group, communicating expectations	KI (R) F3/KDif, Ex (G) F4/GoS
	15	The DSI conducted a National Research and Technology Foresight Project which emphasised integrated product development and production system design to speed up production time.	Communicating vision and expectations	Gov (G) F4/GoS
	16	The project also listed RP, virtual prototyping, CAD, CAM, and tooling amongst the key technologies that would support this aim.	Communicating vision, advocacy	Gov (G) F4/GoS, F7/CoL
	17	In response to the Foresight Project's key findings, the South African government provided funding for AM research and more AM systems. Additionally, government initiatives such as THRIP were established.	Resource mobilisation, market conditions	Gov (G), Aca (R), KI (R) F6/RM, Gov (G) F5/MF
	18	The THRIP initiative provided 50% funding to industry-academia research projects, given that industry partners also provided 50%.	Market conditions	Gov (G), Aca (R), KI (R), Comp (R) F5/MF
	19	Several institutions, including CUT, SU and the CSIR, utilised this programme for industry-related AM research.	Resource mobilisation	Gov (G), Aca (R), KI (R), Comp (G) F6/RM
1999	20	The DSI and CSIR established the National CAD/CAM Training Centre.	New project with commercial aim, advocacy, resource mobilisation	KI (P) F1/EA, Gov (G), KI (R) F6/RM, F7/CoL
	21	The DSI also launched the Technology Stations Programme. As a result, the stations effectively became AM demonstration centres, enabling potential buyers to access and test AM technology before making financial commitments.	New project with commercial aim, research studies, enabling market conditions	Gov (P) F1/EA Gov (G), Comp (R) F2/KDev, F5/MF
	22	A group of members from the CSIR, GCC and the CRPM conceptualised RAPDASA, a non-profit organisation to represent the South African AM and wider rapid product development community.	Collaboration, new firm with commercial aim	KI (G), Aca (R) F3/KDif Rap (P) F1/EA

	23	Due to a lack of AM awareness in South Africa, industry partners still had a very conservative perspective regarding AM, academic partners were sceptical about AM, and globally AM was only seen as prototyping technologies.	Non advocacy, communicating distrusting perspective	CSoc (G) -F7/CoL, Comp (G), Aca (G), Ex (G) -F4/GoS
	24	RAPDASA's objectives were to demonstrate AM technology to South Africans to convince them of the importance of developing AM technology to maintain international competitiveness and to include industry partners in the research community.	Communicating vision	Rap (G, R) F4/GoS
	25	RAPDASA contributed to the annual Wohler's Report, which strengthened RAPDASA's position in the international arena.	Advocacy	Ex (G), Rap (R) F7/CoL
2000	26	The first annual international RAPDASA conference was hosted in 2000.	Conference	Rap (P) F3/KDif
	27	Growing awareness of the need for AM and competitive product development to support the South African manufacturing industry led to the conversion of the National CAD/CAM Training Centre into the National Product Development Centre. The Centre was actively supported by the DSI, and within the first year, a series of CSIR short courses and research studies were hosted at the Centre.	Communicating vision and support, new project with commercial aim, resource mobilisation, collaboration, research studies	Gov (P) F4/GoS, F7/CoL, KI (P) F1/EA, Gov (G), KI (R) F6/RM, KI (G, P), Aca (R, P) F2/KDev, F3/KDif
	28	The Centre acted as the knowledge hub of the national AM network.	Knowledge share, collaboration	KI (P) F2/KDev, F3/KDif
	29	Du Preez [43] ascribed the Centre's success to the network of partners as they enabled human and financial resources to be leveraged towards a common goal.	Collaboration, enabling market conditions	Aca (R), KI (G), Comp (R) F3/KDif, F5/MF
2001	30	In November 2001, RAPDASA hosted the annual GARPA meeting coinciding with the annual RAPDASA conference. Although this was only the second annual conference, fourteen international delegates attended the conference.	Conference, advocacy	Rap (P) F3/KDif, Ex (G), Rap (R) F7/CoL
2002	31	In August 2002, the DSI released the National Research and Development Strategy.	Communicating expectations and vision, advocacy	Gov (P) F4/GoS, F7/CoL
	32	Along with the strategy, R125 million were allocated to technology and innovation for the advanced manufacturing and logistic industries.	Resource mobilisation	Gov (G), Aca (R), KI (R) F6/RM
2003	33	In 2003, the National Integrated Manufacturing Strategy and National Advanced Manufacturing Technology Strategy for South Africa was released by the DSI.	Communicating expectations and vision, advocacy	Gov (P) F4/GoS, F7/CoL
	34	These strategies aimed to stimulate advanced manufacturing, product development and AM in South Africa.	Communicating vision and support	Gov (P) F4/GoS
	35	The strategies allocated R650-million to support projects, centres, and networks of innovation for the following three years.	Resource mobilisation	Gov (G), Aca (R), KI (R) F6/RM

	36	In the same year, the CSIR launched the Rental Pool Programme through DSI funding.	New project with commercial aim, resource mobilisation	KI (P) F1/EA, KI (R), Gov (G) F6/RM
	37	In its first year, it supported seven projects.	Resource mobilisation, research studies	Aca (P) F2/KDev, KI (G), Gov (G), Aca (R) F6/RM
2004	38	In 2004, RAPDASA again hosted their annual conference coinciding with the annual GARPA meeting.	Conference	Rap (P) F3/KDif
	39	More than a hundred South Africans attended the conference.	Conference attending	Rap (G), KI (R), Aca (R), Comp (R), Gov (R) F3/KDif
	40	Progressively more private companies were implementing AM systems, and industry leaders became active members of the RAPDASA management committee.	Advocacy	Comp (G), Rap (R) F7/CoL
	41	The conference attendees identified several weaknesses and potential threats within the South African AM industry.	Communicating outcomes	Aca (G, R), KI (G, R) -F4/GoS
	42	They included a) a limited range of AM systems and material combinations were available in the country, b) several prominent South African industries were still not implementing AM technologies, c) there was a lack of fundamental research in academia which made peer-reviewed publications challenging, and d) the tooling industry had growing international competition.	Market conditions, technology installation, research studies,	Gov (G), Ex (G) -F5/MF Comp (G) -F1/EA KI (G) -F2/KDev, -F3/KDif
	43	By December 2004, 29 AM systems were implemented in South Africa by universities and private companies, which stimulated further research opportunities.	Technology implementations, advocacy, research studies	Aca (P), Comp (P) F1/EA, F7/CoL, Aca (P), Comp (P) F2/KDev
	44	The continuous growth was ascribed to the stabilised Rand exchange rate and decreased machine price fluctuations.	Market conditions	Gov (G) F5/MF, Ex (G) F5/MF
2005	45	By 2005, the Technology Stations Programme was well established.	Firm expansion	Gov (P) F1/EA
	46	The DSI closed the National Product Development Centre and redirected its funding to the technology stations.	Firm closure, resource mobilisation	Gov (P) -F1/EA, Gov (G) F6/RM
2006	47	In 2006, the CRPM implemented the Direct Metal Laser Sintering system.	Technology implementation	Aca F1/EA
	48	During this period, AM technologies were no longer globally viewed as rapid prototyping technologies but as additive manufacturing technologies.	Communicating vision and perception	Ex (P) F4/GoS
2007	49	The South African government invested in FabLabs and set aside R16-million.	Firm expansion, resource mobilisation	Gov (P) F1/EA, Gov (G) F6/RM
	50	By the end of 2007, six FabLabs were established across the country.	Firm expansion	Gov (P) F1/EA

	51	112 AM systems were implemented in South Africa, of which one was the first titanium AM system in the country.	Technology implementation, advocacy	Aca (P), Comp (P) F1/EA F7/CoL, Aca F1/EA
	52	The purchase of this system was motivated by international companies showing great interest in South Africa's titanium-bearing reserves.	Market conditions	Ex (G), Aca (R) F5/MF
2008	53	In 2008, 136 AM systems were implemented in South Africa and lower cost systems, improved part quality, and ease of use materials became available globally.	Technology implementation, advocacy, market conditions	Aca (P), Comp (P) F1/EA F7/CoL, Ex (G) F5/MF
	54	Designers were starting to combine rapid tooling with AM technologies as the advantages of geometric freedom in small batch production were realise.	Research studies	Aca (P), Comp (P) F2/KDev
	55	Universities, with SU and CUT taking the lead, research focused on new materials, improving machine accuracy and novel industrial applications.	Research studies	Aca (P) F2/KDev
2009	56	Aerosud Innovation Centre partnered with the CSIR to manufacture titanium aerospace parts. Together they conceptualised an R&D project named `Aeroswift'.	Project with commercial aim, collaboration	KI (G), Comp (R) KI F3/KDif, Comp (P), KI (P) F1/EA
	57	In the same year, the CSIR's Rental Pool Programme had grown to support 32 programmes per year.	Resource mobilisation	KI (G), Gov (G), Aca (R) F6/RM
2011	58	In 2011, project Aeroswift was officially initiated through funding provided by the DSI and the CSIR.	Project with commercial aim, resource mobilisation	Comp (P), KI (P) F1/EA, Gov (G), KI (G) F6/RM
		As part of the project, Aerosud and the CSIR developed an advanced 3D printer for metal components, the world's largest 3D printer.	Research studies, advocacy	Comp (P), KI (P) F2/KDev, F7/CoL
2012	59	In the same year, the Idea2Product laboratory was established at VUT to introduce AM principals to impoverished Gauteng communities through open-sourced technology transfer models. The laboratory provided free support to any product developer from concept inception to the final prototype.	Project with commercial aim, collaboration	Aca (P) F1/EA, Aca (G), CSoc (R) F3/KDev
	60	At the end of 2012, industry and public ownership of personal 3D printers had far outgrown the academic ownership of high-end systems. De Beer ascribes this trend to a wide variety of industries that were adopting AM as an outcome of the South African national strategies.	Technology installation, advocacy, market conditions	Comp (G), CSoc (G) F1/EA, F7/CoL], Gov (G), Comp (R) F5/MF
	61	At the annual RAPDASA conference, researchers identified the need for a South African AM roadmap. Globally, an AM movement was developing, and the wide variety of research studies made collaborations between research groups difficult as the research differed in application areas.	Conference, providing feedback, advocacy, collaboration	Rap (P) F3/KDif, Aca (G), Gov (R) F4/GoS, Ex (G) F7/CoL, Aca (G, R) -F3/KDif

		Therefore, the DSI authorised a group of researchers to develop an AM roadmap. For several months, these researchers extensively researched the application areas that would offer the South Africa AM industry competitiveness in the global AM market.	Research studies, advocacy, communicating vision and expectations	Gov (G), Aca (R) F4/GoS, F7/CoL, Aca (P) F2/KDev
2014	62	In 2014, the South AM Technology Roadmap was presented at the annual RAPDASA conference.	Conference	Rap (P) F3/KDif
	63	The roadmap aimed to enable South African companies to become global industry leaders by guiding the identification of market, research and technology development opportunities and investment decisions. It prioritised research focus areas included qualified AM parts for the medical and aerospace industries, improving the efficiency of traditional manufacturing sectors, new AM materials and technologies, and SMME development.	Communicating outcomes and vision	Aca (G, R), Comp (R) F4/GoS
	64	Furthermore, Stellenbosch University also established an Idea2Product laboratory.	New firm with commercial aim	Aca (P) F1/EA
	65	The laboratory provided on-demand 3D printing, 3D scanning and 3D-printing training courses to academic and societal actors and consulted consultation services to product developers and private 3D printer owners.	Research and learning activities	Aca (G), CSoc (R) F2/KDev
	66	At the end of 2014, in response to the Roadmap, the CPAM was developed.	Collaboration, research studies	Aca (G, P), KI (G, P), Comp (R) F3/KDif, F2/KDev
		They learned that through collaboration, more resources and opportunities became available. The programme received R 30.7 million from the DSI.	Collaboration, communicating outcomes, resource mobilisation	KI (G), Aca (R) F3/KDif, F4/GoS, Gov (G), Aca (R), KI (R) F6/RM
	67	In addition to the DSI funding, the South African government invested approximately R 358 million in AM technology research and development projects.	Resource mobilisation	Gov (G), Aca (R), KI (R) F6/RM
2015	68	In December 2015, there were 3500 AM machines in South Africa.	Technology implementation, advocacy	CSoc (P), Comp (P), Aca (P) F1/EA, F7/CoL
	69	A discussion forum for Science, Engineering, Technology for Socio-Economic Growth in South Africa was held which noted that not all the universities conducting AM research owned AM systems and that only a limited number of South African companies were acting as AM service bureaus.	Forum, communicating outcomes, lack of resource mobilisation, market conditions	Gov (P) F3/KDif] Gov (P) F4/GoS, Aca (P) -F6/RM, Comp (G) -F5/MF
	70	In addition, the Rand's weak exchange rate against the Dollar and Euro made AM systems less affordable.	Market regulations	Gov (G), Aca (R), Comp (R), CSoc (R) -F5/MF
2016	71	In April 2016, the DSI released the AM Strategy for South Africa. The strategy identified aerospace and military, medical and dental, tooling, casting,	Communicating expectations and providing guidance,	Gov (G), Aca(R), KI (R), Comp (R) F4/GoS, Gov (G)

		and automotive industries as the prioritised industries for 2014 to 2023. The CPAM programme became the strategy's implementation programme.	advocacy, research activities	F7/CoL, Gov (G), Aca(R), KI (R), Comp (R) F4/GoS, Aca (P), KI (P) F2/KDev
	72	The CRPM became the first African AM centre to receive ISO 13485 certification for 3D printing of medical devices.	Research studies, advocacy	Aca (P) F2/KDev, F7/CoL
	73	It proved to the South African manufacturing industry that AM technology could deliver certified products and that it was worth implementing.	Communicating research outcomes, advocacy	Aca (G), Comp (R) F4/GoS, F7/CoL
2017	74	In 2017 the Rental Pool Programme supported nearly 300 research projects through equipment sharing.	Research studies, resource mobilisation	KI (G), Gov (G), Aca (R) F2/KDev, F6/RM
2018	75	There were also 6000 AM systems installed in South Africa.	Technology implementation, advocacy	KI (G), Aca (G), CSoc (G), Comp (G) F1/EA, F7/CoL
	76	After 2018, the number of AM systems in the country became uncountable as the implementation of the systems, particularly the personal 3D printer systems, grew at a high rate.	Technology implementation, advocacy	CSoc (P) F1/EA, (P) F7/CoL
	77	The technology was well known globally, and lower cost machines became available.	Advocacy, market conditions	Ex (G) F7/CoL, Ex (G), CSoc (R) F5/MF
2019	78	2019 marked the twentieth year of the annual RAPDASA conference.	Conference	Rap (P) F3/KDif
	79	RAPDASA grew impressively as more than 300 delegates from academia, industry, and the government attended the conference and was recognised for playing a central role in developing Industry 4.0 in South Africa.	Collaboration, knowledge development through research studies	Rap (G), KI (R), Aca (R), Comp (R), Gov (R) F3/KDif, Rap (P) F2/KDev

14.6. Case II: The Additive Manufacturing of Machining Tools out of WC-Co

Table A.2: Event Analysis Table of Case II

Year	#	Event	Recognisable activity	IS function(s)
01/2018	1	AM researchers from Fraunhofer ILT were exploring new research opportunities, as it was a common culture in Germany that government research funding was mainly awarded to research projects with industry-driven topics and that industry participation.	Research studies, communicate vison	FH (P) F2/KDev OvG (P) F4/GoS
04/2018	2	Fraunhofer ILT researchers identified an opportunity to manufacture hardmetal cutting tools with a low cobalt proportions.	Research studies	FH (P) F2/KDev
	3	The Fraunhofer ILT researchers invited the Aachen researchers to collaborate with them on feasibility studies to test the potential of their solution.	Collaboration, communicate vison	FH (G), Aach (R) F3/KDif, F4/GoS
06/2018	4	The researchers from Fraunhofer ILT and Aachen combined resources and conducted feasibility studies to test their solution.	Research studies, collaboration, resource mobilisation	FH, Aach (P) F2/KDev, (G) F3/KDif, F6/RM
	5	As the studies proved their solution feasible, the researchers decided to launch an official collaboration to conduct an official research project to develop their solution.	Research studies, collaboration. New project launch	FH (P), Aach (P) F2/KDev FH (G), Aach (G) F3/KDif, RC (P) F1/EA
	6	The researchers decided to apply for Otto von Guericke e.V funding.	Market conditions supporting research	GoV (G), RC (R) F5/MF
07/2018	7	Industry involvement was a prerequisite to obtaining research funding.	Communicating research vision	GoV (G), RC (R) F4/GoS
	8	The researchers invited numerous manufacturing companies throughout Germany and Europe to collaborate on the AM of WC-Co project.	Communicating research vision and outcome	RC (G), Ind (R) F4/GoS
10/2018	9	Eighteen SMEs experienced in either AM technology or hardmetal properties had agreed to participate in the project by February 2019.	Collaboration, advocacy	RC (G), Ind (R) F3/KDif, Ind (G), RC (R) F7/CoL
03/2019	10	The researchers submitted their project proposal to the Otto von Guericke e.V group.	Communicating vision and research outcomes	RC (G), OvG (R) F4/GoS
05/2019	11	The project was awarded approximately €700,000 for a thirty-month period.	Resource mobilisation, advocacy	OvG (G), RC (R) F6/RM, F7/CoL
06/2019	12	In June 2019, Cobalt was classified as a hazardous, carcinogenic, mutagenic, and toxic substance in Switzerland.	Market regulations	Reg (P) F5/MF
	13	Furthermore, the regulations stated that all persons working with cobalt power should wear impervious protective suits with protective gloves and face masks.	Market regulations	Reg (P) F5/MF
	14	The Swiss SME informed the researchers of the new regulations shortly after the release.	Communicating vision	Ind (G), RC (R) F4/GoS

	15	The researchers ordered the impervious protective gear they required.	Resource mobilisation	RC (P) F6/RM
09/2019	16	In September, the researcher groups and industry partners came together for a kick-off meeting.	Collaboration	RC (G), Ind (R) F3/KDif
	17	The researchers shared their objectives as well as the initial barriers they would experience.	Communicating vision	RC (G), Ind (R) F4/GoS
	18	The industry partners collaborated to find solutions and shared their visions and the resources they could offer the researcher if required.	Collaboration, communicating vision	Ind (P) F3/KDif, RC (R), Ind (G) F4/GoS
10/2019	19	The AM of WC-Co research project officially launched. Monthly group progress meetings were scheduled.	New project, research studies, collaboration	RC (P) F1/EA, RC (P) F2/KDev, RC (P) F3/KDif
11/2019	20	The Fraunhofer ILT researchers presented the project at the Formnext 2019 international conference, where two more industry partners agreed to join their collaboration.	Conference, communicating research outcomes	RC (G), Ind (R) F3/KDif, F4/GoS
02/2020	21	The Cobalt Institute and the European Chemical Agency announced that the European Union approved the harmonised classification and labelling of Cobalt as a hazardous, carcinogenic, mutagenic, and toxic substance. The European Union's required all workspaces and machines where cobalt powder is handled to be encapsulated.	Market regulations	Reg (P) F5/MR, Reg (P) F5/MR
	22	These regulations brought the laboratory and testing aspects of the project to a temporary pause. As this unforeseen expense was not part of the project budget, each research group had to pay for their encapsulations and impervious protective gear from their own funds.	Research and studies, resource mobilisation	RC (P) -F2/KDev, RC (P) -F6/RM, F6/RM
04/2020	23	Germany announced a nationwide lockdown.	Market regulations	Reg F5/MR
	24	This forced the researchers to work from home, where they continued with all facets of their research that did not include laboratory testing and manufacturing. Preference was given to parties supporting the fight against the COVID-19 pandemic.	Market regulations, research and studies	RC (P) -F2/KDev, Reg (P) F5/MF
10/2020	25	The researchers had not yet received their impervious protective gear, and their encapsulations had not yet been manufactured. This meant that although the lockdown regulations permitted their laboratory work to continue, the cobalt regulations did not.	Resource mobilisation, research and studies, market regulations	RC (P) -F6/RM, -F2/KDev, F5/MR
	26	Therefore, the research groups applied for a twelve-month project extension from the Otto von Guericke group.	Communicating research extension	RC (G), OvG (R) F4/GoS
	27	The extension was granted from March 2022 to March 2023 without the provision of additional funding.	Communicating vision	RC (R), OvG (G) F4/GoS

12/2020	28	Finally, in December 2020, the researchers received their impervious protective gear.	Resource mobilisation	RC (P) F6/RM
01/2021	29	The installations of the encapsulations of their workspace and machines commenced in January 2021.	Resource mobilisation	RC (P) F6/RM
02/2021	30	In February 2021, when the researchers' workspaces and machines were encapsulated, and the German lockdown regulations once again enabled the researchers to continue their laboratory work, the manufacturing and testing aspects of the project continued.	Market regulations, research studies	Reg (G), RC (R) F5/MF, RC (P) F2/KDev
03/2021	31	The research groups had weekly meetings to discuss the progress each group had made.	Collaboration, research studies, communicating research outcomes	RC (P) F2/KDev, F3/KDif, F4/GoS
04/2021	32	Through these meetings, the researchers quickly realised that they required more WC-Co powder which the industry partners then provided them with.	Resource mobilisation	RC (G), Ind (R) F4/GoS, Ind (G), RC (R) F6/RM
06/2021	33	The researcher had samples to prove that their techniques and methods worked. They were hopeful to have samples close to the quality of conventionally manufactured material to show to their industry partners by the end of the year.	Feasibility studies, vision	RC (P) F2/KDev RC (G), Ind (R) F4/GoS
08/2021	34	The research collaborators continued with their respective research focus areas and conducted investigative research.	Research studies	RC (P) F2/KDev
10/2021	35	The research collaborators continued with their respective research focus areas and conducted investigative research.	Research studies	RC (P) F2/KDev
12/2021	36	The research collaborators continued with their respective research focus areas and conducted investigative research.	Research studies	RC (P) F2/KDev
02/2022	37	During these eleven months, the research collaborators sent regular updates to their industry partners, who in turn provided them with advice or encouragement.	Communicate research outcomes, guidance	RC (G, R), Ind (R, G) F4/GoS
04/2022	38	The Fraunhofer researchers found that the breakthroughs made, and insights gained in the research collaboration project during these months supported and contributed to their other research projects.	Research studies	RC (G), FH (R) F2/KDev
05/2022	39	By the end of May 2022, the hardmetal parts were ready for field testing. Four industry partners volunteered to conduct the tests for the research collaborators.	Research studies, field testing	RC (P) F2/KDev, Ind (P) F2/KDev
	40	During these tests, the research collaborators shared their progress at the 20th Plansee Seminar in Austria per their research funding agreement to make their research available in the public domain.	Conference, communicate research outcomes	RC (G), Ind (R) F3/KDif, F4/GoS

14.7. Case III: Dyze Design's Hardmetal Nozzle

Table A.3: Event Analysis Table of Case III

Year	#	Event	Recognisable activity	IS function(s)
07/2015	1	Dyze Design team saw a market opportunity for high-performance 3D printer components.	Market conditions	Cus (P) F5
	2	Dyze Design was established [417].	Entry of firms	DD (P) F1
	3	The community was risk averse.	Market conditions	Inv **(P)** -F5
	4	Dyze Design participates in government competitions and programmes.	Demonstrations; Regulations supporting niche markets	DD (G) F1 Gov (G) F5
08/2015	5	Dyze Design won the Montréal Foundation Inc innovation competition and received a CAD 10,000 grant [351].	Demonstrations; Grants Regulations supporting niche markets; Advocacy	DD (G) F1, (R) F5, F6 Gov (G) F5, F6, F7
11/2015	6	Dyze Design winners of the Accelerator competition's National Bank Award [352]. The award included a CAD 10,000 grant, twelve-week professional development training and two mentoring sessions with one of Canada's most successful entrepreneurs [352].	Demonstrations; Grants Regulations supporting niche markets; Advocacy	DD (G) F1, (R) F6 Gov (G) F5, F6, F7
	7	Dyze Design received training and mentoring sessions.	Learning activities; communicating vision; Training activities	DD (R) F2, F4 Gov (G) F3
02/2016	8	Dyze Design launched a research and development.	Projects with commercial aims; pilot project	DD (G) F1, F2
	9	Dyze Design considered and studied a wide variety of materials to identify a solution material.	Assessing the availability of raw materials.	DD (G) F2
06/2016	10	Dyze Design identified tungsten carbide as the most suitable material.	Assessing the availability of raw materials.	DD (G) F2
	11	Dyze Design did not have the necessary machines.	Infrastructure development	DD (G) -F6
	12	Therefore, they looked for suppliers that met their requirements.	Communicating vision and defining expectations	DD (G) F4
	13	It was difficult finding suppliers due to the product specifications.	Alliances between actors	Sup (G) -F3
08/2016	14	Dyze Design found adequate suppliers.	Alliances between actors	DD (G) F3 Sup (G) F3
	15	Dyze Design collaborated with their suppliers and conducted numerous iterations of feasibility studies.	Feasibility studies Alliances between actors	DD (G) F2, F3 Sup (G) F3
	16	Dyze Design received tax incentives from the Canadian Government's Scientific Research and Experimental Development Tax Incentive Program [418].	Setting tax incentives	Gov (G) F5 DD (R) F5
05/2017	17	Dyze Design was chosen to be part of Centech's Propulsion development program [403].	Portfolio expansions; regulations supporting niche markets; advocacy	DD (G) F1, (R) F5 Gov (G) F5, F7

07/2017	18	Dyze Design received training.	Learning activities; Training activities; providing directions	DD (R) F2 Gov (G) F3, F4
12/2017	19	They needed capital to manufacture the nozzles.	Communicating research outcomes; no investments	DD (G) F4, -F6
	20	Searched for investors and venture capitalists to invest in their product but did not find any as the investors were more interested in software products.	Joint ventures; defining expectations	Inv (G) -F3, F4
	21	Dyze Design reached the end of their R&D phase of the nozzle project	Feasibility studies; alliances between actors communicating research outcomes	DD (G) F2, F3, F4 Sup (G) F3
02/2018	24	Dyze Design contacted numerous websites, companies and journals within the 3D printing and tungsten carbide communities to announce their campaign [397], [398], [404].	Awareness campaigns, communicating vision and defining expectations	DD (G) F3, F4 (R) Sup, Cus F3
03/2018	25	Kickstarter campaign launched [404].	Projects with commercial aims, awareness campaigns	DD (G) F1, F3
	26	Within the first two days, almost 30% of the goal amount was raised by early supporters [404].	Investments	DD (R) F6 Cus (G) F6
	27	In response to the support and positive feedback received, Dyze Design released photos of objects printed with one of the nozzle prototypes on Kickstarter and thanked the early supporters for the support [404].	Communicating outcomes	DD (G) F4 Cus (R) F4
	28	By March 16, 2018, Dyze Design had raised the goal of CAD 15,000 and released a statement to thank their supporters [404].	Investments, Communicating outcomes	DD (G) F4, (R) F6 Cus (G) F6
04/2020	30	When the campaign ended in April, the tungsten carbide nozzle project was successfully funded as 355 buyers pre-ordered a total of CAD 34,572 worth of nozzles from people throughout the world [404].	awareness campaigns; investments, advocacy,	DD (R) F6, F7 Cus (G) F6, F7
	31	Dyze Design once again released a statement to thank their supporters and thereby disseminate knowledge of how much demand there was for their product [404].	Communicating outcomes	DD (G) F4 Cus (R) F4
06/2018	33	Several manufacturing and quality difficulties were encountered, which delayed the production of the nozzles	Feasibility studies	DD (G) -F2 DD, Sup (G) F3/KDif
07/2018	34	Dyze Design tried to reassure their supporters of their process and send regular updates of their progress to their supporters over the Kickstarter platform.	Communicating outcomes	DD (G) F4 Cus (R) F4
09/2018	35	The production of the tungsten carbide nozzles commenced	Product development	DD (G) F2, F3 Sup (G) F3
	36	During the production process, Dyze Design attended numerous international trade shows in the United States of America	Demonstrations, conferences	DD (G) F1, F3 Cus (R) F3
	37	Although attending these trade shows was very costly to the small start-up company, they	Awareness campaigns, investments	DD (G) F3, (R) F6 Cus (G) F6, (R) F3

		reached countless international buyers interested in their products.		
	38	At these trade shows, Dyze Design quickly realised that as personal 3D printers were globally becoming less expensive, their tungsten extruder product was too expensive for their 3D printing enthusiasts target market	Communicating vision and defining expectations	Inv (G) -F4, -F7 DD (R) F4, F7
	40	They did, however, also notice that their tungsten extruder was used in some industrial 3D printers, worth CAD 60,000.	Communicating vision and defining expectations, advocacy	Cus (G) F4, F7 DD (R) F4, F7
10/2018	41	Dyze Design, therefore, decided to, in addition to their current cost-effective tungsten extruder for personal 3D printers, develop no-cost compromise, high quality, high performance, reliable tungsten carbide extruders for industrial 3D printers.	Portfolio expansions	DD (G) F1
	42	Dyze Design also wanted to build on their international personal 3D printers client base from the Kickstarter campaign.	Portfolio expansions	DD (G) F1
	43	They contacted numerous internet stores worldwide selling 3D printer components to advertise their tungsten carbide nozzles and extrusion components.	communicating vision	DD (G) F4
11/2018	44	Through these internet stores, Dyze Design found several European distributors willing to sell their products to the European market	Alliances between actors	DD (G) F3 Cus F3
	45	Dyze Design invested in online advertisements, wrote blogs about their products, and converted their website into an electronic store to enable customers to view and purchase their products electronically.	Portfolio expansions, investment	DD F1, F6
01/2019	46	The final nozzle batch was delivered, and the R&D project of the tungsten carbide nozzle officially concluded.		-
	47	The campaign gained awareness for the entire company as their website visitation and products sales received a significant increase.	awareness campaigns, advocacy, investments	DD (R) F3, F6, F7 Cus (G) F6, F7
02/2019	48	In February 2019, when the tungsten carbide nozzle R&D project concluded, Dyze Design launched another R&D project to develop high quality, high performance, reliable tungsten carbide extruders for industrial 3D printers with the capital that was raised from the previous trade shows.	Feasibility studies, investments	DD (G) F2, F6
06/2019	49	Dyze Design attended numerous international trade shows in the United States of America and Germany to sell their products and promote their upcoming industrial 3D printing extruder.	Conferences, demonstrations, communicating research outcomes, investments	DD (G) F1, F3, F4, (R) F6 Cus (G) F6, (R) F3, F4
09/2019	50	Dyze Design released a prototype of their high flow industrial extrusion to test the product's potential in the global market	Demonstrations, pilot study, awareness campaign	DD (G) F1, F2, F3 Cus (F3)
	51	The prototype received excellent feedback	Showing interest	Cus (G) F4
	52	Dyze Design went ahead with the production and commercialisation of the product.	Portfolio expansions, Product development	DD F1, F2

12/2019	53	Dyze Design released the typhoon extruder into the global market.	Projects with commercial aims	DD F1
01/2020	54	Dyze Design appoint a sales representative to tend to the needs of their customers.	Portfolio expansions, recruiting human resources	DD (G) F1, F6
05/2020	56	They displayed their products at several international conferences where they reached numerous personal and industrial 3D printer clients.	Conferences, demonstrations, communicating research outcomes, investments	DD (G) F1, F3, F4, (R) F6 Cus (G) F6
	57	To gain access to funding and technical equipment to attend the trade shows, Dyze Design partnered with LOJIQ [419] and Del [420], financial and entrepreneurial support organisations established by the Canadian government.	Subsidies (such as cost-sharing incentives)	DD (R) F5, F6 Gov (G) F5, F6
06/2020	58	Dyze Design also participated in more global entrepreneurial and development competitions and programmes offered by the Quebec and Canadian governments.	Demonstrations, regulations supporting niche markets	DD (G) F1, (R) F5 Gov (G) F5
	59	Dyze Design won the Innovations and Technology Excellence Awards of CCIRS - Chambre de commerce et d'industrie de la Rive-Sud [421].	Demonstrations, regulations supporting niche markets, advocacy	DD F1 Gov F5, F7
09/2020	60	Dyze Design partnered with several German, Dutch, and Canadian universities to supply their research groups with their tungsten carbide nozzles, extruders, and industrial extruder systems	Projects with commercial aims, developing prototypes, alliances between actors	DD (R) F1, F2, F3 Aca (G) F3
	61	The universities were impressed by the low-priced, high-quality products Dyze Design could offer them.	Showing interest, advocacy	Aca (G) F4, F7 DD (R) F7
10/2020	62	Furthermore, Dyze Design partnered with engineering universities in Montreal, Canada, to allow students pursuing their engineering degrees to complete their internship credits at Dyze Design.	Alliances between actors	DD (G) F3 Aca (G) F3
	63	This partnership enabled Dyze Design to share their expertise with students and establish relationships with potential future employees.	Training activities, recruiting human resources, learning activities	DD (G) F3 Aca (R) F2
		The Canadian government supported Dyze Design's relationship with the engineering universities through tax incentives of the internship salaries.	Setting tax incentives and tax exemptions	Gov (G) F5
11/2020	65	Dyze Design was also a finalist for the ADRIQ innovation award [400].	Demonstrations, regulations supporting niche markets, advocacy	DD (G) F1, (R) F5 Gov (G) F5, F7
	66	Dyze Design also started to write more scientific literature such as whitepapers.	Seminars, advocacy	DD F3, F7

14.8. Case IV: Sandvik and Varel's high-precision nozzles

Table A.4: Event Analysis Table of Case IV

Date	#	Event	Recognisable activity	IS function(s)
06/2013	1	Sandvik established a centrally funded AM R&D Centre	Portfolio expansions, Investment	San (G) F1, F6
	2	The centre's objective was to test the capability of the AM printing processes and start the journey to become global competitors in the AM market	Communicating vision	San (G) F4
	3	They evaluated different kinds of AM technologies and had a specific interest in binder jetting. Furthermore, as Sandvik has an extensive application in the mining industry, they evaluated various advanced (hard and robust) materials, such as cemented carbides and different types of tool steel	research and studies	San (G) F2
06/2015	4	In 2015, the researchers from the AM R&D centre started to test the printing of cemented carbides	research and studies	SanR (G) F2
	5	Their objective was to develop cemented carbide printing processes to manufacture high-quality hardmetal products that could be implemented in the mining industry.	Communicating vision	SanR (G) F4
03/2016	6	In early 2016, the researchers had developed a binder jetting method to print good quality cemented carbides	research and studies	SanR (G) F2
	7	As they had been busy with R&D projects for almost three years, they were anxious to identify application opportunities and commercialise some of their findings, amongst them the binder jetting method for cemented carbides.	Communicating vision	San (G) F4
04/2016	8	In April 2016, a senior researcher at AM R&D researchers contacted a product manager from the carbide's division within the Sandvik group	Joint ventures	SanR, SPM (G) F3
	9	As the product manager was knowledgeable of Sandvik's cemented carbide product range and the carbide market, the researcher informed him of their binder jetting progress with cemented carbides and invite him to join them at the AM centre to assist them with the commercialisation of their R&D findings	Communicating vision	SanR, SPM (G) F4
	10	A few R&D findings were presented to the product manager and considered for further development and commercialisation, but as there were no suitable or economic market opportunities, they were eliminated.	Communicating vision, showing disinterest, Market regulations	SanR (G) F4 SPM (G) -F4, -F5
	11	Industry was still sceptical about AM technology as the manufacturing time were much slower than the traditional manufacturing technologies and, therefore, a lot more expensive	Market regulations	SPM (G) -F5
	12	In contrast, there were industry partners who were excited to invest in AM technology were not familiar with cemented carbides but only with materials such as tool steel	Market regulations	SPM (G) -F5
	13	Collaboration and application opportunities with Varel were presented and considered feasible	Projects with commercial aims	SanR (G) F4, SPM (G) F1, (R) F4
12/2016	14	As Sandvik had a manufacturing technology and was looking for possible applications, Sandvik's senior R&D	Communicating vision, Lobbying activities	SanR (G) F4, F7 VPM (R) F4

		engineer contacted a product application manager at Varel to share their binder jetting progress		
	15	In addition, he invited Varel to share their ideas for (new) products that could be improved or developed with Sandvik's binder jetting process	Communicating vision, Lobbying activities	SanR (G) F4, F7 VPM (R) F4, F7
05/2017	16	Several months later, Varel aspired to reduce their nozzle stock levels. Varel then contacted Sandvik and proposed their cemented carbide nozzles as an application for Sandvik's binder jetting process	Communicating vision	SEng (R) F4 VPM (G) F4
	17	In May 2017, Sandvik's senior R&D engineer and carbide product manager submitted their collaboration proposal to Varel	Joint ventures Communicating vision	SanR, SPM (G) F3, F4 VPM (R) F3, F4
06/2017	18	In June 2017, the R&D project officially launched, and Sandvik's senior R&D engineer and product manager, alongside Varel's' product application manager, set out to develop their cemented carbide nozzles with the binder jetting technology.	Project with commercial aim, research studies, joint venture	PDT (G) F1, F2, F3
	19	The project had no predetermined timeline or budget, only an objective to manufacture implementable cemented carbide nozzles and add value to Varel's drilling solutions	Communicating vision Investments	San (G) F4, F6 PDT (R) F4, F6
09/2017	20	The product development team commenced work to print externally threaded cemented carbide nozzles	research studies, joint venture	PDT (G) F2, F3
12/2017	21	For the following year, the three collaborators studied and developed the AM process in parallel with the development of the nozzles	research studies, joint venture	PDT (G) F2, F3
05/2018	22	By May 2018, the collaborators realised that the binder jetting process was not sufficient for the stable production of the threaded nozzles	Research studies, advocacy	PDT (G) F2, -F7
	23	The nozzles required precision threads that the process could not deliver as deformations occurred in the subsequent sintering processes. The collaborators realised that, although the AM process would reduce the nozzle lead times by 50-70%, the manufacturing process still required a lot of work and not improve Varel's drilling performance but could also be manufactured with traditional manufacturing techniques	Communicate research outcomes, advocacy	PDT (G) -F4, -F7 Varel, San (R) F4, F7
	24	Therefore, the collaborators decided to investigate new nozzle designs that were impossible with traditional manufacturing techniques	Research study suspended	PDT (G) -F2
06/2018	25	In June 2018, the collaborators commenced work on the second-generation nozzles	Project with commercial aim, research studies, joint venture	PDT (G) F1, F2, F3
	26	It, therefore, also correlated with Sandvik's objective to create real value with AM technology Therefore, it was decided that all the research efforts and resources would be redirected towards the second-generation nozzles	Communicate research outcomes, investments	PDT (G) F4, (R) F6, -F6 San (R) F4, (G) F6, -F6
07/2018	27	Consequently, in July 2018, the threaded nozzles (first-generation nozzles) were put on hold indefinitely	Research study suspended Project terminated	PDT (G) -F1, -F2
12/2018	28	development of the second-generation nozzles continued	research studies, joint venture	PDT (G) F2, F3
03/2019	29	refinement of the second-generation nozzles continued	research studies, joint venture	PDT (G) F2, F3

06/2019	30	In June 2019, the nozzles were ready for laboratory testing	research studies	PDT (G) F2
08/2019	31	As the nozzles passed their laboratory testing the nozzles were prepared for field testing	research studies	PDT (G) F2, F7
	32	Therefore, the product development team applied for an opportunity to field test the nozzles at Varel's facilities	Communicate research outcomes	PDT (G) F4 Varel (R) F4
09/2019	33	the field testing of the nozzles commenced in September 2020	research studies	Varel (G) F2
05/2021	34	As good progress was made with the second-generation nozzles, further funding was obtained.	investment	San (G), PDT (R) F6
	35	The collaborators commenced with the design of the third-generation nozzles in May 2021	Project with commercial aim, research studies, joint venture, advocacy	PDT (G) F1, F2, F3, F7
	36	The third-generation process will add more value to Varel's drilling solutions as they enable improved quality with improved directional and precision flow under higher pressures	Advocacy	PDT, (G) San (R) F7
	37	The third-generation process will also allow Sandvik to produce an even broader product range	Advocacy	PDT, (G) San (R) F7
06/2021	38	By June 2021, the field testing successfully **[Varel (G) F2/KDev, PDT (R) F7/CoL]** concluded. Consequently, the nozzles were ready to be manufactured and implemented into Varel's drilling solutions **[PDT (G) F2/KDev, F4/GoS, F7/CoL, Varel (R) F4/GoS, Sand (R) F7/CoL]**.	research and studies, communicate research outcomes, advocacy	Varel (G) F2 PDT (R) F7 PDT (G) F2, F4, F7 Varel (R) F4 Sandvik (R) F7
	39	Throughout the development of the three nozzle generations, the collaboration between Sandvik's senior R&D engineer and product manager and Varel's product application manager grew into an alliance.	Alliances between actors	PDT (G) F3
	40	Therefore, although Varel is no longer part of the Sandvik group, the collaboration between the two groups continues, and more products for different applications are currently being developed.	Projects with commercial aims, research and studies	San, Var (G) F1, F2

Appendix B
Expert review questionnaire

Appendix B provides the questionnaire distributed to the expert reviewers to validate the CIMO-based EHA framework, as mentioned in Chapter 6.

STELLENBOSCH UNIVERSITY
ELECTRONIC CONSENT TO PARTICIPATE IN RESEARCH

TITLE OF RESEARCH PROJECT:	Evaluating Sectoral Innovation System Functional Performance: The Case of the South African Cemented Tungsten Carbides Sector
REFERENCE NUMBER:	ING-2020-18663
PRINCIPAL INVESTIGATOR:	Michelle McClelland
ADDRESS:	145 Banghoek Rd, Stellenbosch Central, Stellenbosch, 7600
E-MAIL:	michellemcclelland@sun.ac.za

Thank you once again for agreeing to participate in this expert review. This questionnaire consists of two sections to be completed by the expert reviewer once the appropriate consent has been given. Before completing the given questionnaire, background information on the study and the CIMO-based framework should be reviewed. Participation is entirely voluntary. All participants will remain anonymous. The questionnaire forms part of the PhD's framework evaluation. Therefore, your answers will be used to improve the proposed framework. Ethical clearance to conduct expert reviews has been granted by the Stellenbosch Research Ethics Committee (project number: ING-2020-18663).

Expert's details

Years of experience: ________________ Date: ________________

Field of expertise: Innovation systems or Manufacturing

Framework importance and relevance

This section aims to gain your perspective of the overall framework. For every question, please select the appropriate column that best reflects your opinion. Any comments may be included in the

Additional comments: Overall **Framework** table.

"In my opinion, the framework..."

Statement	Strongly Disagree	Disagree	Undecided	Agree	Strongly Agree
1. Is easy to understand.					
2. Is easy to use.					
3. Addresses a real-world problem or need.					
4. Incorporates the concepts needed to understand the development (evolution) of a (manufacturing) innovation systems.					
5. Is compatible with existing analysis frameworks on innovative development research or practices.					
6. Is applicable in the manufacturing context.					

7. Is generalisable – it may be applied to contexts other that manufacturing.					
8. Provides the adequate level of detail for application in practice.					
9. Identifies appropriate concepts and categories for its stated purpose.					
10. Appropriately categorises the concepts included.					

Additional comments: Overall Framework

Framework components: Importance and relevance

As mentioned, the framework aims to structure how the development and evolution of (manufacturing) innovation systems may be studied and analysed. Therefore, this section aims to gain your perspective of the framework components, their importance and relevance. The questions will ask you to rate your perception of how important and relevant each component is to the framework's objective. Please select the appropriate Likert scale ratings that best reflects your opinion. Any comments may be included in the

Additional comments: Framework **components** table.

Level of Importance	Rating
Very low importance	1
Low importance	2
Moderate importance	3
High importance	4
Highest importance	5

Level of relevance	Rating
Irrelevant	1
Likely to be irrelevant	2
Neutral	3
Likely to be relevant	4
Highly relevant	5

Framework components and indicators	Importance	Relevance
1. Context definition		
1.1 Defining the system boundary		
1.2 Defining the phase of development		
1.3 Defining the objective of the IS		
1.4 Identifying the IS structures		
2. Interventions		
2.1 (F1) Entrepreneurial Activity		
2.1.1 Innovating for new technology or product opportunities and improving existing offers		
2.1.2 Identifying innovation opportunities		
2.1.3 Develop business cases for identified opportunities		
2.1.4 Identifying potential customer segments and partners		
2.1.5 Lobby for identified opportunities		

2.1.6 Relevant phase of development		
2.2 (F2) Knowledge Development		
2.2.1 Knowledge absorption capabilities		
2.2.2 Sources of knowledge development		
2.2.3 Research Collaboration		
2.2.4 Training of internal actors		
2.2.5 Feasibility and stopping criteria		
2.2.6 Determine technology readiness and maturity		
2.2.7 Relevant phase of development		
2.3 (F3) Knowledge Diffusion		
2.3.1 Maintaining and expanding a knowledge network		
2.3.2 Establishing and maintaining key partnerships		
2.3.3 The intensity of knowledge sharing		
2.3.4 Distribution methods: Knowledge		
2.3.5 Distribution methods: Value		
2.3.6 Relevant phase of development		
2.4 (F4) Guidance of Search		
2.4.1 Setting goals, objectives and strategies for innovation system, new technologies and innovation development		
2.4.2 Known constraints		
2.4.3 Main Promoters		
2.4.4 Continuous improvement culture		
2.4.5 Relevant phase of development		
2.5 (F5) Market Formation		
2.5.1 Market orientation		
2.5.2 Social structures and policies		
2.5.3 Facilitate the creation of (niche) markets		
2.5.4 Relevant phase of development		
2.6 (F6) Resource Mobilisation		
2.6.1 Financial resources		
2.6.2 Physical resources		
2.6.3 Knowledge resources		
2.6.4 Acquiring resources		
2.6.5 Level of collaboration		
2.6.6 Resource mobilisation plan		
2.6.7 Relevant phase of development		
2.7 (F7) Creation of Legitimacy		
2.7.1 Exposure of innovation to outside world		
2.7.2 Foster a technology focused brand		
2.7.3 Mitigating resistance to change		
2.7.4 Raising political lobby and exploiting maximum value from innovations		
2.7.5 Lobbying partnerships		
2.7.6 Relevant phase of development		
3. Mechanisms		
3.1 Identification of motors of innovation		
3.2 Identification of important IS structures		
3.3 Identification of development barriers		
4. Outcomes		
4.1 Defining the IS specific outputs		
4.2 Defining the Capitals developed by the IS and motors of innovation		

The capitals included are		
4.2.1 Business capital		
4.2.2 Financial capital		
4.2.3 Human capital		
4.2.4 Intellectual capital		
4.2.5 Natural capital		
4.2.6 Political capital		
4.2.7 Produced capital		
4.2.8 Social capital		
4.3 Comparing the obtained and desired outcomes		
4.4 Identifying the systemic problems (which actors, relationships, institutions, or infrastructure is related to the problem and why)		
4.5 Utilising the indicators to develop an improvement strategy to support the specific motor of innovation		

Additional comments: Framework components

Appendix C
Survey of the innovation activities of South African additive manufacturing enterprises

This appendix presents Chapter 13's survey instrument and invitation email.

14.9. Email content

Dear [insert name],

Thank you so much for agreeing to participate in this study!

This survey is being used to gather information on the innovative activities of the additive manufacturing enterprises operating in South Africa. The survey will be used to substantiate the findings of a doctoral dissertation funded by the National Research Foundation. The collective findings will present a clear picture of how much each innovative function can be linked to the success or failure of an enterprise to commercialise its value offerings successfully. The objectives of this study are threefold, namely to

1. Identify the range of additive manufacturing enterprises operating in South Africa
2. Identify which innovation activities are deemed essential to delivering innovative solutions.
3. How difficult these activities are to perform and to what extent they are currently performed.

This survey should take roughly 20 minutes to complete. Please be assured that the information gathered via this survey will be kept strictly confidential and will at all times remain completely anonymous. Furthermore, the information will not be used outside the scope of the research purposes listed in the above objectives.

Please follow the link below to start the survey: https://www.surveymonkey.com/r/H7S23G9

If you are interested in the findings of this study, please fill in your email address at the end of the survey, and an executive summary will be shared with you upon completion of the study. We appreciate your involvement immensely!

For any enquiries, please contact Michelle McClelland, the lead researcher, via email at michellemcclelland@sun.ac.za.

Yours sincerely,

Lead researcher: Michelle McClelland,

Supervisors: Prof SS Grobbelaar, Prof N Sacks

14.10. Survey content

14.10.1. Confidentiality agreement

This survey gathers information regarding seven best practices of manufacturing enterprises in their pursuit to develop and commercialise innovations. The practices are as follows:

1. Entrepreneurial activity	The transformation of knowledge, interaction networks and infrastructure into beneficial business opportunities
2. Knowledge development	All activities associated with learning and the obtainment of information
3. Knowledge diffusion	All activities, channels and networks through which knowledge is shared among actors
4. Guidance of search	The direction of people and resources towards appropriate opportunities and the provision of clarity, visibility and understanding
5. Market formation	All factors influencing the market adoption of an innovation
6. Resource mobilisation	The alignment of resources to enable the development, diffusion, and use of innovations
7. Creation of legitimacy	The creation of institutional compliance and support of social acceptance for innovations to overcome the obstacles associated with `newness' within a market

This information will provide insight and credibility to a doctoral study on manufacturing enterprises in South Africa. None of the information gathered in this study will be linked to you personally. By completing this survey, you acknowledge that you have read this and are thereby consenting that we may use your information anonymously. No question is mandatory, and you are free to abandon the survey at any time should you feel uncomfortable with the questions.

It will take approximately 20 minutes to complete this survey. If you have any additional questions or information, please email Michelle McClelland, the lead researcher, michellemcclelland@sun.ac.za.

Your time and valuable input are greatly appreciated!

Lead researcher: Michelle McClelland, Supervisors: Prof SS Grobbelaar, Prof N Sacks
Department of Industrial Engineering
Stellenbosch University

14.10.2. Demographics

1. In which sector of the economy is your company operating in?
    - Primary (raw materials/mining)
    - Secondary (manufacturing/value-added services)
    - Tertiary (retailers/customer front)

2. Please select the manufacturing materials you typically specialise in or utilise
    - Ferrous metals (Iron-based materials such as steels)
    - Non-ferrous metals (non-iron based materials such as titanium and aluminium)
    - Both ferrous and non-ferrous metals
    - Composites (such as carbon fibre, fiberglass)
    - Plastics (PLA, PVC, ABS, PET)

3. For how many years has your company been in business for in 2022?
    - 0-5
    - 6-10
    - 10 +

4. What size category is the company?
    - Micro (<5 employees)
    - Very small (<20 employees)
    - Small (<50 employees)
    - Medium (<100 employees)
    - Large (>100 employees)

5. Additive manufacturing (3D printing) is the manufacturing a 3D object in a layer wise fashion using the appropriate technology for that material. What is your company's stance on additive manufacturing?
    - Not interested
    - Currently investigating implementing an AM technology
    - Have implemented AM technology
    - Our business is solely based around additive manufacturing

Optional questions depending on Q5's answers

6. Please motivate why you are not interested in adopting additive manufacturing

    Comment box

7. Please indicate in which phase of adoption your company is
    - We have recently started to consider the implementation of an AM technology
    - We are investigating the technologies benefits, risks, and profitability
    - We are about to purchase or first AM technology

8. Please indicate which type of AM technology you are considering (material and technology)

    Comment box

9. Please indicate how many AM technologies or systems you have implemented
    - *Comment box*

10. Please provide an estimate of the revenue percentages your company gains from delivering AM products or services to the following application areas.

    With comment box
    - Aviation
    - Aerospace and defence
    - Medical and dental
    - Research and development
    - Tooling
    - Additive manufacturing hobbyists
    - Others (please specify)

14.10.3. Importance, difficulty, extent performed

	Likert scale ratings	**1**	**2**	**3**	**4**	**5**
Indicators	**Level of Importance**	Very low importance	Low importance	Moderate importance	High importance	Highest importance
	Level of difficulty	Very easy	Easy	Moderate	Difficult	Extremely difficult
	Extent performed	Not at all	To a small extent	To some extent	Moderate extent	Large extent

14.10.4. Entrepreneurial activities

The transformation of knowledge, interaction networks and infrastructure into beneficial business opportunities

11. Please rate your perception of how important the following activities are for your company and how difficult they are to perform.

Activity	Importance	Difficulty	Extent performed
Studying international technology trends and markets to identify commercial projects or technology to invest in			
Attending expos, conferences and exploring university outputs to identify commercial projects or technology to invest in			
Engaging with customers and end-users to identify commercial projects or technology to invest in			
Identifying South African customer segments who would buy or use the newly implemented technology			
Buying additive manufacturing systems from South Africa suppliers			
Competing with South Africa additive manufacturing companies			
Competing with international additive manufacturing companies			
Demonstrating new technology, products, or services to potential investors throughout the development process to gain investments			

14.10.5. Knowledge development

All activities associated with learning and the obtainment of information

12. How is knowledge gained and developed in your company? Please rank the following sources according to how often they are utilised in your company (1 – utilised most often, 4 – utilised least)

Information source	Ranking	Difficulty
Engaging with academic researchers		
Interaction with product or service end-users		
Learning from a knowledge network (a group of companies who share information with each other)		
Learning through experimentation, prototypes, and feasibility studies		
Learning from other companies in my company's value chain		

13. Please rate your perception of how important the following activities are when developing new products and services, how difficult they are to perform and to what extent they are performed in your company.

Activity	Importance	Difficulty	Extent performed
Determining technology readiness and maturity			
Testing whether products or services will be of acceptable quality and price to buyers			
Setting stopping criteria to terminate too costly or infeasible product development projects			
Offering technical training to company personal on newly implemented equipment, machinery, and systems			

14.10.6. Knowledge diffusion

All activities, channels and networks through which knowledge is shared among actors

14. Please rate your perception of how important the following activities are, difficult they are to perform and to what extent they are performed in your company.

Activity	Importance	Difficulty	Extent performed
Maintaining an information sharing network with collaborative companies			
Conducting projects in collaboration with universities, government research institutes or government agencies			
Initiating collaborative projects with other companies			
Forming strategic alliances with companies with similar end goals to obtain resource benefits (such as access to resources, more funding, lower costs materials)			
Collaborating with product or service end-user throughout their development process			
Launching marketing campaigns to communicate value offerings to customers, clients, and partners			
Demonstrating products and services at conferences, workshops, trade centres and seminars			
Attracting customers with the company's brand			

14.10.7. Guidance of search

The direction of people and resources towards appropriate opportunities and the provision clarity, visibility and understanding

15. Please rate your perception of how important the following activities are, difficult they are to perform and to what extent they are performed in your company.

Activity	Importance	Difficulty	Extent performed
Outlining clear innovation objectives in the company strategy			
Encouraging a continuous improvement culture			
Identifying laws and regulations that support or provides benefits to companies that use specific technologies or offer certain products and services			
Improving the company personal's confidence in the abilities of new technologies			
Improving the company personal's confidence in the company's ability to utilize the abilities of new technologies			

16. Please rank the constraints that inhibit or block the successful development of innovative solutions from 1 to 6 (1 – biggest constraint, 6 – most minor constraint)

Information source	Ranking	Difficulty
Lack of sufficient resources		
Lack of sufficient supply chain		
Lack of legislative support		
Internal resistance to change		
Customers are resistant to change		
Unsupportive market conditions		

14.10.8. Market formation

All factors influencing the market adoption of an innovation

17. When developing products and services with additive manufacturing, do you utilise governmental incentives for collaborations with specific actors, such as universities, government research institutes, or government agencies?
    - No, no incentives exist
    - Yes, for discounted prices
    - Yes, for tax benefits

18. Do you utilise any Government agencies or schemes when developing technology? If so, which ones? *With comment box*
    - No
    - Yes

19. Please rate your perception of how important the following activities are, difficult they are to perform and to what extent they are performed in your company.

Activity	Importance	Difficulty	Extent performed
Surveying for new local customer segments and distribution channels			
Testing technology and product acceptability, affordability, accessibilities before product or service development			
Assisting the creation of niche markets			
Identifying laws and regulations that support market conditions for your company's products and services (such as favourable tax regimes, incubators, public-private partnerships)			
Determining a product or service's market readiness and competitiveness			
Determining the efficiency of company personal's knowledge and skills when developing a product or service			
Determining the availability and accessibility of physical infrastructure and resources when developing a product or service			
Determining the availability and accessibility of financial resources when developing a product or service			
Accessing innovation platforms where resources can be borrowed from			

14.10.9. Resource mobilisation

The alignment of resources to enable the development, diffusion, and use of innovations

20. Please rate the following three types of resources, on a scale from 1 to 4, according to their importance to the company (1 – most essential resource, 4 - least essential resource). Furthermore, rate them according to their difficulty in obtaining. (5 – extremely difficult)

Activity	Ranking	Difficulty
Human infrastructure: Actors having the efficient knowledge and skills required		
Financial infrastructure: Access to capital is available		
Physical infrastructure: All relevant resources and consumables are available		
Data infrastructure: Data sharing between company systems and machinery		

21. Please rate the following sources of capital in order of their importance to the company. Furthermore, indicate the sources' difficulty in obtaining.

Activity	Ranking	Difficulty
Acquiring funding from governmental support, incentives, subsidies, and grants		
Acquiring funding from banks loans and investments from external investors		
Acquiring funding from end-users		

22. Please rate your perception of the availability and accessibility of the following recourses from 1 to 5. (1 – easily available or accessible, 5 – extremely unavailable or inaccessible).

Activity	Availability	Accessibility
Sufficient and sustainable capital for technology acquisition and adoption		
Technological infrastructure that supports the adoption of new technology and the development of new products and services		
Sufficient knowledge and skills within the knowledge network to successfully adopt new technology and utilize it to develop innovations		

14.10.10. Creation of legitimacy

The creation of institutional compliance and support of social acceptance for innovations to overcome the obstacles associated with `newness' within a market

23. Please rate your perception of how important the following activities are for your company and how difficult they are to perform

Activity	Importance	Difficulty	Extent performed
Establish trust in the company's brand or name			
Ensuring your product or service live up to the values of your brand			
Effectively marketing the company's products or services			
Minimising the need for new skill development before users can use or benefit from your products or services			
Advertising partnerships with well-known brands			
Offering potential customers the opportunity to try and test your products or services before they purchase it.			

24. Do you advertise your partnerships with particular brands or organisations?
    - No
    - Yes
25. Please provide a reason and the partnerships you advertise
    - *Comment box*

14.10.11. Conclusion

If you are interested in the findings of this doctoral study, please provide your email address in the comment box below, and an executive summary of the findings will be sent to you upon completion of the study.

Comment box

Thank you for your time and help in making this study valuable to social enterprise development in South Africa!