Towards an Integration of Socio-technical Transitions and the Fourth Industrial Revolution

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April 2022

DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third-party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

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ABSTRACT

Contemporary societal systems are faced with an array of grand sustainability and sustainable development challenges. Mandates to transition these systems to more sustainable configurations have become widely institutionalised through global targets such as the Sustainable Development Goals presented by the United Nations. Socio-technical Transitions (STTs) are a demanded topic in sustainability discourse due to the possibilities that they present in the analysis of contemporary systems in transition to more sustainable states. The incorporation of the human 'socio' aspects with technology aspects which is distinct to socio-technical studies is a key proponent to harnessing technologies for society's good as the modern world thrives off technological advancement. Furthermore, sustainability and sustainable development analysts highlight those digital revolutions are a key contributor to global systemic transformations. The contemporary world is currently undergoing a fourth industrial revolution which is changing the nature and functioning of global systems. The rise of the Fourth Industrial Revolution (4IR) presents possibilities for contemporary societal systems in the quest to sustainability and sustainable development.

Both the 4IR and the STTs have evident connections to sustainability and sustainable development; therefore, an integration of the concepts is envisaged to further support the quest for sustainability and sustainable development in contemporary societal systems. However, on investigating the extent to which these concepts have been jointly analysed within academic literature, it was found that these concepts are not sufficiently integrated. Furthermore, literature that attempts some extent of analysing the concepts together was found to hold theoretical disconnects and conceptual gaps. This research is designed to provide a premise on which the 4IR and STTs are integrated with the ultimate aim of contributing to the effective and efficient transition of societal systems. The research employs existing theoretical and conceptual research on the 4IR and STTs to infer and demonstrate an integration between the concepts. The research is therefore a non-empirical, qualitative study that utilises both inductive and deductive approaches in an investigative or exploratory manner.

The aim of this research is achieved through the development of an Integrated Fourth Industrial Revolution and Socio-technical Transitions Framework (I4IR-STT framework). The framework is conceptual in nature and is developed following requirement specifications constructed from deductions made through the gaps and disconnects identified in existing academical literature. The framework has three key features i.e., transition aspects, technology aspects and relationships. Given the conceptual and generic nature of the framework, it is accompanied by practical utility in the form of an operationalisation strategy to enable a user to apply the framework to a societal system of interest. The I4IR-STT framework was evaluated in three ways: first, with subject matter experts in the Fourth Industrial Revolution and Socio-technical Transitions fields, second through an illustrative case study application of the framework and third through an assessment of the framework against the requirement specifications for its development. Experts verified the theoretical correctness and reasonableness of the framework's content. A self-assessment of the framework against its requirements specifications demonstrated that the framework met the stipulated requirements for its development. Finally, the illustrative case study demonstrated the applicability, practicability and usability of

the framework through its operationalisation strategy. The overall evaluation of the framework demonstrates that the framework achieves the stated research aim and provides a premise for the integration of the 4IR and STTs.

OPSOMMING

Kontemporêre samelewingsisteme word gekonfronteer met 'n verskeidenheid groot volhoubaarheid- en volhoubare ontwikkelingsuitdagings. Mandate om hierdie stelsels oor te skakel na meer volhoubare konfigurasies het wyd geïnstitusionaliseer geraak deur wêreldwye doelwitte soos die Verenigde Nasies se Doelwitte vir Volhoubare Ontwikkeling. Sosio-tegniese oorgange (STT's) is 'n prominente onderwerp in volhoubaarheidsdiskoers as gevolg van die moontlikhede wat dit bied in die ontleding van kontemporêre sisteme in oorgang na meer volhoubare kondisies. Die inkorporering van die menslike 'sosio'-aspekte met tegnologiese aspekte - wat onderskei word van sosio-tegniese studies - is 'n sleutelvoorstander tot die inspanning van tegnologie vir die samelewing se voordeel, aangesien die moderne wêreld van tegnologiese vooruitgang floreer. Verder beklemtoon ontleders van volhoubaarheid en volhoubare ontwikkeling dat digitale revolusies 'n sleutelbydraer is tot globale sistemiese veranderinge. Die hedendaagse wêreld ondergaan tans 'n vierde industriële revolusie wat die aard en funksionering van wêreldwye stelsels verander. Die opkoms van die Vierde Industriële Revolusie (4IR) bied moontlikhede vir kontemporêre samelewingsisteme in die strewe na volhoubaarheid en volhoubare ontwikkeling.

Beide die 4IR en die STTs het duidelike verbintenisse met volhoubaarheid en volhoubare ontwikkeling. Om hierdie rede, word 'n integrasie van die konsepte in die vooruitsig gestel om die strewe na volhoubaarheid en volhoubare ontwikkeling in kontemporêre samelewingsisteme verder te ondersteun. In die ondersoek van die mate waartoe hierdie konsepte gesamentlik binne akademiese literatuur ontleed is, is dit egter gevind dat die integrasie van hierdie konsepte nie voldoende is nie. Verder is dit gevind dat literatuur wat tot 'n mate probeer om die konsepte saam te analiseer, teoretiese ontkoppelings en konseptuele gapings inhou. Dus is hierdie navorsing is ontwerp om 'n uitgangspunt te verskaf waarop die 4IR en STT's geïntegreer word met die uiteindelike doel om by te dra tot die effektiewe en doeltreffende oorgang van samelewingsisteme. Die navorsing gebruik bestaande teoretiese en konseptuele navorsing oor die 4IR en STTs om 'n integrasie tussen die konsepte af te lei en te demonstreer. Die navorsing is dus 'n nie-empiriese, kwalitatiewe studie wat beide induktiewe en deduktiewe benaderings op 'n ondersoekende of verkennende wyse benut.

Die doel van hierdie navorsing word bereik deur die ontwikkeling van 'n Geïntegreerde Vierde Industriële Revolusie en Sosio-tegniese Oorgangsraamwerk (I4IR-STT raamwerk). Die raamwerk is konseptueel van aard en word ontwikkel volgens vereiste spesifikasies wat saamgestel is uit afleidings wat gemaak is deur die gapings en ontkoppelings wat in bestaande akademiese literatuur geïdentifiseer is. Die raamwerk het drie sleutelkenmerke, naamlik oorgangsaspekte, tegnologie-aspekte en verhoudings. Gegewe die konseptuele en generiese aard van die raamwerk, gaan dit gepaard met praktiese bruikbaarheid in die vorm van 'n operasionaliseringstrategie om 'n gebruiker in staat te stel om die raamwerk op 'n samelewingsisteem toe te pas. Die I4IR-STT-raamwerk is op drie maniere geëvalueer: eerstens met vakkundiges in die Vierde Industriële Revolusie en Sosio-tegniese Oorgangsvelde; tweedens deur 'n illustratiewe gevallestudietoepassing van die raamwerk; en derdens deur 'n assessering van die raamwerk se vereiste spesifikasies. Kenners het die teoretiese korrektheid en redelikheid van die raamwerk se inhoud geverifieer. 'n Selfevaluering van die raamwerk teenoor sy vereiste spesifikasies het getoon dat die raamwerk aan die gestelde vereistes voldoen. Laastens, die

illustratiewe gevallestudie het die toepaslikheid, uitvoerbaarheid en gebruikbaarheid van die raamwerk deur sy operasionaliseringstrategie gedemonstreer. Die algehele evaluering van die raamwerk demonstreer dat die raamwerk die gestelde navorsingsdoelwit bereik en 'n uitgangspunt bied vir die integrasie van die 4IR en STT'e.

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DEDICATION

Iwe, orikubaasa kukora ebirikukirira kimwe,

ebi nashabire nari ebindarateekatekire,

ahabw'aamani gawe agarikorera omirinye;

Iwe Ruhanga wangye, Mukama wangye,

*oheebwe ekitinisa kyoona ahabwe'mbabazi zawe ezitahwa*ho.

Amiina.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Acronyms

4IR	Fourth Industrial Revolution
AR	Augmented Reality
AV	Autonomous Vehicles
BD	Big Data
CPS	Cyber Physical Systems
EEP	Enterprise Engineering Process
GDP	Gross Domestic Product
IE	Industrial Engineering
IoT	Internet of Things
OS	Operationalisation Strategy
PA	Predictive Analytics
PABD	Predictive Analytics and Big Data
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RO	Research Objective
R&D	Research and Development
SD	Sustainable Development
SDGs	Sustainable Development Goals
SE	Systems Engineering
SLR	Systematic Literature Review
SME	Subject Matter Expert
SNM	Strategic Niche Management
ST	Sustainability Transitions
STS	Socio-technical Systems
STTs	Socio-technical Transitions
TIS	Technology Innovation System
TM	Transitions Management

VR	Virtual Reality
WC	Western Cape
WEC	World Economic Forum
Wi-Fi	Wireless Fidelity

CHAPTER 1: INTRODUCTION

In this chapter, this research is outlined by establishing the main study concepts of sustainability, socio-technical systems and transitions and the Fourth Industrial Revolution (4IR). The research problem, aim and objectives of the research are stated. The research methodology, scope and design framed from the objectives are also presented.

1.1 RESEARCH BACKGROUND: TRANSITIONS TO SUSTAINABILITY

The contemporary world is faced with a multitude of grand challenges such as depletion of natural resources, global warming, pollution and an excessive consumption of goods and resources. These issues have created a concern for continuity for future generations and hence the concept of sustainability has become increasingly prominent. Sustainability and sustainable development both allude to the "*development which meets the needs of current generations without compromising the ability of future generations to meet their own needs*" (World Commission on Environment and Development, 1987). As a design principle and mode of practice, sustainability and sustainable development are applied to many fields in an effort to ensure equitable economic growth, environmental conservation and social prosperity for all.

Sustainability and sustainable development are analysed within three overlapping dimensions i.e., the environment (ecological sustainability), the economy (economic sustainability) and society (social sustainability) (Kates *et al.*, 2005). Globally, sustainability and sustainable development have been popularised and institutionalised in the contemporary society by the needs and targets stated in the United Nations' Sustainable Development Goals (SDGs) as shown in Figure 1 below:

Figure 1: SDGs. Source: United Nations (2019)

SDGs have become a global mandate as a result of the grand sustainability challenges and thus have exerted a global need to transition global systems to more sustainable states (Savaget *et al.*, 2018).

1.1.1 INTRODUCTION: THE FOURTH INDUSTRIAL REVOLUTION (4IR)

Sachs *et al.* (2019) highlight that in order to ensure that SDGs are achieved, six transformations need to be enacted across the global systemic structures. These include:

i. Education, gender and wellbeing;
ii. Health, wellbeing and demography;
iii. Energy decarbonisation and sustainable industry;
iv. Sustainable food, land, water and oceans;
v. Sustainable cities and communities; and
vi. Digital revolution for sustainable development.

As implied by the sixth transformation, technology plays a major role and is considered a pillar for sustainable development (Kongoli, 2016). Contemporary digital technologies can be harnessed to make major contributions to any SDG (Sachs *et al.*, 2019). Sustainable development within the technological domain requires the design and redesign of technological systems that are not only appropriate but reduce the impact of previous industrial revolutions and practices on the world's resources, while simultaneously fostering growth within the three sustainability criteria of society, environment and economy (Beder, 1994; de Man & Strandhagen, 2017).

The Fourth Industrial Revolution (also known as 4IR for short) is posing major shifts on the global technological landscape (Schwab, 2016). This revolution seeks to connect resources, services, products and human beings in real time through digitalisation and digitisation (Stock *et al.*, 2018). It is predicted that there will be major impacts on sustainability and the transitions thereof as result of the shift towards application of technologies and concepts in the 4IR (Tran, 2014).

Literature highlights a variety of perspectives and links between sustainability or sustainable development and the 4IR. These views include the 4IR as a driver for sustainability thus sustainability is an incentive for its expansive implementation (Agamuthu, 2017; Anggusti & Siallagan, 2018; Habanik *et al.*, 2019; Kamble *et al.*, 2018; Stock *et al.*, 2018); links between 4IR and sustainability in the context of the social, economic and ecological sustainability dimensions (de Man & Strandhagen, 2017; Papetti *et al.*, 2018; Stock *et al.*, 2018) and several expounds relating 4IR to sustainability of processes, technologies and whole industries in industrial practice (Carvalho *et al.*, 2018; Dossou, 2018; Kiel & Arnold, 2017; Kumar *et al.*, 2018; Papetti *et al.*, 2018; Stock & Seliger, 2016). However, despite the growing anticipation for the predicted sustainability benefits of the 4IR, there is still considerable uncertainty on the implications of the paradigm shift amongst various practitioners and sectors within society (Müller *et al.*, 2018; World Economic Forum, 2019, 2020).

With growing societal awareness to the benefits and effects of technology and increasing sustainability challenges, there is strong practical and theoretical relevance in the study of the interconnectedness of societal systems and technologies as is contemporarily posed by the 4IR (Bonilla *et al.*, 2018; Habanik *et al.*, 2019; Müller *et al.*, 2018). It is therefore essential for the various domains that apply concepts of the 4IR and the technologies therein to understand the systems within which the 4IR is being enacted. Sustainability transition studies inherently incorporate, structure and provide a platform to explore and understand these dynamics (Sorrell, 2018).

1.1.2 PERSPECTIVES ON TRANSITIONS TO SUSTAINABILITY

The European Environment Agency (2018) presents five perspectives in approaching systemic transitions to sustainability. These perspectives, as shown in Figure 2 below, include socio-economic, socio-ecological, action-oriented perspectives, integrated assessment modelling and socio-technical approach.

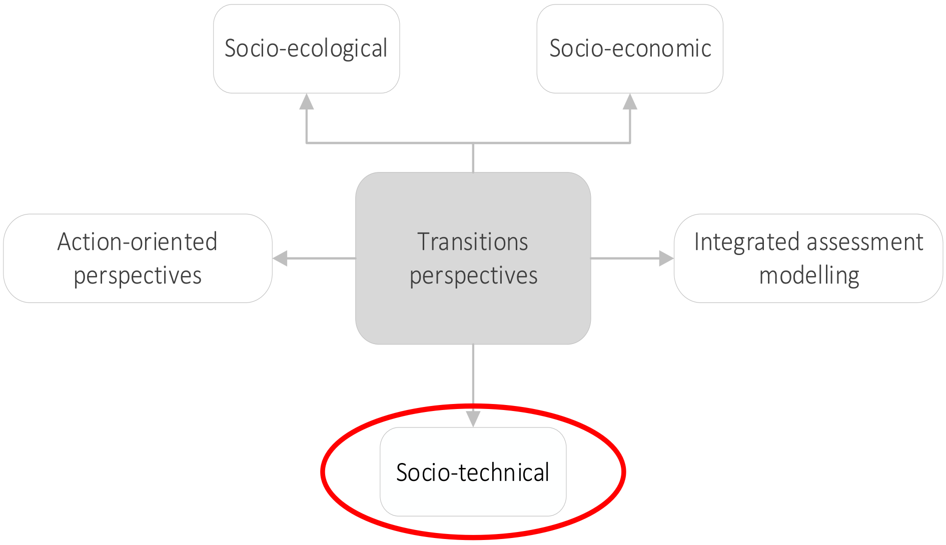

Figure 2: Perspectives on transitions (European Environment Agency, 2018)

The socio-economic perspective addresses transitions from two focal points in the economic paradigm; market capitalism and economic sub-systems analysing the co-evolutionary processes that include change in production patterns, work relations and culture. Socio-ecological perspectives combines elements of natural and social sciences aiming at incorporating bio-physical and human social dimensions in the analysis of sustainability at different scales. Action-oriented perspectives focus on the roles of actors that aim to influence societal systems. Integrated assessment modelling approaches take a quantitative perspective in analysing systemic change while combining frameworks and understandings from socio-technical, socio-economic and socio-ecological approaches. (European Environment Agency, 2018).

The socio-technical perspective takes the approach of understanding complex multifunctional systems designed to fulfil societal functions and analyses how these systems are designed and therefore transitioned to meet sustainability goals (European Environment Agency, 2018). The approach, which is further described in the Section 1.1.3 below, is qualitative and focuses on processes and how arising issues in Socio-technical Systems can be alleviated through transitions (European Environment Agency, 2018).

According to Kongoli (2016), activities and actions from any field or discipline are sustainable if they fulfil economic and social development and environmental protection and meeting the needs in all three sustainable development dimensions (Kongoli, 2016). Socio-technical theory, however, describes socio-technical design as collaborative effort from various disciplines but specifically engineering, sociology, psychology, and computer science. Although engineers have been traditionally linked to the hardware components of socio-technical design; disciplines such as Systems Engineering and Industrial Engineering incorporate principles from other fields such as social science, business commerce, computer science and psychology. This gives Industrial and Systems Engineering academics and professionals an advantage in having a more holistic approach to socio-technical analysis and design (Whitworth & Ahmad, 2013).

Within the Industrial Engineering (IE) spectrum, there exist theories and approaches such as systems thinking and design, innovations systems and sustainable innovations which carry underlying sustainability motives (Elzen *et al.*, 2004; Du Preez *et al.*, 2009). These theories and approaches emphasize that systems cannot be analysed in stand-alone fashion due to mutually reinforcing dynamics from various actors, the technologies and systemic environments within which these systems are embedded. This ultimately align with the socio-technical perspective in emphasizing and integrating the technical and social dichotomies in contemporary societal systems (Savaget *et al.*, 2018). Furthermore socio-technical theory apply principles of systems engineering and systems thinking in its inherent design (Baxter & Sommerville, 2011; Oosthuizen & Pretorius, 2016).

Given the evident correlations between socio-technical approaches and Industrial and/or System Engineering, this research takes a socio-technical approach to analysing sustainability transitions within contemporary societal systems. The relevance of technology within sustainability research presents a case for investigating how new technologies are integrated within society for the common sustainability good.

1.1.3 SOCIO-TECHNICAL TRANSITIONS

Socio-technical Transitions (STTs) are strongly related to concepts of sustainability and sustainable development (Baxter & Sommerville, 2011). STTs have origins in Socio-technical Systems (STS), which are described as a cluster of interlinked social and technical entities operating at multiple complex systemic levels yet are simply designed to meet societal needs such as transport or mobility, energy, food production and distribution and health care delivery (Sorrell, 2018). STS have both the humanistic or social factors and the technical factors equally considered in their systemic design (Baxter & Sommerville, 2011). STS analysis presents a unique perspective towards sustainability as such systems employ multi-level interactions coupled with the overall systemic view.

Socio-technical Transitions (STTs) are large-scale transformations of (unsustainable) STS and involve long-term processes and shifts to “newer”, sustainable socio-technical configurations, in which these configurations are target oriented towards addressing specific sustainability issues (Geels, 2011). Given the various needs and contemporary sustainability issues within STS, transitions commonly referred to as STTs, are viewed as their sustainable progression (Geels, 2011). With this context and understanding, STTs are therefore sometimes interchangeably referred to as sustainability transitions (Geels, 2011; Sorrell, 2018; Tran, 2014).

Although technology is a key component around which STTs occur (Geels & Kemp, 2007), society is just as important, as it is provides resources and affects the dynamics of change towards sustainability (Baxter & Sommerville, 2011). This highlights the importance of incorporating economic, political and social humanistic factors within the dynamics of STTs. Literature highlights that actors within STTs are faced with various challenges through factors such as agency, political framings, social behaviour, industrial structures and environmental and demographic shocks (Elzen *et al.*, 2004). The incorporation of such social and humanistic factors elevates the complexity of STTs as they add variability and stochasticity to the system's dynamics in comparison with a purely technological outlook. Tran (2014) further argues that solutions to sustainability issues cannot be achieved through mere incremental development of technologies but have to be aggregately incorporated within all aspects of society.

Savaget *et al.* (2018) makes the argument that the complexity of STTs due to an equalised social and technical component is what positions their potential to steering towards sustainable development as considerable. In the modern context, the development of the 4IR is posing large-scale shifts on society as a whole with effects on the quest towards sustainability given the contemporary grand sustainability challenges. It is evident that there exist plausible interconnections between STTs and the 4IR.

Although there is a growing database of literature examining the impacts of 4IR on sustainability and sustainable development and vice versa, the question lies in the extent to which the 4IR has been analytically examined within the context of STS transitions to sustainable states also known as STTs. Therefore, research that focuses on jointly analysing STTs and the 4IR is imperative to groundwork in the analysis of STTs in efforts to meet global systems' sustainability and sustainable development goals within the 4IR era.

1.2 RESEARCH PROBLEM, AIM AND OBJECTIVES

Literature shows that there is a global need to meet sustainability and sustainable development goals (United Nations, 2019; United Nations Department of Economic and Social Affairs, 2014). The analysis of STTs has shown value in the understanding of how contemporary societal systems may be configured to achieve sustainability and sustainable development targets (European Environment Agency, 2018; Köhler *et al.*, 2019). STTs analysis has, therefore, become a distinct and demanding topic amongst global sustainability debates (Köhler *et al.*, 2019). Furthermore, given the current global sustainability conundrum, the rise of the 4IR as a technological paradigm has sparked multiple discussions in both academic literature and practice on the paradigm's sustainability implications (Schwab, 2016; World Economic Forum, 2019, 2020). The 4IR as a paradigm represents a technological shift that poses possibilities for sustainability and sustainable development within societal systems (World Economic Forum, 2020). Furthermore, the 4IR shows opportunities and possibilities in supporting and contributing to sustainability transitions research (Morrar *et al.*, 2017; Noor, 2019; Stock *et al.*, 2018). It is therefore envisaged that an integration of these concepts (i.e., STTs and the 4IR) may further contribute to contemporary societal systems' analysis in the effort to meet global sustainability and sustainable development targets and goals.

A number of frameworks, approaches and theories exist that are geared towards the analysis and evaluation of sustainability transitions and/or STTs (European Environment Agency, 2018; Köhler *et al.*, 2019). However, one of the key areas of critique of such frameworks, approaches and theories is that they are often applied retrospectively and lack ways in which to practically operationalise and institutionalise the principles and driving forces that bring about transitions to sustainability in contemporary societal systems (Geels, 2019).

Given the evident links between the 4IR and STTs to sustainability and sustainable development, it is envisaged that an integration between the 4IR and STTs would further serve the modern world's quest towards sustainability and sustainable development. It is observed, however, that this integration seems to be lacking in literature (Asiimwe & de Kock, 2019). This research is therefore concerned with STTs and the 4IR as they present prospects for the sustainable transitioning of contemporary societal systems and presents a premise for the conceptual integration of STTs and 4IR.

1.2.1 AIM AND OBJECTIVES

The aim of this research is to contribute towards increasingly effective and efficient management of societal systems transitions through the integration of the 4IR and STTs. This aim is to be achieved through the development of a research product that provides a premise for the conceptual integration of STTs and the 4IR. The research objectives (ROs) that support the attainment of the stated aim and output are as below:

i. RO 1: Contextualise STTs and the 4IR as presented in their core literature and as pertaining to this research;
ii. RO 2: Investigate the extent to which STTs and the 4IR have been jointly considered within academic literature to confirm or refute the apparent lack of integration of both concepts previously mentioned. Sub-objectives include:
    a. RO 2.1: Conduct a bibliometric analysis examining the literature landscape;
    b. RO 2.2: Conduct a content analysis examining how the concepts are jointly addressed and analysed in literature; and
    c. RO 2.3: Conduct a gap analysis to compare literature obtained to the 4IR and STTs contextualisation and thus identify the gaps and disconnects to be addressed in this research;
iii. RO 3: Articulate a development strategy from which the research product is to be designed and developed. Sub-objectives include:
    a. RO 3.1: Develop requirement specifications for the research product;
    b. RO 3.2: Present the methodology employed for the development of the research product; and
iv. RO 4: Develop the research product to demonstrate an integration between the 4IR and STTs. Sub-objectives include:
    a. RO 4.1: Develop the envisioned research product;
    b. RO 4.2: Develop an operationalisation strategy for the research product;
    c. RO 4.3: Evaluate the proposed research product with subject matter experts (SMEs); and
    d. RO 4.4: Conduct an illustrative case research to evaluate the research product.

1.2.2 ETHICAL IMPLICATIONS OF THE RESEARCH

This research deals primarily with conceptual data in the form of academic and grey literature. Material used for the research includes literature published from various journals and search databases such as Scopus. Thereafter, the ensuing research product is developed from the theory obtained. This research, therefore, does not have ethical implications. The evaluation of the research product is partially conducted through interviews with various Subject Matter Experts (SMEs) or scholars and an illustrative case application. However, this exercise does not incur any ethical implications.

1.3 RESEARCH SCOPE

In this section, this research's delimitations and limitations are presented in sub sections 1.3.1 and 1.3.2 below:

1.3.1 DELIMITATIONS

This research therefore has the following delimitations:

i. The focus of this research is on the integration of the 4IR and STTs as they pertain to contemporary societal systems. For the purposes of this research, the term "societal system" is employed to meta-physically[1] describe a system that fulfils a societal function and that undergoes a sustainability transition to a more sustainable configuration and achieves its sustainability or sustainable development targets. It is understood from literature that STS are analytical approach/description of societal-systems (Savaget *et al.*, 2018). Therefore, societal systems in reality house the analytically defined elements and dimensions of an STS. Henceforth, the term societal system is used as a meta-physical reference to the analytically described STS. Although STS are not the key research focus of this research, they are presented to give a background to the analytical structure of STTs.

ii. The research looks at the 4IR in general and is not specific to a single technology within the technologies that are driving the revolution.

1.3.2 LIMITATIONS

The following limitations are presented to ensure the effective applicability of this research:

i. The research is limited to a macro societal system's level of analysis employed in the integration of STTs and the 4IR i.e., in a broader nature and with concern and emphasis on society's overall goals and systemic transitional features (Bond, 1999). As Kim (1999) argues, it is redesigning concepts at this systemic level that offers more leverage to shape and influence STTs towards more sustainable states.

ii. The research henceforth also analyses sustainability and sustainable development from a macro level of analysis i.e., for societal benefit and to address grand sustainability challenges such as climate change, global warming and health crises. In this case, systems analysed (as in line with STTs studies) are systems that fulfil societal functions and hence are faced with grand sustainability. A system state that is "more sustainable" in reference to such systems would mean one that does not harm or lessen

[1] Meta-physical referring to the existential nature of something as is in real life.

detriment on society's resources within these systems for future generations and achieves its set contemporary sustainability and sustainable development targets and goals.

iii. The in-depth analysis and utilisation of other frameworks in the analysis of STTs and the 4IR is outside the scope of this research. STTs frameworks presented in Chapter 2, Section 2.2.2 are utilised to give the reader a contextual understanding of the background of STTs but are not extensively applied throughout the research for its stated aim.

iv. Design restrictions and boundary conditions are presented in Chapter 5, which also serve as limitations to the research product developed. These include:

   a. The research product is developed from an Industrial Engineering (IE) perspective as it is the research discipline. Expounds from other fields such as social sciences and business commerce may be progressively added by SMEs in those fields;
   b. The research product does not provide new meaning to STTs and the 4IR. However, it integrates both concepts using theory and examples provided in literature;
   c. The research product is not developed as a practical tool but offers a descriptive approach towards conceptualising the integration of the 4IR and STTS;
   d. The research product takes exclusively takes an STTs perspective towards transitions and henceforth excludes socio-economic, socio-ecological perspectives;
   e. The research product must be utilised by users with some basic prior knowledge of the concepts at hand; and,
   f. The research product cannot be applied directly without contextual additions by users.

v. This research takes a positive synergistic outlook on the 4IR and its technologies.

1.4 RESEARCH DESIGN

In this section, the methodology and approach utilised in the conducting the research to achieve its stated aims and objectives are presented. Mouton (2001) presents a typology for the design of research studies shown in Figure 3 below. Within the typology, research studies are broadly classified as empirical or non-empirical. Empirical studies utilise evidence-based qualitative or quantitative data either from primary sources such as surveys and experiments or from secondary sources such as historic studies, secondary and statistical data. In contrast, non-empirical studies utilise theoretical data such as from philosophical studies, literature reviews and conceptual analysis.

Mouton (2001) also further maps research study designs using a map presented in Figure 4 below. The map primarily plots studies based on the types of data used i.e., existing or primary data and the type of research i.e., either as an empirical or non-empirical research (Mouton, 2001). This research is mapped in the non-empirical and existing data quadrant as highlighted in Figure 4 below:

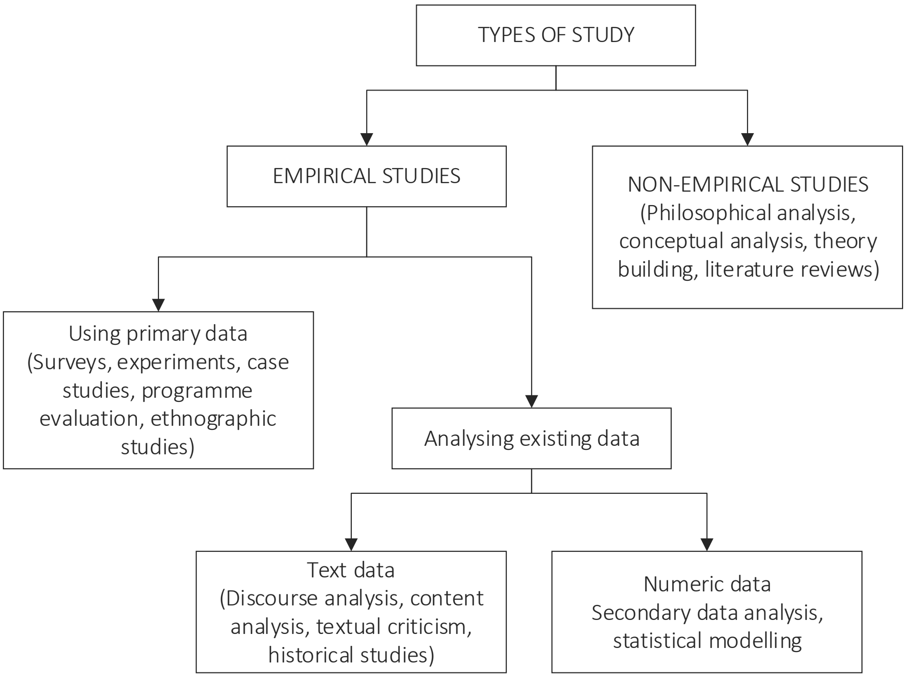

Figure 3: Typology for research design types. Source: Mouton (2001)

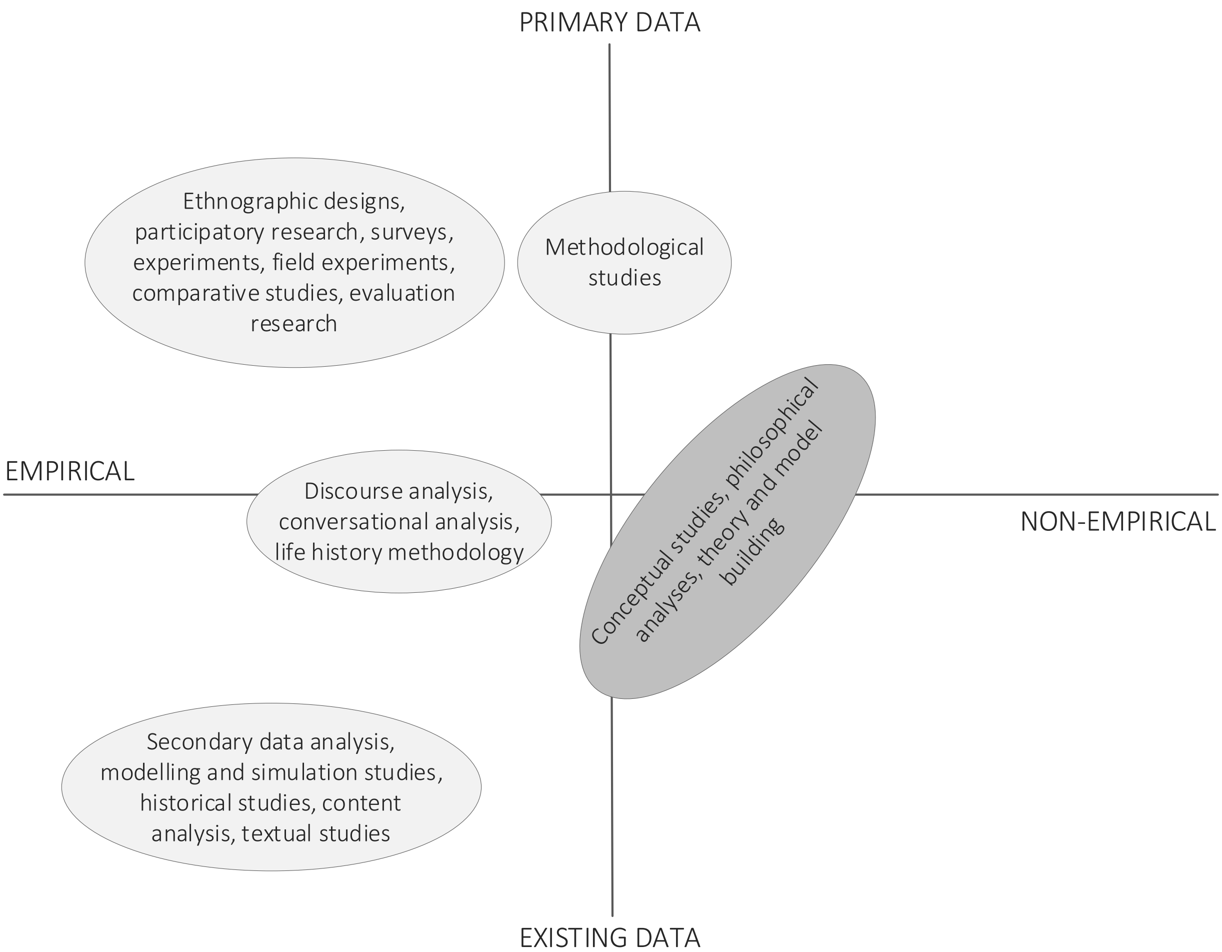

Figure 4: Mapping research designs. Source: Mouton (2001)

Given the nature of the problem statement, this research employs existing data in the form of theoretical and conceptual research that analyses the 4IR and STTs in order to infer and demonstrate an integration between the two concepts. Following the classification done by Mouton (2001), this research is therefore primarily designed as a non-empirical qualitative research study with the aim of building a research product that is conceptual in nature and that contributes to the STTs and 4IR bodies of knowledge.

1.4.1 RESEARCH APPROACH

As mentioned above, the research primarily builds on existing frameworks, theories and discussions from STTs and 4IR literature. The intended product of this research is a conceptual framework to facilitate an integration between the 4IR and STTs. The research employs both inductive and deductive approaches at various stages to fulfil its objectives. For example, the research takes an inductive approach in analysing literature to understand the concepts of STTs and the 4IR and the extent of their integration in academic literature and thereafter develop a research product for their integration. After the product's development, the research takes a deductive approach to evaluate the product through a case study and an evaluation process with various Subject Matter Experts (SMEs).

The research also takes an investigative or exploratory approach to develop and apply the research product. Therefore, the process of stating and testing a hypothesis was not necessary, but the reader is ultimately guided in understanding how the concepts of the 4IR and STTs are integrated using several examples from literature and a demonstrative case study. A descriptive approach is undertaken to primarily describe the nature and characteristics of STTs and the 4IR and thereafter investigate and demonstrate an integration between the two concepts (Saunders *et al.*, 2007).

1.4.2 RESEARCH METHODOLOGY

This research employs a two-fold literature analysis in the form of a conceptual review referred to as a contextualisation and a Systematic Literature Review (SLR). First, the contextualisation is conducted and presented to give context to the concepts of STTs and the 4IR. This gives an understanding of the concepts of the 4IR and STTs as they are presented in their specific literature.

Thereafter, a Systematic Literature Review (SLR) was conducted to investigate the extent to which these main concepts have been jointly analysed within academic literature. This was done to objectively ascertain the extent of an integration of the STTs and 4IR in the available academic literature. Findings from the SLR are presented through a bibliometric and a content analysis. Results from bibliometric analysis have also been published in an article in the Southern African Journal for Industrial Engineering's 30th Special Edition (Asiimwe & de Kock, 2019). Thereafter, a literature synthesis was conducted which culminated in a gap analysis between the conceptual literature and literature analysed in the SLR. This synthesis was utilised to form an integration strategy which includes development methodology for the research product and requirement specifications for the envisioned product. The research product is consequently developed and presented with an operationalisation strategy.

The research product and operationalisation strategy are evaluated using two main strategies i.e., through semi-structured interviews with Subject Matter Experts (SMEs) and a case study application. It is envisaged that interviews with SMEs verified and validated the adequacy and soundness of theory and logic utilised in the research and developed product as well as the adequacy of the product's representation of a conceptual integration between the 4IR and STTs. Furthermore, the case study is envisaged to demonstrate the applicability, practicability and usability of the research product in relation to the real-world context.

Following the above, this research was broken down and conducted as a four-phase project with the ultimate aim of fulfilling the research objectives. The phases, which are aligned to the research objectives are described below:

i. Phase 1 encompassed the introduction and contextualisation which were conducted in fulfilment of research objective 1;
ii. Phase 2 is aimed at understanding the knowledge gap. Resulting from it, the bibliometric, content and gap analyses are presented to fulfil research objective 2;
iii. Phase 3 of the research is a presentation of the research product development strategy through which the research product's development process and requirement specifications are presented in fulfilment of research objective 3; and
iv. Lastly, in Phase 4, the developed research product presented in fulfilment of research objective 4. This includes a presentation of the product's operationalisation strategy, the product's evaluation process and a conclusion of the research.

1.5 DOCUMENT STRUCTURE

All research and findings from this research are presented in this thesis document. This document is structured in eight chapters which are summarised in Table 1 below:

Table 1: Thesis document chapters

Chapter and title	Content brief/description	Research objectives or sub objectives
Chapter 1: Introduction	An introductory chapter to the research presenting a brief background on STTs and the 4IR, the research aim and objectives, scope and design.	N/A
Chapter 2: Contextualisation	A conceptual introduction to STTs and the 4IR giving the reader an understanding of the concepts as analysed for this research.	RO 1
Chapter 3: Systematic Literature Review: methodology and bibliometric analysis results	A presentation of the SLR highlighting the strategy, methodology and initial findings in the form of a bibliometric analysis.	RO 2.1
Chapter 4: Content and gap analysis	A continuation of the SLR focusing on the document content analysis, which culminates in the research 's gap analysis.	RO 2.2; RO 2.3
Chapter 5: Development strategy – approach and specifications	A presentation of the research product's development strategy which highlights requirements specifications and the research product's development methodology.	RO 3.1; RO 3.2
Chapter 6: A framework for the integration of socio-technical transitions and the fourth industrial revolution	A presentation of the research product that integrates STTs and the 4IR. An operationalisation strategy of the research product is also presented in the chapter.	RO 4.1; RO 4.2
Chapter 7: Evaluation of the I4IR-STT framework and operationalisation strategy	A presentation of the evaluation of the developed research product and operationalisation strategy detailing outcomes from interviews with SMEs, a presentation of the self-evaluation of the requirements specifications and presentation of the case study application.	RO 4.3; RO 4.4
Chapter 8: Research conclusion	A conclusion of the research presenting an overview of the research, contributions of the research and recommendations for future work.	N/A

A summary of this structure highlighting respective chapters and their content is presented in alignment with the phases and objectives of the research process is shown in Figure 5 below:

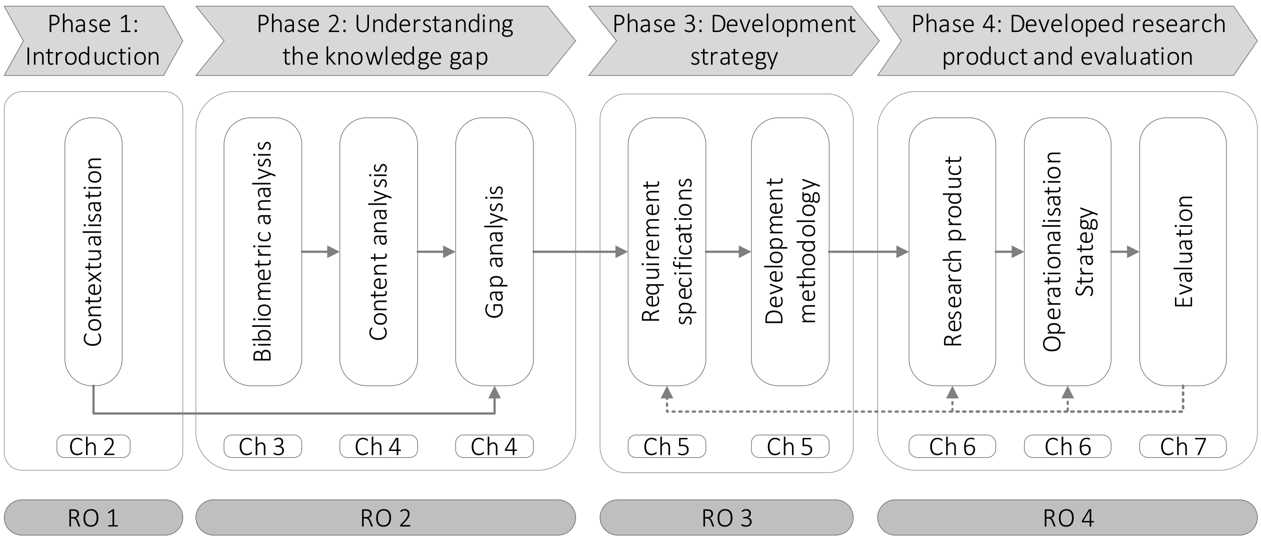

Figure 5: Research design and document structure

1.6 CHAPTER 1 CONCLUSION

In this chapter, the research is introduced through the background concepts of sustainability, STS transitions and the 4IR highlighting how these concepts may be linked. The research problem entailing a proposal for the integration of the concepts of 4IR and STTs has been presented with aiding objectives and the motivating aim. Ethical implications of the research are also presented.

Furthermore, the research strategy and methodology have been presented. A SLR is to be employed to investigate the 4IR and STTs within literature and assess the extent to which they have been jointly considered. It is envisaged that findings from literature will confirm or refute the stated research problem. In the next chapter, a contextualisation of STTs and the 4IR is presented. This analysis highlights definitions, theory and discussions of the concepts as presented in their core theoretical literature as well as their relationship to sustainability and sustainable development.

CHAPTER 2: CONTEXTUALISATION

In this chapter, an overview of the main concepts for this research is presented as found in literature. Section 2.1 opens the chapter with an introductory background of STTs through STS. Thereafter, a discussion on STTs is presented in Section 2.2. This is followed by Section 2.3 which presents a discussion of 4IR in literature in the context of sustainability transitions. It is important to emphasize that the STS introduction presented in this chapter from literature is meant to give the reader context and a further understanding of STTs literature and its background. While STS are not the main focus of this research, the discussed STS literature will give background to the analysis of their subsequent transitions, presented in Section 2.2. Lastly, an overview of the 4IR is presented in Section 2.3, with a brief highlight of sustainability discussions on the 4IR in literature.

2.1 TRANSITIONS PERSPECTIVE BACKGROUND: SOCIO-TECHNICAL SYSTEMS

Socio-technical Systems (STS) are described in literature as those that are primarily technical but consider human interaction with the technology and the operations of the systems as primary factors for the system's optimal functioning (Baxter & Sommerville, 2011). The current advancement of technology would define most systems as socio-technical due to human accessibility and interaction with technology (Baxter & Sommerville, 2011). STS examine and consider the effects of technology on people and social structures and vice versa (Sutcliffe & Minocha, 1999) and involve a cluster of elements such as technology, regulations and policies, user practices, cultural practices, markets, infrastructure, maintenance and supply networks (Elzen *et al.*, 2004). Multiple examples of STS applications within literature fall under various socio-economic sectors and industrial fields such as transportation (Kemp & Rotmans, 2004), healthcare (Farla *et al.*, 2012) , energy (Tran, 2014; Verbong & Geels, 2010), business and organisations (Sutcliffe & Minocha, 1999). These systems are designed to fulfil some social/societal need hence the emphasis on the 'socio' aspect of their make-up (Elzen *et al.*, 2004; Geels, 2004; Sutcliffe & Minocha, 1999). STS may be examined from different systemic levels of analysis as illustrated in Figure 6 below:

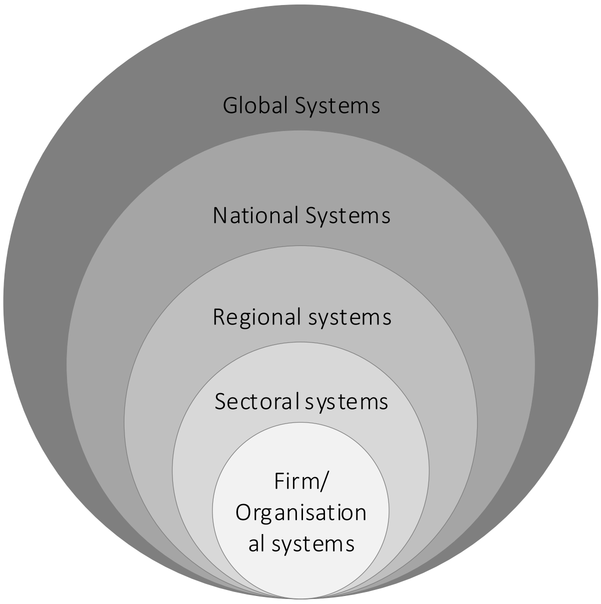

Figure 6: System levels (Elzen *et al.*, 2004)

Furthermore, Geels (2004) argues that STS do not function autonomously but are a result of the activities of various actors embedded in social groups. The various social groups highlighted in literature that carry and reproduce STS include schools, universities, regulatory bodies, engineering groups, financial groups, technical institutes, business organisations, societal groups such as NGOs, media, public authorities and governmental bodies (Elzen *et al.*, 2004; Farla *et al.*, 2012; Geels, 2004; Sutcliffe & Minocha, 1999). These social groups differ in configuration from one sector to the next and their relationships shift over time as new groups emerge (Geels, 2004).

2.1.1 SOCIO-TECHNICAL SYSTEMS: ORIGINS AND CHARACTERISTICS

STS design originated from the evolution of computing (Whitworth & Ahmad, 2013). As computers evolved from industrial machinery to personal computers that meet the needs of the individual, the rise of the internet fostered various software capabilities evolving into social computing (Whitworth & Ahmad, 2013). Technology today operates in a co-evolutionary relationship with society (Geels, 2004; Whitworth & Ahmad, 2013). Contemporary STS have a primary, dynamic and co-evolutionary relationship between developed technology and the society within which the technology functions.

Due to the holistic integration between technology and society, STS design employs systems thinking, knowledge and design (Whitworth & Ahmad, 2013). STS comprise of combinations of complex, dynamic sub systems characterized by feedback loops, self-organisation and hierarchies (Geels & Schot, 2007; Tran, 2014). It is on this basis that STS are often referred to as complex systems or system of systems (Tran, 2014). Characteristics of STS highlighted in literature (Baxter & Sommerville, 2011; Elzen *et al.*, 2004; Geels, 2003; Whitworth & Ahmad, 2013) include:

i. STS are interdependent;
ii. STS adapt to and pursue goals in external environments;

iii. STS have internal environments comprising of separate abut interdependent technical and social sub-systems;

iv. The system goals of STS can be achieved through multiple means; and

v. The system performance of STS relies on the optimisation of both the technical and social systems in tandem.

2.1.2 SOCIO-TECHNICAL SYSTEMS: STRUCTURE AND MAKEUP

STS are inherently defined by their function within society, i.e., the fulfilment of some form of societal function such as transportation, communication and health care provision, is central to the operation of STS as opposed to mere technological innovation supplied and user interaction on the demand side (Elzen *et al.*, 2004). Geels (2004) highlights that this functioning is dependent on the interplay between various actors, institutions, social, economic and political systems that co-evolve with technology in a push–and–pull interaction. Furthermore, technologies are developed and utilised within user contexts which are made up of their competencies, interpretations, preferences and cultural values and are shaped by existing regulations, infrastructures and artefacts. This creates the dynamic nature of STS (Elzen *et al.*, 2004). Geels (2004) describes STS to be comprised of two basic sides shown in Figure 7 below. These include a supply/production side and a demand/application side.

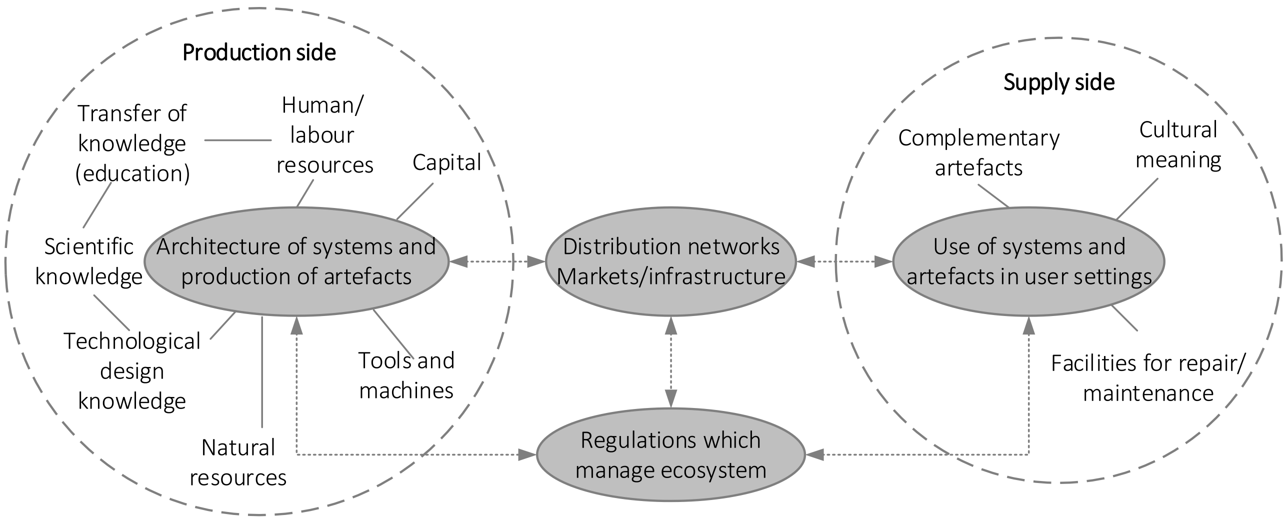

Figure 7: Basic elements and resources of STS. Source: Geels (2004)

The demand and supply side are especially emphasized in sectoral systems of innovations and technological systems, which are two branches of STS studies. Sectoral systems of innovations are described as the system of organisations and institutions that are active in developing, generating and utilizing technologies and are related through processes of interaction, co-operation in technology development and participation in competitiveness and selection in innovation and market related activities (Geels, 2004). Technological systems are described as networks of various agents with a specific institutional infrastructure and in a technological area and how they create, diffuse and utilise technologies (Geels, 2004). Technological systems are also described by Geels (2004) as social systems. It is important to note that STS cannot be exclusively described as either one or the other but are a combination of the two. Therefore, although demand and supply sides of STS are often differentiated in some analyses, they are mutually interdependent (Elzen *et al.*, 2004).

Furthermore, Geels (2004) analytically describes STS in three dimensions i.e., the landscape, regime and niches as shown in Figure 8 below:

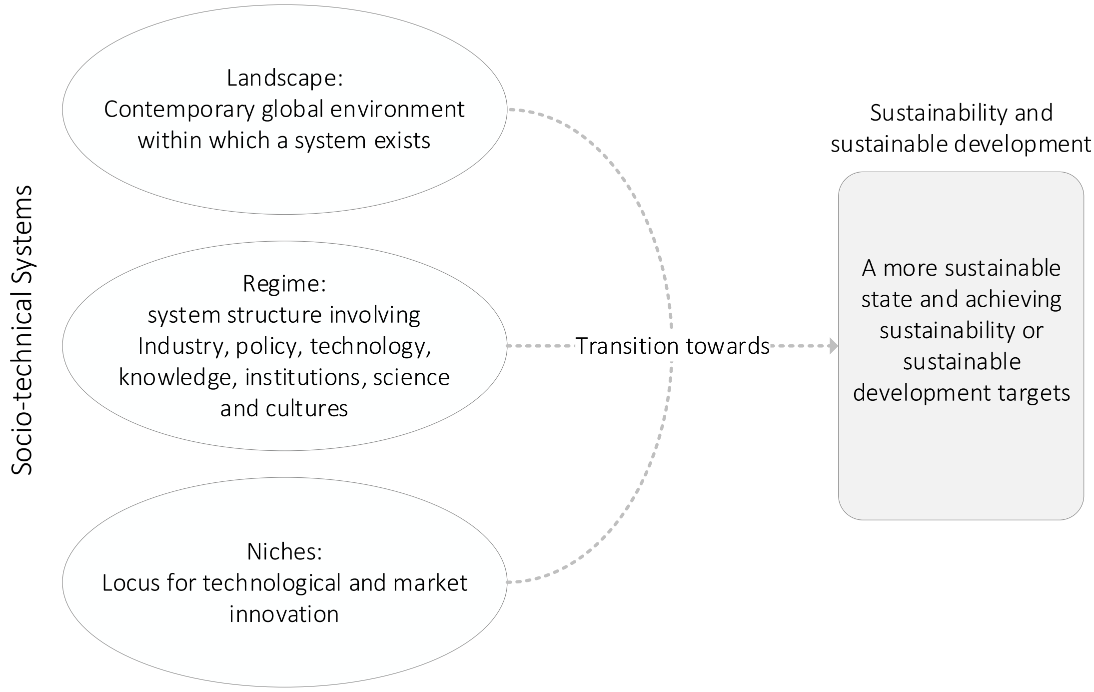

Figure 8: Socio-technical system transitions to sustainable states (Geels, 2004)

Niches are the locus in which radical innovations are developed that often geared towards solving existing STS problems. Niches may take the form of technological niches or small-market niches. Niches have fewer clear set of rules, structures, role relationships and interlinked dependencies and also carry less certainty about the social network. (Geels, 2004).

The regime is defined as a semi-coherent set of rules entrenched in various infrastructures, processes, institutions and activities within STS. These rules can include engineering practices, process technologies, product characteristics, process procedures and skills required, ways of handling people and artefacts, definitions for arising issues/problems (Geels, 2003, 2004). Furthermore, according to Geels (2004) STS regimes are a meta-coordination of societal regimes which include technological and product regimes, science regimes, policy regimes, socio-cultural regimes and users, markets and distribution networks (Geels, 2004). These regimes although autonomous, are dependent on another. Regimes are often the stabilizing dimension within STS. (Geels, 2004).

The STS landscape dimension encompasses the environment within which the system operates. It consists of deep structural trends and slow changing factors such as cultural and normative values, broad societal politics, long economic development, migrations and environmental issues. Furthermore, it is where technological trajectories are situated (Geels, 2003). Landscapes consist of even stronger structures than regimes and are beyond the direct influence of actors within an STS (Geels, 2004).

The niche, regime and landscape dimensions are further comprised of three interdependent sub-dimensions which include the system itself, its actors and the rules that govern how the system operates. Systems do not operate autonomously but work through actors who actively steer these systems. Actors – who may be categorised into individuals or specific groups of people - share rules and values through collectives and generate patterns of activity which become similar over recurring local practices. Actor strategies, preferences and interests are not fixed but change overtime as a result of social action. (Geels, 2004)

The niche, regime and landscape dimensions have been extensively developed and utilised in STTs literature through the Multi-Level Perspective (MLP) framework. The MLP has emerged as a dominant analytical framework in understanding the dynamics of STS and STTs (Köhler *et al.*, 2019) and is later presented in subsection 2.2.1 below.

In this section, a brief overview of STS and their configuration has been presented. This, as previously mentioned, has been done to give a contextual background for STTs. In the next Section, STTs are presented and elaborated on.

2.2 SOCIO-TECHNICAL TRANSITIONS

Geels (2004) describes transitions as large scale transformations that change the way societal functions are fulfilled or a change an STS from one configuration to another (Geels, 2004). Transitions may be evolutionary where a new configurations emerge contingently or goal oriented where an end-goal or target or outcomes guides decisions taken by relevant stakeholders within the STS (Kemp & Rotmans, 2004). Furthermore, according to Geels (2003), change aspects of transitions include (Geels, 2003):

i. Technological substitution: which comprises of the emergence of new technologies, their diffusion and the replacement of the old technologies by the new;
ii. Co-evolution: changes with actor related elements such as user practices, regulations, industrial networks, infrastructure, and cultural meanings; and
iii. Emergence of new functionalities: newer radical technologies merge with particular technical properties which articulate new functionalities. Once new functionalities are introduced, then new performance measurements also emerge.

Furthermore, Elzen et. al (2004) and Kohler et. al (2019) describe characteristics of transitions as described below (Elzen *et al.*, 2004; Köhler *et al.*, 2019):

i. STTs are large scale changes in the elements and structures of STS;
ii. STTs require and are comprised of multi-actor processes;
iii. STTs develop in a co-evolutionary manner as a consequence of changes within the supply side and demand sides of STS; and
iv. STTs unfold over long periods of time spanning over decades.

It is noted that literature on STTs distinguishes between transformations and transitions. Transformations are described as changes at the landscape level of STS, which cause pressure on the regimes thereby re-orienting innovative actives. They reflect the different STS dimensions affecting one another and co-evolving into dimensional change (Elzen *et al.*, 2004). Transitions on the other hand are defined as the transition of one entire STS into a whole new one (Geels & Kemp, 2007). Transitions, describe the change from one systemic state to another and they possess internal characteristics which give stability (Elzen *et al.*, 2004). Elzen *et al.* (2004) notes that the different STS dimensions systemically encompass fields, disciplines, industries and sectors within spatial and geographical contexts which are all interlinked and interdependent. This implies that transformations are embedded within larger global systemic transitions.

2.2.1 SOCIO-TECHNICAL TRANSITIONS PROCESS: A MULTI-LEVEL PERSPECTIVE

According to Geels, the MLP is an *"analytic and heuristic concept to understand the complex dynamics of socio-technical change"* (Geels, 2003). The MLP dominates as the main framework for the analytical analysis of STTs. First conceptualised by Rene and Kemp (1998), this framework has been further developed and popularized in transitions studies by Frank Geels (Elzen *et al.*, 2004; Geels, 2004, 2011; Geels & Kemp, 2007; Geels & Schot, 2007, 2010; Verbong & Geels, 2010). This framework not only serves as an analysis tool for STTs but also gives an analytical understanding of the structure and make-up of STS (as presented in Section 2.1.2) and a descriptive understanding of how transitions happen. MLP highlights multidimensional interactions between the different categorical levels of an STS, essential for that system's change towards sustainability. It also addresses two core analytical puzzles of transition; namely, change and stability which in addition to lock-in and path dependency characterize internal dependencies for transitional shifts (Geels & Kemp, 2012). Geels (2003) further developes the Multi-Level Perspective using the landscape, regime and niche dimensions described in Section 2.1.2. Geels (2003) argues that although the MLP is a complex study, it is useful analysing the shifts in STS towards more sustainable configurations. (Geels, 2003).

The niche, regime and landscape dimensions introduced in Section 2.1.2, encompass various activities which contribute to the transitions process. Within niches, radical technological innovations making small waves in the STS are generated within niches. Niches provide space and locations for actor learning processes thereby allowing for growth and building of social networks which support innovations (Geels, 2003). Regimes being the semi-coherent rules carried by various social groups account for the stability of STS. This is done by provision for orientation and co-ordination of activities related and relevant to actor groups. In regimes, innovation occurs in small increments. (Geels, 2003) The landscape sets the external environment within which actors in niches and regimes operate and function. It contains technological trajectories and slow-changing heterogeneous factors and is often very difficult to change. This is where long term system goals and targets are set for system transition. (Geels, 2003). Transitions are thus not caused by changes from one single system factor but are driven by actors in an interplay of many processes and activities. As previously mentioned, STTs are explained in literature by the use of the MLP shown in Figure 9 below:

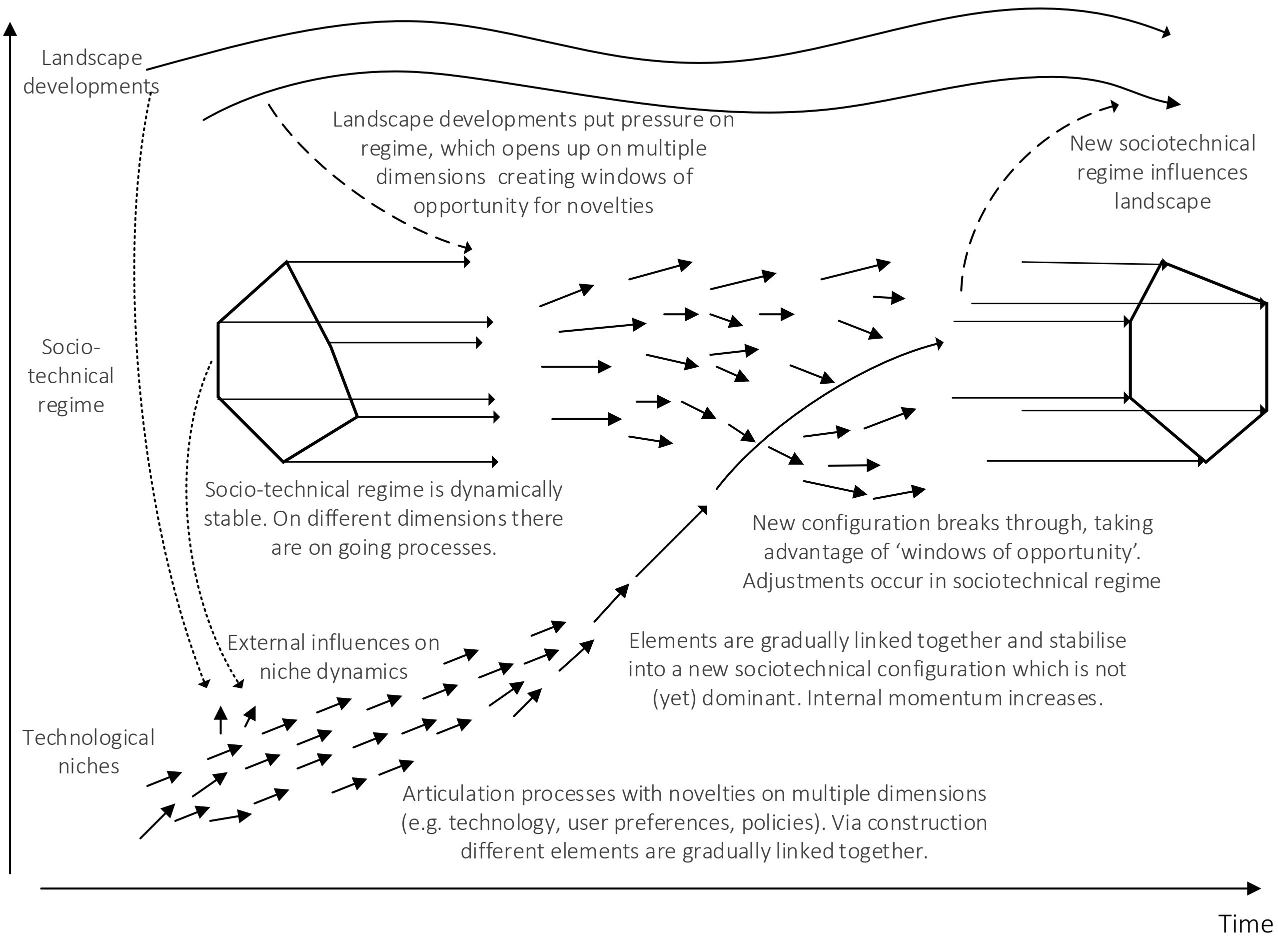

Figure 9: Geels' MLP framework for understanding STS transitions. Source: Geels (2004)

From the MLP, developments within the landscape add pressure to regimes initiating transformations within the incumbent STS. Landscape developments may have a reinforcing relationship with the regime which may form no drivers for transitions (hence stability) or may be disruptive which exerts pressure on the regime creating instability. According to Geels & Schot (2007) landscape developments are described by four types of environmental changes which include:

i. Regular change: which refers to landscape changes which are experienced with low intensity and exert a gradual change;
ii. Specific shock: describes changes in the landscape that occur rapidly and with high intensity. These are said to be rare and are relatively narrow in scope;
iii. Disruptive: These describe changes in the landscape that develop gradually but have high intensity effects in one dimension of the landscape; and
iv. Avalanche changes: These changes occur very infrequently but are of a high intensity, have a high speed and simultaneously affect multiple dimensions of the landscape.

The regime dimension is typically the dimension responsible for the stability of an STS (Geels, 2004). However, when the activities of different actor groups and resulting trajectories in the regime head in different directions, misalignment and instability occurs in the regime (Geels, 2005). Instability reorients the direction of innovations within the niche dimension (Schot & Kanger, 2018). Niche innovations are described to have either a quasi-static or dynamic interaction with the regime's incumbent technologies depending on the transition time-frame (Geels & Schot, 2007; Sandén & Hillman, 2011). Dynamic interaction is immediate and takes into account changes in the system such as user demand, the production systems and knowledge pool (Sandén & Hillman, 2011). In contrast, a quasi-static interaction occurs in the long term/later stages of a transition process and considers factors such as resource flow and demand size in the regime. These are considered to be constant in describing the nature of the relationship between niche technologies and the regime's incumbent technology (Sandén & Hillman, 2011).

Sandén & Hillman (2011) present a comprehensive account of the nature of relationships between niche technologies and the regime's incumbent. These relationships are encompassed in both the dynamic interaction and quasi-static interactions and are summarised in Table 2 below:

Table 2: Nature of relationships between niche technologies and the regime's incumbent. Source: (Sandén & Hillman, 2011)

Nature of relationship	Description
Competitive	The niche technology and incumbent technology compete in an inhibitive manner for resources or market that is in short supply
Complementary	Niche technologies and the regime's incumbent interact in a favourable manner that is supportive to both.
Neutralism	Niche technologies and the regime's incumbent do not overlap and are therefore unaffected by each other.
Parasitism (and predation)	Niche technology interacts with the regime's incumbent in a way that inhibits the incumbent yet benefits the niche technology.
Commensalism	Niche technology interacts with the regime's incumbent in a way that it is benefitted yet the incumbent is unaffected.
Amensalism	Niche technology interacts with the regime's incumbent in way that it is inhibited yet the incumbent is unaffected (example, blockchain and normal banking)

Furthermore, it is observed that with regard to timing, the level of development of the niche innovations influences the path the transitions follows when the landscapes pressures are imposed on the regime (Geels & Schot, 2007). Geels & Schot (2007) propose the following as viable indicators for maturity of niche innovations ready for breakthrough:

i. When learning processes have a dominant design and are stabilised in it;
ii. When innovations have powerful actors as part of their support network;
iii. When price and performance indicators are improved with expectations for more improvements; and
iv. When the innovations are more than 5% of the market share of market niches.

When instability is present, the right combination of elements and linkages for innovations eventually stabilise into a new socio-technical configuration which, although not yet dominant, gains internal momentum. This configuration later takes advantage of the windows of opportunity into the regime dimension created by instability leading to adjustments in the regime. A new STS arises, there after influencing the landscape.

Changes in the transition process are described as occurring in four phases. These, according to Kemp & Rotmans (2004) include the predevelopment phase, take off phase, breakthrough phase and stabilization phase as can be seen in Figure 10 below.

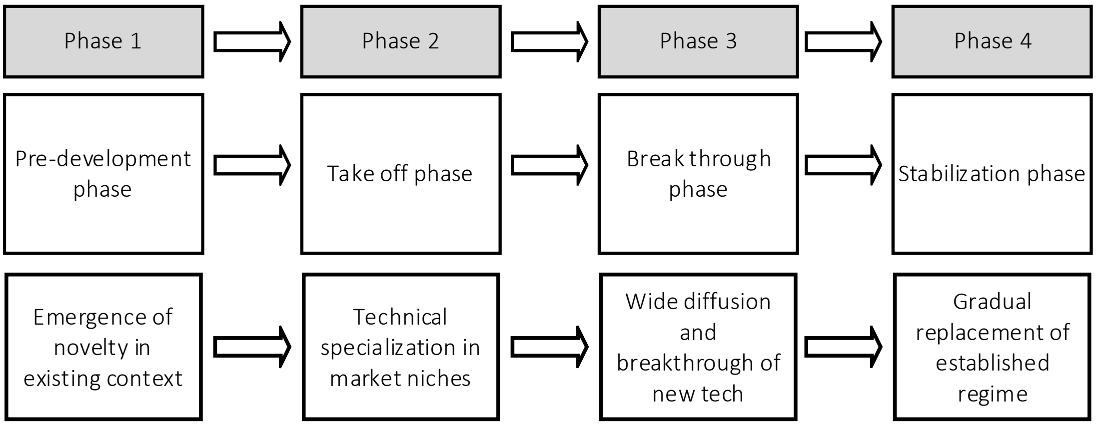

Figure 10: Phases in transitions (Kemp & Rotmans, 2004)

In the **pre-development phase**, experimentation with various emerging technologies in the existing context occurs with little visible change within the overall system. At the **take-off phase**, however, the change process initiates, and the state of the system begins to shift as the specialisation begins to occur within market niches. At the **breakthrough or acceleration phase**, technologies breakthrough and diffuse creating competition in existing regimes. This ripples into structural changes that are visibly observed combined with changes accumulating within the economic, sociocultural, ecological and institutional spheres. Then finally in the **stabilization phase**, there is gradual replacement of the existing regime with wider transformations. Thereafter the speed of changes within society decreases with a new dynamic equilibrium being created (Geels, 2003; Kemp & Rotmans, 2004).

Phases in the transitions process are supported by forces and conditions for change (Frantzeskaki & de Haan, 2009). Conditions for change are drivers that foster the transition process and are based on the idea of functional mismatch which causes instabilities. These include:

i. Tensions: mismatches between the landscape (environment of the STS regime) and the incumbent regime;
ii. Stress: internal mismatches within the incumbent regime; and
iii. Pressure: mismatches between the incumbent regime and an emerging new STS functioning from in a developing niche (also sometimes referred to as a niche-regime).

On the other hand, forces for change are descriptive variables of STS states during a transition. These according to Frantzeskaki & de Haan (2009) include:

i. Formation forces: These forces pertain to the potential for societal innovation and include:
    a. Presence of a niche;

   b. Presence of new demand which encompasses both market and societal demand for a niche; and
   c. Presence of a new form of systemic functioning.

ii. Supportive forces: These forces strengthen or weaken the trend in the transition. They include:
   a. Standardization of practices/routines;
   b. Provision of resources;
   c. Exercise of power by external or internal centres of influence.

iii. Triggering forces which perturb or induce shock to the system. These include:
   a. Systemic failures which include system inefficiencies, ineffectiveness and inadequacies to meet supply and demand of the system;
   b. Crises which occur without an apparent advance warning and impose extreme influence on a system; and
   c. Exogenous events which are uncontrollable and unpredictable events that suddenly occur, surprising the STS.

Forces for change can be enabling or inhibiting. Furthermore, forces are characterised by direction and origin of the force (Frantzeskaki & de Haan, 2009). Table 3 below highlights the forces for change as well as their direction and underlying conditions for change as presented in Frantzeskaki & de Haan (2009).

Table 3: Forces for transitional change, their direction and underlying conditions for change. Source: Frantzeskaki & de Haan (2009)

Condition for change	Direction of forces	Forces driving transitional change
Tensions	Top-down (landscape on to regime)	Crises; exogenous events; Standardization of practices; Provision of resources; Exercise of power; Imposition of new functioning
Stress	Internal (within regime)	Systemic failures; Self-regulation of the system
Pressure	Bottom-up (niche on to regime)	Presence of a niche; Presence of a new demand; Presence of new functioning

Instabilities caused by misalignments due to tensions within STS are highlighted as key initiators for changes towards system transformations and transitions. All actors within the system possess unique and collective perceptions values, preferences, strategies, and resources. Misalignments occur when these attributes encounter rising tensions due to the various reasons presented below as identified by Geels (2004):

i. Changes within the landscape such as changes in values in the broader culture and changes in politics thereby adding pressure to the regimes;
ii. Persistent internal technical problems that trigger actors to explore and pursue new technical directions. Actors' shared perceptions of problem agendas are important as these persistent problems may lead to an undermining of trust with existing technologies.;
iii. Change in user preferences due to reasons such as new discovered technologies;

iv. Competitiveness and changes in strategies within companies or countries which creates openings within a regime; and

v. Negative impact of systemic activities and technologies on the external environment for example climate change causing pressure on the regime.

To summarise, the overall process through which STTs are enacted is through the dynamic interaction between niche, regime and landscape dimensions of STS. When STS have an overall alignment in trajectories of technological development, rules, infrastructure, supply and demand within the niche, regime and landscape dimensions, they become stable and lock-in. However, when STS are unstable, opportunity for change arises. Instability occurs when pressure from the landscape dimension causes tensions in the regime dimension and creates room for windows of opportunity for niches to break through and create a new dominant socio-technical regime (Elzen *et al.*, 2004).

2.2.2 THEORETICAL FRAMEWORKS FOR UNDERSTANDING SOCIO-TECHNICAL TRANSITIONS

Literature presents four overarching frameworks utilised in the understanding of STTs within the real-world context. These frameworks have gained academic credibility overtime through critique and refinement. According to Kohler et al (2019), they include:

i. The Technological Innovation Systems (TIS) approach;

ii. Strategic Niche Management (SNM);

iii. Transitions Management (TM); and

iv. The Multi-Level Perspective (MLP).

These frameworks are drawn from innovation studies which provides the origin of transitions studies. Additionally, these frameworks capture complexities in transitions such as co-evolutionism, path dependency, emergence and non-linear dynamics through a systemic approach (Köhler *et al.*, 2019).

The MLP, which has been presented in Section 2.2.1 above, is different from the TIS, SNM and TM in that it presents a descriptive analysis of STTs. The MLP serves as the overarching descriptive analytical framework for STTs. SNM, TIS and TM are utilised as intervention frameworks, i.e. they are used to deliberately influence STTs in contemporary STS for example through strategic and policy interventions (Markard *et al.*, 2020). The TIS, SNM and TM are explored in the subsections below.

2.2.2.1 TECHNOLOGICAL INNOVATIONS SYSTEMS (TIS) APPROACH

The Technology Innovations Systems (TIS) approach focuses on the innovation of a particular technology from an STS perspective and specifically studies the development, diffusion and use of this technology in society (Bergek *et al.*, 2008). The approach is particularly technology and process-focused and draws ideas from innovations systems theory and industrial economics (Bergek *et al.*, 2008). The approach is therefore centred on the niche dimension and its activities in the STTs process. The framework outlines the following seven processes which it presents as key functions of technology development and diffusion process:

i. Knowledge development and diffusion;
ii. Influence on the direction of search;
iii. Entrepreneurial experimentation;
iv. Market formation;
v. Legitimation;
vi. Resource mobilisation; and
vii. Development of positive externalities.

The TIS approach embodies how these functions enable relevant actors to develop a particular technology within STS, by relating these functions to inducement mechanisms (or drivers), blocking mechanisms (or hindrances) and policy issues. Bergek *et al.* (2008) further present an analysis scheme to enable the user to utilise the approach. This is a six-step guiding process and is shown in Figure 11 below.

The first step is to define the TIS in question for subsequent analysis. In the second step, the structural components of the TIS (including the various actors, networks and institutions at play) are identified. The third step is to then analyse the TIS through the functions. The functions enable one to identify what is going on in the TIS in order to identify a functional pattern that describes how each function is filled in the STS. In the fourth step, the functions are assessed on how well they are being achieved and goals are set according to the desired functional pattern. The fifth step involves the identification of drivers and hindrances for the desired functional pattern of the TIS. Key policy issues pertaining to these drivers and hindrances are identified in the sixth step for mitigation. (Bergek *et al.*, 2008).

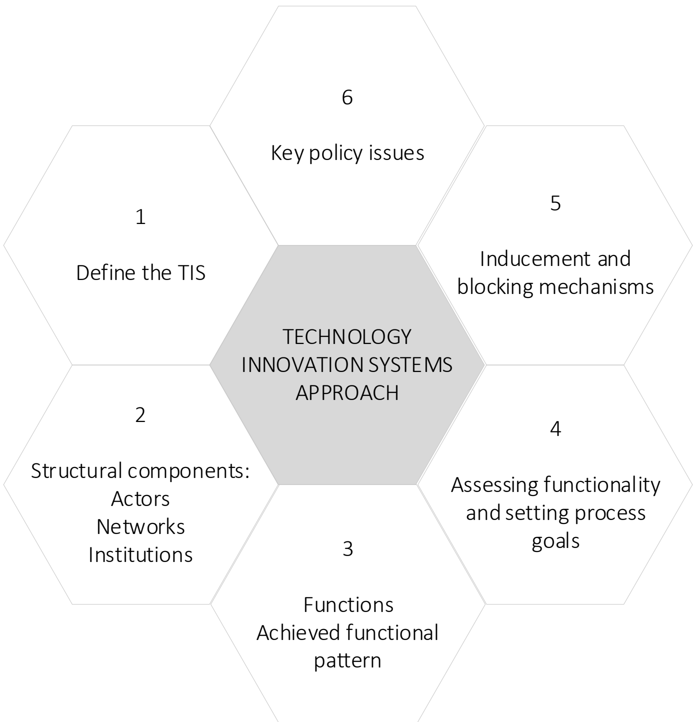

Figure 11: Analysis scheme for the TIS. Source: Bergek *et al.* (2008)

Because TIS analyses transitions by focusing on the emergence of a single technology within its ecosystem, it is by implication, one-dimensional in its approach to technology. Therefore, the approach's potential to sufficiently cover all aspects of a socio-technical transition has been criticised in transitions literature due to this lack of adequate attention to the interaction of multiple technologies (Köhler *et al.*, 2019; Markard *et al.*, 2015). Despite this, the TIS serves as a useful framework for analysing niche technologies and giving insight into emergence and the processes within the niche dimension of STS (Markard *et al.*, 2015).

2.2.2.2 STRATEGIC NICHE MANAGEMENT (SNM)

Strategic Niche Management (SNM) is primarily developed to manage the development of innovations that are socially desirable and serve long-standing sustainability goals as well as radical ones that differ significantly from the existing regime (Schot & Geels, 2008). This is based on the argument by SNM scholars that for many radical innovations especially those with sustainability potential, the market niche and demand are not necessarily readily available as these innovations are not incremental to the technologies within the existing regime (Schot & Geels, 2008). SNM therefore conceptualises and analyses the emergence of innovations and niche technologies as they develop to conquer the existing regime through experimental designs. Schot & Geels (2008), through the SNM, present three processes for the successful development of a technological niche:

i. Articulation of expectations and visions to provide direction for learning processes, create traction and legitimate security and a development environment for the technology;
ii. Building of social networks to create constituency behind the new technology, facilitate actor interactions and to obtain necessary resources; and
iii. Learning processes at multiple regime domains which include "*technical aspects and design specifications, market and user preferences, cultural and symbolic meaning, infrastructure and maintenance networks, industry and production networks, regulations and government policy and societal and environmental effects*" (Schot & Geels, 2008).

The SNM is said in transitions literature to be useful as an ex-post analytical framework, and it draws from the parent MLP framework for the contextual analysis of niches (Köhler *et al.*, 2019; Schot & Geels, 2008). According to Schot & Geels (2008), the SNM has contributed to policy-advice by highlighting various dilemmas that may emerge in transitions and cultivating an appreciation and reflexivity for the dynamics of transitions.

2.2.2.3 TRANSITIONS MANAGEMENT (TM)

Transitions Management (TM) is a policy-oriented and governance focused framework developed for a policy-makers in a prescriptive fashion for how they may influence transitions (Köhler *et al.*, 2019; Loorbach, 2010). The framework, which is also descriptive and multileveled (Loorbach, 2010), suggests four sequential governance activities or spheres through which policymakers may shape transitions. According to Loorbach (2010) and Kohler et al. (2019), these include:

i. Strategy activities for vision development and identification of potential pathways, long-term goal formulation and norm setting;

ii. Tactical activities for developing steering activities and plans within the regime and STS with investment commitments;
iii. Operational activities which include experiments, demonstrations and implementation activities; and
iv. Reflexive activities for evaluation and monitoring and readjustment of plans and formulation of best practices.

Loorbach (2010) further presents a Transitions Management Cycle (TMC) which provides a basis for the operationalisation of transitions management. This cycle (as presented in Figure 12 below) presents four components which visualise connectivity of the above activities in a non-sequential format. Loorbach (2010) elaborates further on the activities.

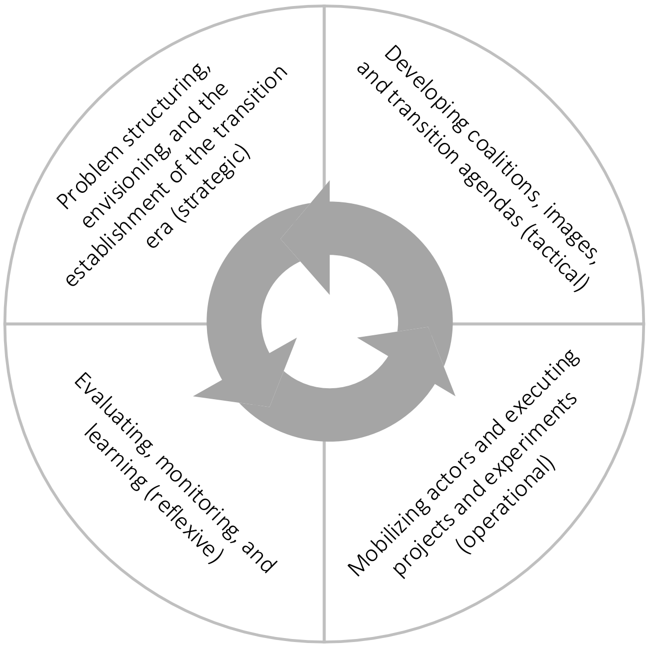

Figure 12: Transitions Management Cycle. Source: Loorbach (2010)

According to Loorbach (2010), the framework is recurrent and repetitive and can be applied to various levels of analysis from an STS down to project level. Furthermore, the framework aims towards long-term sustainability goals which normalises its operationalisation. The framework, however, shadows regular policy processes, providing an innovative way in which new ideas may be developed and introduced. Thus, in application, it should be adapted, diffused and translated to the different contexts in order to fully implement it (Loorbach, 2010).

2.2.3 THE NEED FOR ANALYSING SOCIO-TECHNICAL TRANSITIONS

Modern societies are faced with several grand challenges. Contemporary production and industrial systems have contributed to the depletion of natural resources, the acceleration of climate change through greenhouse emissions and extensive pollution of water and other resources. Furthermore, among other problems, society is riddled with poverty and economic inequality issues, social justice issues, rapid population growths that pose challenges to food production and a host of infectious and non-infectious diseases putting strain on health systems. These issues are systemically embedded in modern societal structures cultures, norms and rules and are as a result of society's consumption pattern and the persistent industrial drive for profitability at all costs (Sachs *et al.*, 2019).

It is evident that the contemporary global systemic trajectory is unsustainable (Sachs *et al.*, 2019). The UN reports that as of 2019, most global countries are still not meeting SDG targets (Sachs *et al.*, 2019) and arguably, solutions based on small incremental changes may not be sufficient to attain global SDGs (Sachs *et al.*, 2019; Tran, 2014). There is a need for holistic systemic transitions which aggregate component changes across an entire STS which involves changes not just technical change in industry, sectors, systems and architecture but also changes in the systemic environment, societal norms and actor involvement (Elzen *et al.*, 2004). STTs illuminate changes in the entire global systemic architecture and their analysis provides a medium through which shifts in global systems can be understood and leveraged to achieve sustainability or sustainable development targets such as SDGs (Elzen *et al.*, 2004; Geels, 2004).

Literature shows various historical examples of STTs. These include transitions across transportation systems (Kemp & Rotmans, 2004), agricultural food chain (Belz, 2004), waste management systems (Fuenfschilling & Truffer, 2016) and energy systems (Correlje & Verbong, 2004; Verbong & Geels, 2010). Such studies have, amongst other benefits, inform policy makers and regulatory and governing bodies (such as body corporates, social groups and change agents) about the necessary requirements to influence their societies towards more sustainable configurations (Elzen *et al.*, 2004).

2.3 THE FOURTH INDUSTRIAL REVOLUTION (4IR)

The 4IR is a technological paradigm expected to fundamentally shift how humanity and its societies function and orient themselves (Schwab, 2016). The 4IR follows from previous industrial revolutions as recorded in human history. As can be seen in Figure 13 below, the 1st Industrial Revolution brought about mechanisation and mechanical power generation through steam engine. The 2nd Industrial Revolution was triggered by electrification and led to mass production and industrialisation. The 3rd Industrial Revolution was triggered by digitization and electronics and led to flexible and automated production systems. The 4IR has been triggered by the development of Information and Communication Technologies (ICTs) and the internet. The 4IR fuses technologies and innovations across physical, biological and digital domains revolutionising how individuals, industries, sectors, societies, nations and global systems operate (Schwab, 2016). Schwab (2016) highlights three distinct markers of the 4IR from previous revolutions as below:

i. Velocity: The 4IR is marked by increased speeds of innovations and large footprints of exponentially growing data creating visibility and fuelling accelerated shifts and changes within global systems;
ii. Breadth and depth: This paradigm does not merely affect one sector but scales to national and global integrated systems. The paradigm also integrates various disciplines from engineering to computer and data science, health sciences, political and social sciences; and
iii. Systems impact: Entire societal structures and systems are impacted and changed by this paradigm as opposed to mere facets of certain sectors.

Schwab (2016) suggests that the contemporary world is only at the beginning stages of the 4IR. The resulting effects of the 4IR, although yet to be fully conceptualised, are speculated to bring about smart automation amongst other things (Schwab, 2016).

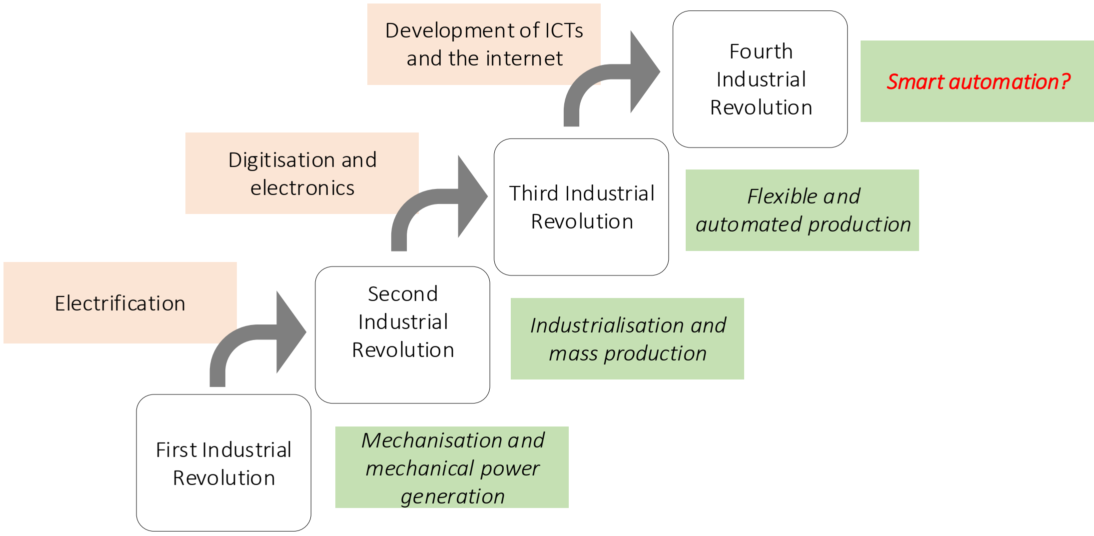

Figure 13: The progression of industrial revolutions (Schwab, 2016)

The 4IR is often commonly mis-conceptualised as Industry 4.0, a term that was coined in Germany around 2011 to describe the 4IR in respect to industrial production value chains and the manufacturing industry (Rojko, 2017). Industry 4.0 especially relates to how business and manufacturing concepts are integrated via the technical building blocks of Cyber Physical Systems (CPS) and Internet of Things (IoT). This creates the concept of a smart factory or industry 4.0 production system (Rojko, 2017).

However, the general scope of the 4IR is much wider than the manufacturing and production industry (Rojko, 2017). It is a fusion of technologies cutting across the physical, digital and biological domains of which Industry 4.0 is one facet (Schwab, 2016; World Economic Forum, 2020) and manifests across various fields and societal systems (Li *et al.*, 2017) including but not limited to agriculture, education, energy, health systems and transportation. The 4IR consists of technologies embedded in systems with decentralised control and advanced connectivity (Rojko, 2017). These systems exchange information in real-time aiming at identifying, locating, tracking, monitoring and optimizing various processes (Rojko, 2017).

Furthermore, other facets and institutionalisations of the 4IR were initiated in other parts of the world. For example, the Industrial Internet concept was initiated in North America in 2012 which integrated physical and digital worlds. This birthed technologies such as Big Data, Cloud computing, Analytics and IoT; and broadened the 4IR to sectors such as health, energy, transportation, mining. The French Industrial Policy also introduced an "Industrie du future" promoting technologies such as additive manufacturing, virtual plants, IoT and augmented reality. The Chinese introduced an initiative in 2015 adapting the concept of Industry 4.0 to suit their industry needs for a vision 2025. This initiative is based on innovation and considering sustainable development elements as well as sustainability goals such as green energy (Rojko, 2017).

2.3.1 TECHNOLOGIES THAT DRIVE THE FOURTH INDUSTRIAL REVOLUTION

From literature, it is observed that the 4IR is being driven by technologies cutting across the the digital, physical and biological domains. (Schwab, 2016) describes these technologies as having two unique characteristics that distinguish them from other technologies outside the paradigm or from previous revolutions;

i. First, they are interlinked with the only underlying distinct associator to the paradigm being the technologies' ability to bridge and blur lines between physical, biological and technological domains; and
ii. Secondly, the velocity of the revolution in terms of innovation, scale and evolution is un-precedented in comparison to previous revolutions. This is attributed to the velocity and volumes of data being generated across blurred domain lines, which enable the technologies to develop and innovate at unprecedented speeds than those previously encountered. Furthermore, this has widely influenced the nature of consumption and utilisation on the demand side of the technology.

Schwab (2016) highlights technologies such as the Internet of Things (IoT), blockchain, digital platforms, autonomous vehicles (AVs), 3D printing, advanced robotics, new or advanced materials and synthetic biology to be the main 4IR technologies. These are considered to be some of the radical or new innovations being brought about through the revolution. However, literature presents technologies such as artificial intelligence (AI), machine learning (ML), Big Data and analytics, cloud computing, augumented and virtual reality as part of the 4IR technologies. Although some of these technologies such as AI, ML or analytics are not radical innovations, they possess the aboved-mentioned characteristics, and are also interwoven and linked with the new technologies emerging within the revolution as presented by Schwab. Furthermore, these technologies have also only recently radically accelerated in development and usage and are also revolutionising the way things are done in various global sectors (Li *et al.*, 2017; Rojko, 2017).

Technologies from the digital domain are observed to be the central driver for the 4IR as they foster and power most other technologies developing from the other domains (Li *et al.*, 2017). Technologies from the digital domain fuel the physical and biological technologies and vice versa; giving new capabilities and making technologies useful beyond their original scope of operations and adding new functionalities and applications to traditionally less digitized sectors such as finance, health, agriculture and education (Schwab, 2016). Table 4 below presents the 4IR technologies, their domains and the sectors or fields they are likely to make an impact on within society.

Table 4: 4IR technologies

4IR Tech driver	Domain	Description	Sectors or fields for potential impact
AI and Machine Learning (OECD, 2019a)	Digital	Teaching machines to independently learn and grow intelligences. Utilised in predictive analysis	Agriculture, healthcare, finance, transport, marketing and advertising,

4IR Tech driver	Domain	Description	Sectors or fields for potential impact
		and decision-support for efficiency, cost saving and resource allocation.	science, criminal justice, security, the public sector, communication
Internet of things (OECD, 2018)	Digital-physical	Communication interconnectivity and interoperability of devices and objects through direct internet connections or networks.	Transportation, health care, urban planning, manufacturing, public health, agriculture,
Big Data and analytics (Jifa & Lingling, 2014; UN Global Pulse, 2012)	Digital	Big Data contemporarily refers to large sets of data that are commonly semi-structured or unstructured. Analytics is the quantitative analysis of this data in real time for various reasons such as decision-support and information mining.	Financial services, education, health, agriculture, transportation, manufacturing, marketing and advertising, media and entertainment, business and organisations
Cyber Physical Systems (Monostori, 2018)	Physical-digital	Integrations of computation, networking and physical processes.	Agriculture, military and defence, energy, health-care, manufacturing, transportation.
Digital platforms (OECD, 2019b; Schwab, 2016)	Digital	Digital platforms act as digital services that facilitate interactions via the internet between two or more distinct but independent sets of users. Interactions have varied purposes such as social communication and entertainments, payments, tracking and data visualisation and content creation.	Media and entertainment, business and organisations; marketing and advertising; health; education; transportation; finance; e-commerce
Cloud computing (Schwab, 2016)	Digital	On demand delivery of hosted computing services to users with minimal active management intervention over the internet. Major applications include cloud storage and collaborative working work platforms.	Business and organisations
Virtual Reality and Augmented Reality (Papetti *et al.*, 2018)	Digital	Technologies that create a visual experience of a simulated digital model with an enhanced physical feel.	Tourism, Education, Entertainment, Communication
Blockchain (Schwab, 2016)	Digital	Also known as distributed ledgers: secure protocols where decentralised networks of computers collectively verify transactions.	Financial services, security
Autonomous vehicles (Schwab, 2016)	Physical	Vehicles with enhanced operation requiring less manual to no operation at various degrees. These offer adjustments to transportation modes from personal vehicles to public transport allowing the	Transportation

4IR Tech driver	Domain	Description	Sectors or fields for potential impact
		vehicles to self-automate some of their functionalities.	
Advanced materials (Schwab, 2016)	Physical	New synthetically enhanced models/ creations of materials such as metals, ceramics, and crystals with advanced capabilities in lightness, strength and recyclability.	Manufacturing, health-care, science
Advanced robotics (Schwab, 2016)	Physical	Machines (either physical or digital) being utilised to enhance and automate tasks for increased or more efficient output.	Manufacturing, health-care, communications, entertainment, education,
3D printing (Fan & Meixner, 2020; Rojko, 2017)	Physical	Also known as additive manufacturing, which encompasses technologies such as rapid prototyping, 3D Scanning, digital manufacturing and personal fabrication. Creation of a physical three-dimensional object from a digital model.	Manufacturing, health-care, education, aerospace, engineering.
4IR Biotechnologies (Rojko, 2017; Schwab, 2016)	Biological	Within this group, technologies such as genome editing, neurotechnology and synthetic biology are emerging and advancing. Mostly utilised in developing and enhancing biological features in human beings and plants. This may contribute to disease treatment in human beings, enhancing crop breeding in agriculture.	Science, agriculture, health
5G (OECD, 2016, 2018)	Digital	The fifth generation of mobile radio technology with increased or enhanced access to diverse types of radio technologies.	Communications

2.3.2 SUSTAINABILITY DISCOURSE ON THE FOURTH INDUSTRIAL REVOLUTION

Advancements by the 4IR have also opened up discussions and questions around sustainability and sustainable development and vice versa. These discussions centre around how technologies in the 4IR affect society and their contributions to addressing long-standing societal issues. The World Economic Forum (WEC) highlights major issues and topics arising from the 4IR discourse as can be seen in Figure 14 below.

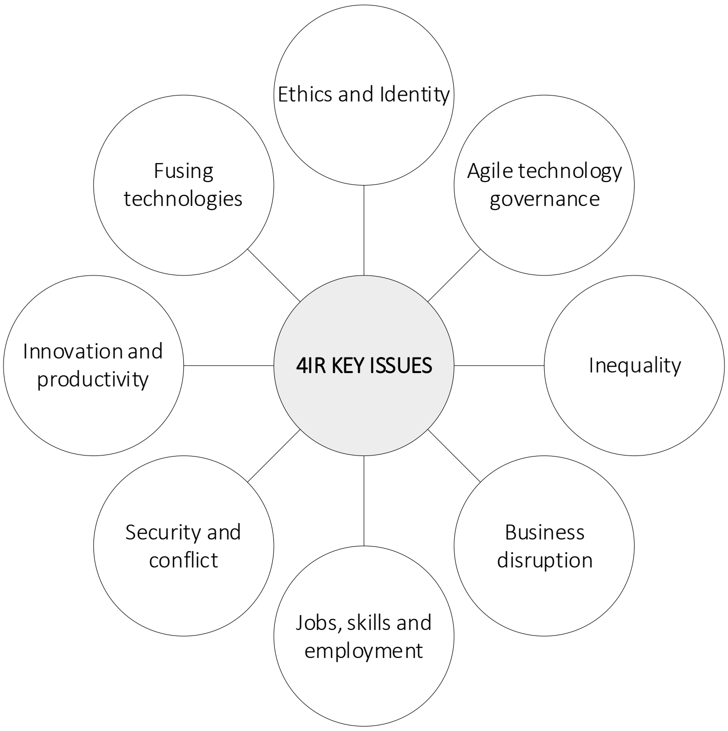

Figure 14: 4IR key topical issues and challenges (World Economic Forum, 2020)

According to the WEC, key issues have related topics as well as related technologies influencing and affecting societies around these topics as can be seen in Table 5 below.

Table 5: Related subtopics to 4IR topics. Source: (World Economic Forum, 2020)

Topics	Technologies involved	Pertaining subtopics and themes arising
Fusing technologies	Information technology; Advanced materials; Virtual and augmented reality; Artificial intelligence and robots; biotechnology; block chain; 3D printing	Digital economies and societies; advanced manufacturing and production; neuroscience
Innovation and productivity	Big Data and analytics; digital platforms; 3D printing; advanced robotics	Entrepreneurship; circular economy; innovation; workforce and employment
Ethics and identity	AI and robotics; biotechnology	Inclusive design; human enhancement; arts and culture; justice and law; future of health and health care; values; behavioural sciences;
Agile technology governance	Internet of Things; 5G; Block chain	Behavioural sciences; agile governance; cyber security; corporate governance; innovation; global governance
Business disruption	AI and robotics; IoT; Digital communications; 3D printing	Advanced manufacturing and production; digital economy and society
Jobs and skills	AI and robotics	Public finance and social protection; work force and employment; justice and law;

Topics	Technologies involved	Pertaining subtopics and themes arising
Inequality	Digital communications	Justice and law; values; workforce and employment; sustainable development; future of economic progress; public finance and social protection; mental health; taxation
Security and conflict	AI and robotics; IoT; Neuroscience; Drones	Values; agile governance; cyber security; international security; space; geopolitics; global risks;

The 4IR encompasses a host of innovative technologies that are transforming processes, products and services in new innovative ways, thereby boosting entrepreneurship. These innovations are disrupting businesses and posing new business models and ways of attaining market share. However, this also affects the nature of work, raising questions on jobs and skills, their transformations and what forms of employment will be available for human beings beyond the revolution. The WEC highlights that while reskilling and advancement of skills is necessary, there is a need to ensure equitable access to acquire the opportunities and benefits from new job formulations. If unchecked, shifts in jobs coupled by the inherent bias of technologies are speculated to lead to new layers of discrimination, further widening inequality gaps (World Economic Forum, 2020).

Furthermore, Schwab (2016) highlights the link between innovation and economic productivity measured, noting that productivity ideally increases with increased innovation and advancement of technology. However, the 4IR possess challenges to productivity measurements as innovative goods and services, although having significantly higher functionality and quality, are delivered to markets for almost zero marginal costs and have gained access to highly competitive markets. This is especially prevalent due to the various digital platforms further reducing costs incurred. This, as Schwab highlights, creates a discrepancy between what is happening on the ground versus what is being measured through traditional productivity measurements. However, the argument is made that it is still the beginning stages of the 4IR and for productivity to be measured via innovation, innovation must be beneficial to both the society and the economy. Therefore, productivity will be reflected in the sustainably transformed societal functions such as energy, transportation, health care, employment, and food production systems. This argument is backed by previous trends in productivity measurements and changes in societal functions. This results in the inclusion of topics such as the circular economy, which provides new models for integrating the 4IR technologies in eco-sustainability initiatives that promote circular material and resource consumption (Schwab, 2016).

The accelerated generation of data across various platforms and its usage is posing major ethical questions. Questions relayed concern topics such as regulation, data security, privacy and concerns for cross-platform/boundary sharing of personal data being generated over various interconnected digital platforms. Furthermore, the question of security expands on a national/global scale as data may be used to control and govern people and influence social norms. Furthermore, integrations with the biological domain introduce new dimensions to discussions on ethics and identity. This arises, for example, with concepts such as human enhancement, machines being given human capabilities and decision making that influences society. Furthermore, the widespread and accelerated nature of technology dependency in the 4IR raises questions on how technologies are designed for inclusiveness to combat societal issues such as inequality and how technology usage may be contributing to increased psychological and mental illness. These affect social spheres and involve various stakeholders from fields such as arts and culture, law and justice, behavioural and social sciences, and health (World Economic Forum, 2020).

2.3.3 THE POTENTIAL OF 4IR TECHNOLOGIES TOWARDS SUSTAINABILITY

Literature highlights various functions of the 4IR technologies and make contributions towards sustainability in its three traditional dimensions. Examples of these are highlighted in Figure 15 below:

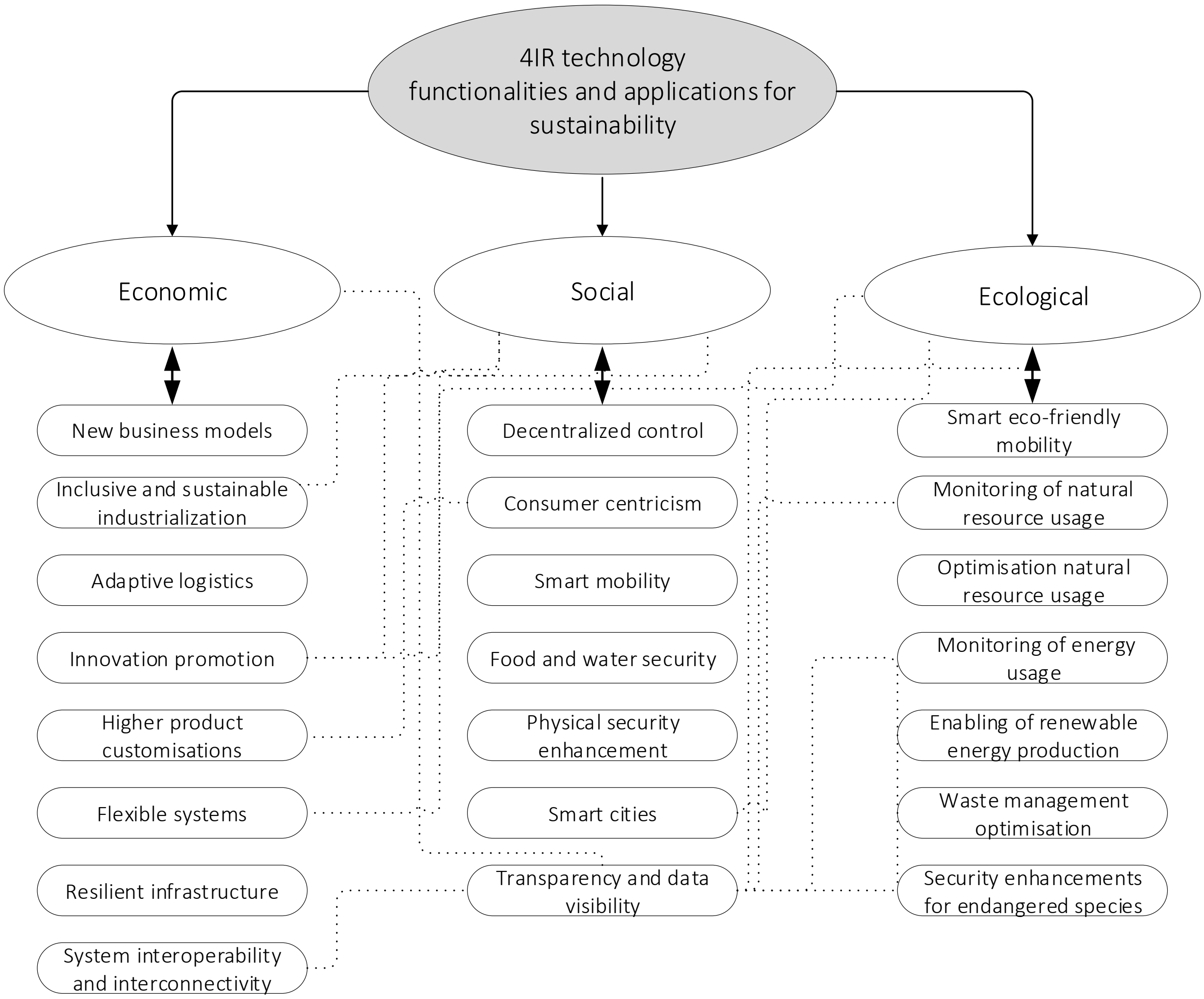

Figure 15: 4IR Technologies' functionalities towards sustainability

The 4IR introduces multiple economic sustainability possibilities global sectors and industries. The transparency, interconnectivity and interoperability brought about by 4IR technologies generates increased value increase through optimisation of business processes, increased efficiency, flexibility in processes, increased quality and customisation of products (Müller *et al.*, 2018). Increased value creation through flexible, interoperable systems is shifting business models and strategies (Müller *et al.*, 2018) and introduction of smart products and services and business processes, which in turn increase competitiveness of businesses (Müller *et al.*, 2018; Rahman *et al.*, 2019; Stock *et al.*, 2018). 4IR technologies result in adaptive and flexible production processes that reduce costs. These all ultimately result in sustainable value creation for industries (Kiel &

Arnold, 2017; Müller *et al.*, 2018; Nagy *et al.*, 2018; Stock *et al.*, 2018). Furthermore, platforms introduced in the 4IR have led to increased innovation which is said to result in increased productivity in the economy (Lin *et al.*, 2017; Morrar *et al.*, 2017; Schwab, 2016).

In the ecological dimension, interconnectivity and transparency by 4IR technologies are highlighted to result into monitoring and optimisation functionalities which lead to benefits such as an awareness of depletion of natural resources (Garcia-Muiña *et al.*, 2018), reduced energy consumption (Birkel *et al.*, 2019), reductions in greenhouse gas emissions (Kayikci, 2018; Müller *et al.*, 2018), optimisation and reduction of carbon emissions in industrial settings (Stock *et al.*, 2018), production of eco-sustainable products (Kayikci, 2018) and promotion of a circular economy (Bressanelli *et al.*, 2018; Garcia-Muiña *et al.*, 2018; Nascimento *et al.*, 2019; Stock *et al.*, 2018). The benefits of these functionalities also extends to awareness and preservation of natural resources as well the earth's flora and fauna (Noor, 2019).

In the social sustainability dimension, increased accessibility to various services and goods through digital platforms, digital accessibility and transparency allows for improved decision making in societal settings shaping norms and values (Morrar *et al.*, 2017). Furthermore, these platforms through their easy accessibility, lowered costs and interconnectivity, present numerous ways for people to create value, alter the nature of assets and lower barriers for individuals to invest and create wealth (Morrar *et al.*, 2017). This contributes to fighting poverty and inequality by empowering more people to become entrepreneurs, modifying and increasing access to education and thereby contributing solutions to social welfare and health issues (Morrar *et al.*, 2017). New business models and product customisations are increasing value for end users through product customisations leading consumer centrism (Nascimento *et al.*, 2019). This is redefining how end users consume products and allows them to have input in the production process leading to products/services that meet societal needs. Within industrial settings, 4IR technologies are said to increase skills among workers as new skills are required to work technologies and introduce new waves of jobs (Müller *et al.*, 2018), better working conditions through flexible working environments and work space optimisation (Papetti *et al.*, 2018).

2.3.4 FOURTH INDUSTRIAL REVOLUTION CONNECTIONS TO SOCIO-TECHNICAL TRANSITIONS STUDIES

It is evident that the 4IR digital technologies are embedded in society and they affect society as much they depend on it (Schwab, 2016). The rapid development of 4IR technologies creates the need for productive deliberation and understanding of the emerging technologies within their specific contexts and application areas as technical innovation often develops significantly within social settings (Morrar *et al.*, 2017). Elzen *et al.* (2004) further argues that consumption of technologies is more than simple adoption and implementation; users must appropriate technologies to their cultures, integrating them into their practices, organisations and routines which requires learning and adjustments (Elzen *et al.*, 2004).

4IR technologies operate and affect various societal structures and as deduced from the literature above, their success is speculated from the preceding positive or negative impacts. Therefore, it may be observed that consumption of 4IR technologies and the appropriation of its usage within the wider society plays a massive role in fulfilling societal needs. Furthermore, acceleration of innovation with the 4IR presents new possibilities for developing solutions targeted at society's grand sustainability challenges (Elzen *et al.*, 2004; Sachs *et al.*, 2019). From the literature presented, it is evident that there may be inherent links between the 4IR and STTs through the 4IR technologies and how they are adopted, applied and utilised in societal systems.

The nature of how socio-technical transformations and transitions may be enabled or aided by the 4IR is uncertain at the moment due to the contemporaneous nature of the 4IR. However, as Schwab (2016) argues, a better understanding of how emerging trends may foster sustainable outcomes is a necessary way forward. This necessitates the analysis of multiple, emerging and contemporary technological advancements and their repurcussions on wider societal systems (Köhler *et al.*, 2019).

2.4 CHAPTER 2 CONCLUSION

In this chapter a contextualisation of STTs and the 4IR has been presented. STTs literature has been presented with a backdrop of the STS context in Section 2.1. This has been done to give the reader a contextual understanding of the STTs origins from STS. The 4IR has been introduced and literature presenting sustainability discussions on the 4IR has also been highlighted. In the next chapter a systematic literature review is presented with the aim of examining the extent to which STTs and the 4IR have been jointly considered and analysed within academic literature.

CHAPTER 3: SYSTEMATIC LITERATURE REVIEW: METHODOLOGY AND BIBLIOMETRIC RESULTS

In this chapter, an introduction to the Systematic Literature Review (SLR) that was undertaken is presented. This includes the methodology and strategy of the SLR as well the results obtained from a bibliometric analysis of the documents. The chapter begins with Section 3.1 in which an overview of the methodology undertaken for the SLR is presented. Subsequently, Section 3.2 presents the bibliometric analysis - which is also published in an article in the Southern African Journal for Industrial Engineering's 30th Special Edition (Asiimwe & de Kock, 2019). The bibliometric analysis is conducted on all documents obtained from the SLR search. Thereafter, the selection criteria part of the SLR methodology and applied on all the documents is presented in Section 3.3. This criterion is applied to obtain suitable literature for information and deductions utilised for this research which are later presented Chapter 4. Section 3.4 concludes the chapter.

3.1 SYSTEMATIC LITERATURE REVIEW METHODOLOGY: INTRODUCTION

An SLR is defined as a replicable and transparent process of analysing literature which enables one to exhaustively identify, evaluate, analyse and interpret literature relevant to a particular topic, and thereby minimizing bias (Bryman & Bell, 2011; Budgen & Brereton, 2006). The SLR is employed in this research as it is argued to be suitable for analysing different concepts within literature where the end target of the research may be to synthesize or integrate said concepts through research products such as models and frameworks (Bryman & Bell, 2011; Budgen & Brereton, 2006; Jabareen, 2009). An SLR is advantageous in such a case as it enables the researcher to obtain objective literature on the concepts at hand with minimal bias (Bryman & Bell, 2011). Budgen & Brereton (2006) further argue that SLRs are favourable and beneficial because they are structured with a clear set of procedures and enable the researcher to have a better quality of review and evaluation thereby increasing the quality of their output. The SLR approach for literature analysis is thus employed in this research with two main objectives as recommended by (Bryman & Bell, 2011) to:

i. Be methodological, thereby being objective in the procedure followed. The aim in this is to ensure a minimization of personal biases; and
ii. Allow for consistency and repeatability/replicability of the SLR process.

3.1.1 STRATEGY

Xiao & Watson (2019) specify three phases in the process of conducting the review. These are:

i. Planning the review;
ii. Conducting the review; and
iii. Reporting outcomes of the review.

These are employed as the overarching guide in the review documentation. Furthermore the following steps from Xiao & Watson (2019) and Budgen & Brereton (2006) are employed commonly across research regarding the methodology of conducting a SLR:

i. Employ a defined search;
ii. Document search strategy;
iii. Specify information to be obtained from the studies;
iv. Specify explicit inclusion and exclusion criteria for primary studies;
v. Specify quality criteria for evaluating primary studies;
vi. Search the literature;
vii. Apply inclusion and exclusion criteria;
viii. Apply quality criteria;
ix. Extract the necessary data;
x. Analyse and synthesize the data;
xi. Report the findings; and
xii. Employ a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram (Model Systems Knowledge Translation Center, 2019)

The detailed step-by-step methodology employed for this research's SLR is illustrated and presented in Figure A.1 in the Appendix. The search strategy and terms employed in the methodology are as presented in Section 3.1.2. Criteria utilised is defined and presented in Section 3.3. The initial PRISMA diagram utilised in documenting the process is also presented in Figure A.2 in the appendix while a final diagram showing the results obtained is presented in Figure 20.

The overarching phases for conducting the SLR by Xiao & Watson (2019) are as listed in the previous Section i.e., planning the review, conducting the review, and reporting outcomes from the review. Table 6 below presents the phases with the reported steps undertaken in each phase. These steps form part and parcel of the detailed SLR process documented in Figure A.1 in Appendix A.

Table 6: SLR phases

	Planning review	Conducting the review	Reporting outcomes
Conducted	Define search keywords (refer to Table 8) Define search strategy (refer to Section 3.1.1, Table 9) Define inclusion and exclusion criteria (refer to Section 3.3.1) Define quality criteria (refer to Section 3.3.2)	Conduct SLR search Apply inclusion and exclusion criteria. Analyse bibliometric data of obtained documents. Apply quality criteria. Analyse the content in documents. Review the methodology	Bibliometric analysis (refer to Section 3.2) Content analysis (refer to Chapter 4 Sections 4.1 and 4.2) Gap analysis (refer to Chapter 4 Section 4.3) Methodology review (refer to Chapter 4 Section 4.5)

Furthermore, the following guiding questions are employed for the SLR:

i. **Q1:** How relevant is research on the integration of the concepts of the 4IR and STTs within the background context of sustainability/sustainable development and STS?
ii. **Q2:** How does literature jointly present and discuss the concepts of the 4IR and STTs?

iii. **Q3:** What themes and topics are discussed or emerge within literature in relation to these concepts?
iv. **Q4:** To what extent are these concepts considered together?
v. **Q5:** What are the gaps within literature in the integration of the 4IR and STTs? and
vi. **Q6:** What deductions may be made for an integration of the concepts within literature?

These questions are envisaged to guide the SLR process so as to obtain useful deductions for this research to fulfil research objective 2 presented in Section 1.2.1 and are answered throughout the subsequent sections in Chapters 3 – 4. Table 7 presents the relevant sections in which these guiding questions are addressed through findings in literature.

Table 7: Guiding questions review.

Code	Guiding question	Section addressed
Q1	How relevant is research on the integration of the concepts of the 4IR and STTs within the background context of sustainability/sustainable development and STS?	Chapter 3; Sections 3.2
Q2	How does literature present and discuss the concepts of 4IR and STTs?	Chapter 4 Sections 4.2 and 4.3.1.1
Q3	What themes and topics are discussed or emerge within literature in relation to these concepts?	Chapter 4 Sections 4.1.5, 4.2.1 and 4.2.2
Q4	How are these concepts considered together?	Chapter 4 Section 4.3.1.1
Q5	What are the gaps and disconnects within literature in the integration of both concepts?	Chapter 4 Section 4.3.2 and 4.3.1
Q6	What deductions may be made for an integration of the concepts within literature?	Chapter 4 Section 4.4

3.1.2 SEARCH TERMS

The SLR focuses on main concepts of STTs and the 4IR within the background context of sustainability or sustainable development, and STS. For the purposes of this research, literature pertaining to the concepts of sustainability and sustainable development, STS and transitions, sustainability transitions and 4IR is collected using Scopus. Scopus, in comparison to other databases such as Web of Science and Google Scholar, is reported to give more coverage, better consistency and accuracy as well as a wider range of journals (Falagas *et al.*, 2008). Criticisms of the database argue that it is limited to more recent articles (Falagas *et al.*, 2008). However, this is not a limitation for this particular research given the neoteric nature of STTs and the 4IR. Search terms included common variations of the term, where applicable, to ensure a comprehensive search.

Following this, it is important to note that for this particular research, the author uses the terms ‘transformations’ and ‘transitions’ interchangeably within the SLR for the sole purpose of comprehensiveness. As presented in the introduction to Section 2.2 and Section 2.2.1, it is understood that literature on STTs defines transitions and transformations as two different processes with transitions encompassing transformations. However, some literature argues that in some instances, a semantic interplay exists in the utilisation of these terms in different contexts dependent on the unit of analysis. For example, transitions occurring within various organisations or industries in a sector may lead to a sectoral system transformation, and a sector's transition may be viewed as a part of a global systemic transformation or transition (Elzen *et al.*, 2004). Given that these arguments point to the possibility of literature adopting the interchangeability of the terms, the author considered it worthwhile to encompass both terms in the search algorithms and thus ensure comprehensive coverage of STTs in the SLR search results. However, in the chapters following the SLR, the term transitions is exclusively used within its intended meaning for this research. Table 8 below shows the different variations of search terms employed.

Table 8: Search term variations where applicable

Term	**Variations**
Socio-technical	Sociotechnical; socio technical; socio-technical
Transition	Transition(s)/Transformation(s)
4IR	Fourth Industrial Revolution; Industry 4.0; 4^{th} Industrial Revolution; I4.0

Searches were done using combinations of sustainability and socio-technical terms with 4IR. This yielded five search categories that are each given a label as shown in Table 9 below:

Table 9: Search combinations and categories

Searches	**1**	**2**	**3**	**4**	**5**
Socio-technical systems	**x**				
Sustainability or sustainable development		**x**			
Socio-technical transition(s)/transformation(s)			**x**		**x**
Sustainability transition(s)/transformation(s)				**x**	**x**
AND					
4IR	**x**	**x**	**x**	**x**	**x**
Category labels	STS_4IR	S_SD_4IR	STT_4IR	ST_4IR	STT_ST_4IR

3.1.3 OVERALL SEARCH RESULTS

Table 10 below displays the search algorithms and the resulting document numbers from the prescribed search categories:

Table 10: Document results

Search Category Label	Scopus Algorithm	Number of documents obtained
S_SD_4IR	TITLE-ABS-KEY ((sustainability OR "Sustainable Development") AND ("Industry 4.0" OR "4th Industrial Revolution" OR "Fourth Industrial Revolution" OR I4.0))	249
STS_4IR	TITLE-ABS-KEY (("sociotechnical*" OR "socio-technical *" OR "socio technical *") AND ("Industry 4.0" OR "4th Industrial Revolution" OR "Fourth Industrial Revolution" OR I4.0))	42
STT_4IR	TITLE-ABS-KEY (((sociotechnical AND transition*) OR (socio AND technical AND transition*) OR (socio-technical AND transition*) OR (sociotechnical AND transformation*) OR (socio AND technical AND transformation*) OR (socio-technical AND transformation*)) AND ("Industry 4.0" OR "4th Industrial Revolution" OR "Fourth Industrial Revolution" OR "I4.0"))	35
ST_4IR	TITLE-ABS-KEY (((sustainability AND transition*) OR (sustainability AND transformation*)) AND ("Industry 4.0" OR "4th Industrial Revolution" OR "Fourth Industrial Revolution" OR "I4.0"))	7
STT_ST_4IR	TITLE-ABS-KEY (((sustainability AND transition*) OR (sustainability AND transformation*) OR (sociotechnical AND transition*) OR (socio AND technical AND transition*) OR (socio-technical AND transition*) OR (sociotechnical AND transformation*) OR (socio AND technical AND transformation*) OR (socio-technical AND transformation*)) AND ("Industry 4.0" OR "4th Industrial Revolution" OR "Fourth Industrial Revolution" OR "I4.0"))	42

As expected, the body of knowledge considering sustainability and sustainable development within the context of 4IR is wider than within the specific categories of STS and STTs or transformations. A closer look at the documents obtained showed that documents obtained within the STT_4IR and ST_4IR search categories are altogether returned in the STT_ST_4IR category. Subsequently, the author analysed only the documents obtained within the search categories S_SD_4IR, STS_4IR and STT_ST_4IR. In the following subsection, an overview of a comparative analysis of timelines, subject areas and publication origin regions between these search categories and highlights of key findings are presented. This analysis and the highlights constitute the bibliometric analysis.

3.2 BIBLIOMETRIC ANALYSIS

According to Iftikhar *et al.* (2019), a bibliometric analysis is defined as a statistical evaluation of published scientific literature in order to measure the influence of the publication within the scientific community. For this research, the analysis is conducted in order to gauge the quantitative extent of scientific research on the main concepts within the research. This is envisaged to inform and validate the relevance of undertaking the research and answer Q1 of the guiding questions (refer to Section 3.1.1). The bibliometric analysis is conducted on all literature obtained within the respective search categories presented in Table 9 above. Findings are reported in subsections 3.2.1— 3.2.3 and include the timeline of publications to assess novelty of concepts, common subject areas and geographic origins of the literature documents. As previously mentioned, these findings are also published in an article in the Southern African Journal for Industrial Engineering's 30th Special Edition (Asiimwe & de Kock, 2019).

3.2.1 TIMELINE OF PUBLICATIONS

Figure 16 below shows a comparison of the documents' publication years. It is shown that literature covering the joint consideration of 4IR within sustainability, STS and ST/STTs concepts is fairly recent. The first document is published within the twenty-first century and all other output up to the time this analysis was conducted has a 5-year time span. This is understandable given that a quick search on Scopus shows that the concept of 4IR although first written on in 1985 and later in 2006, has only been consistently considered within scientific literature output on Scopus since 2011.

As shown in Figure 16, the number of documents can be expected to continuously increase. For example; as of mid-2019, the number of documents published is just over half the number of documents released in 2018 within the S_SD_4IR category. Furthermore, there is an evident gap in STTs and STS literature concerning the 4IR as both have more than three times less the number of publications in the STS_4IR and STT_ST_4IR categories compared to the S_SD_4IR category. Interestingly, transitions literature in the STT_ST_4IR category appears to be increasing in more than parent STS literature in the STS_4IR, but this may indicate an increasing focus on the movement towards sustainability and sustainable development within academic literature.

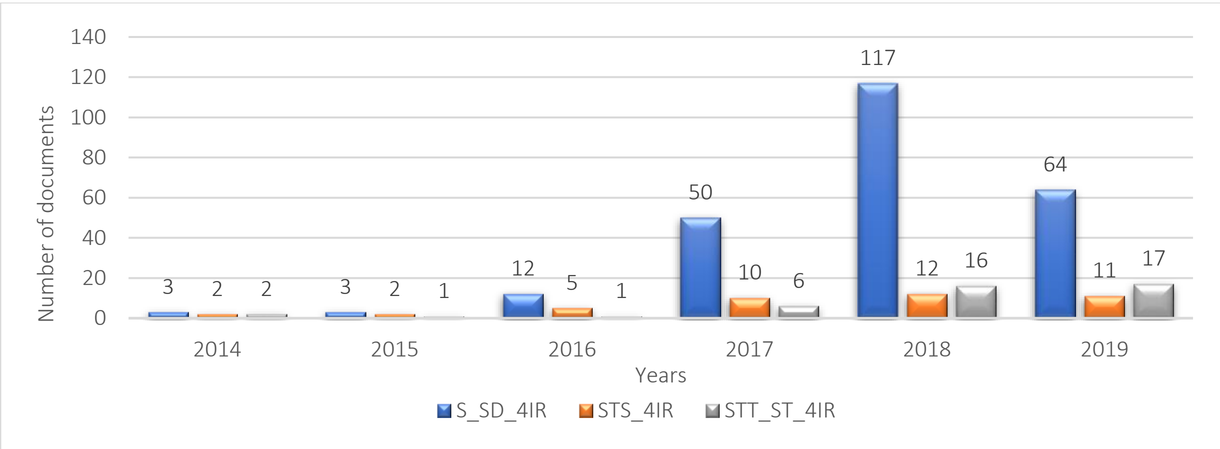

Figure 16: Documents published per year.

3.2.2 SUBJECT AREAS OF STUDY

The most common subject areas in the search categories are shown in Figure 17 below. The most common subject area overlapping all categories is Engineering. STS literature, however, has a higher output in computer science than sustainability/sustainable development and transitions literature. It is also observed that most of the literature is within the science field, with considerably less literature in the commerce and humanities fields. This highlights a technical focus in academical literature.

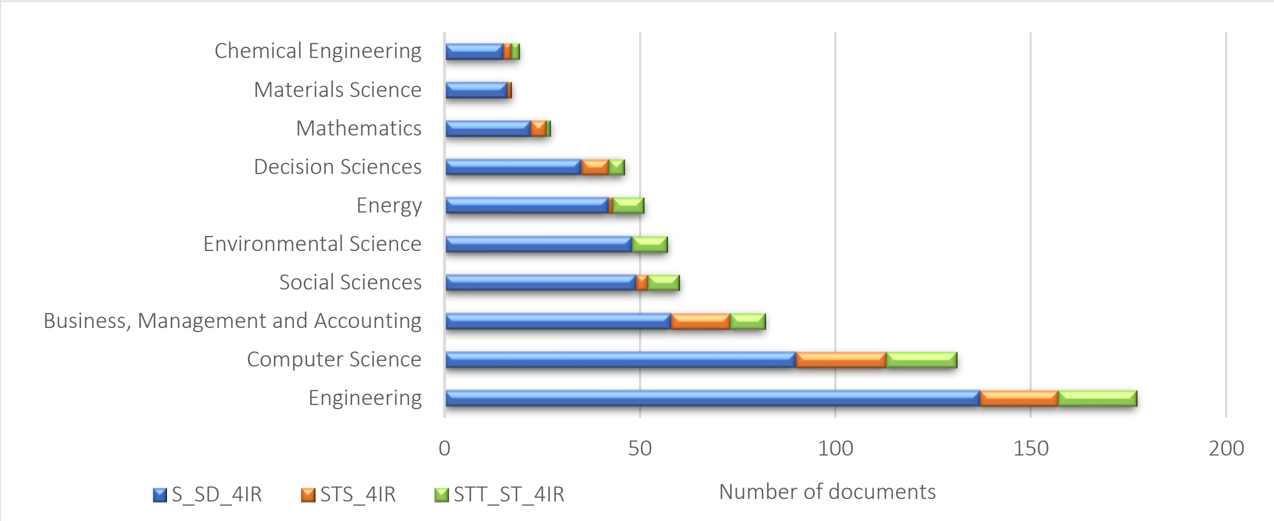

Figure 17: Subject areas of study

3.2.3 DOCUMENT GEOGRAPHIC ORIGINS

Most literature found in the search categories has origins in European continent. Europe has a considerably higher output than any other continent/region. This is a result of the European dominance of 4IR output confirmed in a Scopus search. Furthermore, Germany is found to have the highest output by country across all search categories. Nonetheless, as shown in Figure 18 below, there is a clear gap in research output from other world regions especially from Africa, the Middle East and Oceania.

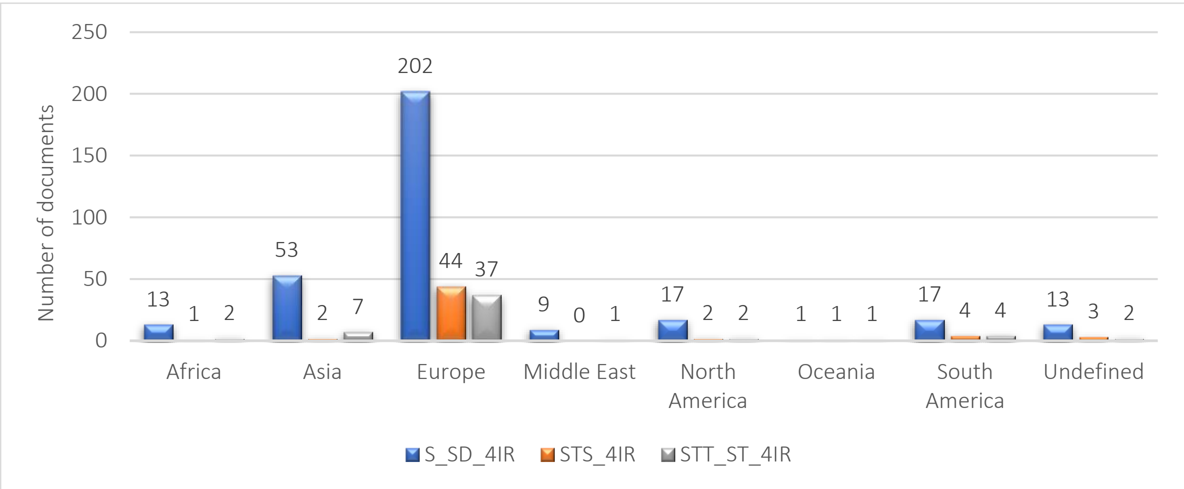

Figure 18: Region of origin of documents

In summary, highlights from subsections 3.2.1—3.2.3 showed that STTs and 4IR are fairly new in academic research, have a higher traction in the technical and science fields such as Engineering and lack better comprehensive coverage from the global research scene from all other continents compared to Europe. The results from this analysis validated the initial interest in STTs and the 4IR, as it is deduced that research on these concepts is relevant to the Engineering field and would contribute to the concepts' growing body of knowledge. Furthermore, research on STTs and the 4IR from a sub-Saharan African context is envisaged to make a valuable addition to the diversity of the global geographical research spectrum on the concepts.

3.3 SYSTEMATIC LITERATURE REVIEW METHODOLOGY: SELECTION CRITERIA

Following the bibliometric analysis, a content analysis was conducted to answer the second of the review questions i.e., *"to what extent have the concepts of sustainability, sustainability development and STS been jointly considered with the 4IR within literature".* Documents utilised in the content analysis underwent a filtering process as stipulated in the SLR methodology.

This section presents the methodology and criteria used to the filter SLR literature for the content analysis. Final documents analysed were selected from the STT_ST_4IR category as shown in Figure 19. A full list of the documents analysed from the category is presented in the Appendix A and the content analysis is presented later in Chapter 4. Descriptions of the criteria applied in assessing literature utilised within this research as well as the results of the applied SLR methodology are presented in subsections 3.3.1 and 3.3.2.

Search Category Label	Scopus Algorithm	Number of documents obtained
S_SD_4IR	TITLE-ABS-KEY ((sustainability OR "Sustainable Development") AND ("Industry 4.0" OR "4th Industrial Revolution" OR "Fourth Industrial Revolution" OR I4.0))	249
STS_4IR	TITLE-ABS-KEY (("sociotechnical*" OR "socio-technical *" OR "socio technical *") AND ("Industry 4.0" OR "4th Industrial Revolution" OR "Fourth Industrial Revolution" OR I4.0))	42
STT_4IR	TITLE-ABS-KEY (((sociotechnical AND transition*) OR (socio AND technical AND transition*) OR (socio-technical AND transition*) OR (sociotechnical AND transformation*) OR (socio AND technical AND transformation*) OR (socio-technical AND transformation*)) AND ("Industry 4.0" OR "4th Industrial Revolution" OR "Fourth Industrial Revolution" OR "I4.0"))	35
ST_4IR	TITLE-ABS-KEY (((sustainability AND transition*) OR (sustainability AND transformation*)) AND ("Industry 4.0" OR "4th Industrial Revolution" OR "Fourth Industrial Revolution" OR "I4.0"))	7
STT_ST_4IR	TITLE-ABS-KEY (((sustainability AND transition*) OR (sustainability AND transformation*) OR (sociotechnical AND transition*) OR (socio AND technical AND transition*) OR (socio-technical AND transition*) OR (sociotechnical AND transformation*) OR (socio AND technical AND transformation*) OR (socio-technical AND transformation*)) AND ("Industry 4.0" OR "4th Industrial Revolution" OR "Fourth Industrial Revolution" OR "I4.0"))	42

Figure 19: SLR full text documents analysed.

3.3.1 INCLUSION/EXCLUSION CRITERIA

Xiao & Watson (2019) specify the establishing of inclusion and exclusion criteria to achieve effectiveness when conducting an SLR. According to Xiao & Watson (2019), the criteria should be practical thus enabling the researcher to filter for literature that is not related to the topics on hand. Because this SLR's search generated only 42 documents for analysis, a more lenient set of exclusion/inclusion criteria is applied to enable maximum comprehensiveness for full texts analysed. The criteria is applied to all documents preceding the full text analysis and is presented as follows:

i. Documents whose abstracts had some reference STTs, STS, the 4IR, sustainability and sustainable development are included in the analysis;
ii. Documents whose full text is presented in any other language other than English are excluded; and

iii. Documents whose full text is unavailable are inevitably excluded from the analysis.

As can been seen in Figure 20, eight documents were excluded based on the above criteria. Proceeding from this, all other thirty-four documents that meet the above criteria had their full texts analysed to answer Q2 and Q3 of the SLR guiding questions. The results of this analysis are presented in Section 4.1.

3.3.2 QUALITY CRITERIA

Following the inclusion and exclusion criteria, quality criteria was applied to all full texts obtained in order to further filter the document's content for the final literature synthesis and gap analysis. Given the aim and focus of this research as presented in Section 1.2, full texts included in the finer content and gap analysis are specified to have possessed the following characteristics:

i. Socio-technical perspective: Full texts should hold an STS approach either in applied or core theory in relation to the context of the document;
ii. STTs: Full texts should examine transitions or transformations from an STS context.
iii. 4IR leverage: The 4IR should be analysed within the document's or applied with the aim of achieving some specified sustainability target or sustainable development goal; and
iv. Sustainability or sustainable development: Full texts should have a holistic consideration for sustainability and sustainable development targets, preferably at a macro level analysis and in all sustainability dimensions.

Full texts analysed are considered for the literature synthesis if they held a combination of all the above characteristics. All thirty-four full texts obtained after the application of inclusion/exclusions criteria were filtered using the quality criteria. The result of this filtering process, as can be seen in Figure 20 below, was six documents.

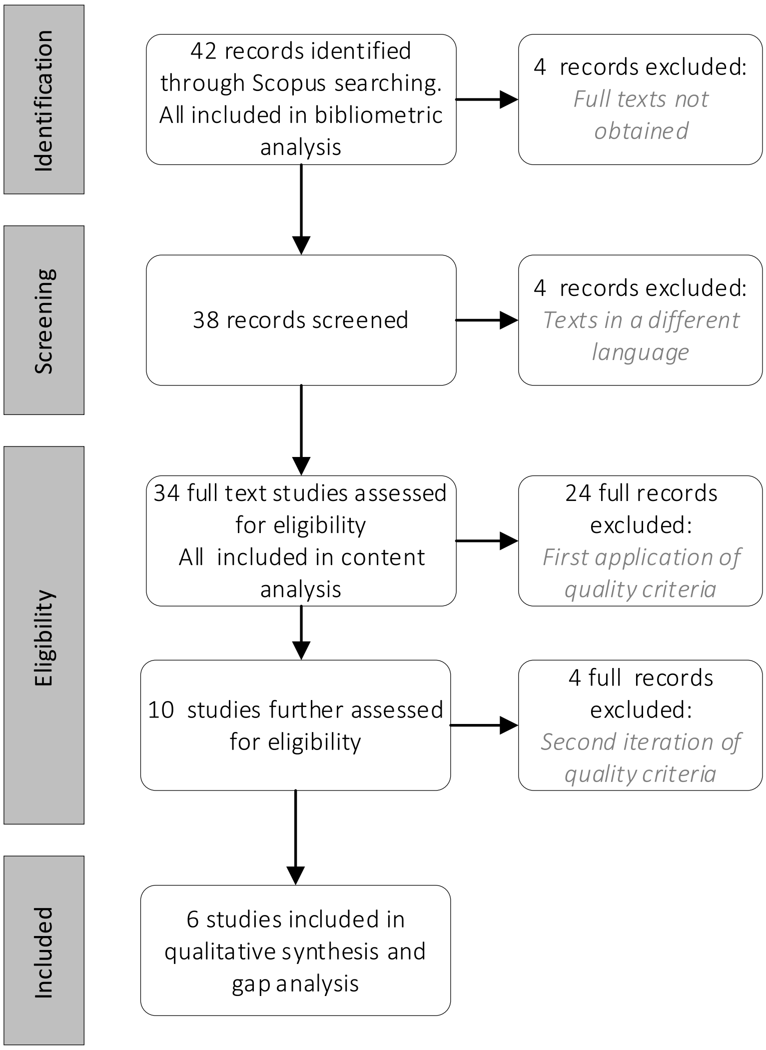

Figure 20: PRISMA diagram summarising SLR document selection process

A content analysis of the final six documents is presented in Chapter 4 Section 4.2.

3.4 CHAPTER 3 CONCLUSION

In this chapter the SLR has been introduced. The methodology utilised has been presented as well as the initial search results in the form of a bibliometric. From the analysis, it is observed that the study of STTs and the 4IR within the background context is of contemporary relevance. Results show a growing body of knowledge, relevant within the engineering field and with potential to expand and include more research input from the wider global research scene. In the next chapter, the second part of the SLR is presented through a content analysis to answer Q2, Q3 and Q4 of the SLR guiding questions (refer to Section 3.1.1). Lastly, a gap analysis conducted to compare content findings from the SLR to the contextualisation literature is be presented to answer Q5 of the SLR guiding questions.

CHAPTER 4: CONTENT AND GAP ANALYSIS

In this chapter, a continuation of the SLR findings is presented. As previously discussed, research objective 2 of this research is to investigate the extent to which STTs and the 4IR have been jointly analysed within literature (refer to Section 1.2.1). From the bibliometric analysis, it is evident that there is room for growth within the body of literature pertaining to STTs and the 4IR. SLR findings presented in this chapter in the form of a content analysis in Sections 4.1 and 4.2. Findings in the content analysis analysed against literature presented in the contextualisation to present a gap analysis in Section 4.3. Furthermore, a construct guidance in the form of deductions from the gap analysis, for the envisaged research product is presented in Section 4.4.

4.1 CONTENT ANALYSIS FROM ALL DOCUMENTS

A content analysis is first conducted on all full text documents within the STT_ST_4IR search category (as presented in Section 3.1.2) after inclusion/exclusion criteria is applied, prior to the quality assessment. This is done in order to answer the SLR guiding questions Q2 i.e., "*how does literature jointly present and discuss the concepts of the 4IR and STTs?*" and Q3 i.e., "*what themes and topics emerge within literature in relation to these concepts?*" as presented in Section 3.1.1. Furthermore, the content analysis is done in order to discover the breadth of the studies obtained (Xiao & Watson, 2019). To begin, it is envisaged to determine initial emerging themes and links within literature so as to determine an initial overview of connections and key themes that may be encountered while analysing the documents. For this purpose, VOSviewer software is utilised.

The author selected a network configuration showing author and index keyword co-occurrence links from the literature found as best suited to determine themes and links. For a more comprehensive picture, a minimum word occurrence of two is chosen as well as a minimum link strength of one, which means that each keyword should have at least been linked with another once. A total of fifty-four keywords met the threshold and are displayed in Figure 21 below. From these, seven clusters are identified categorizing keywords, in red, green, darker blue, yellow, purple, lighter blue and orange. Cluster descriptions are not offered by VOSviewer software and an attempt at forming descriptions for the classification by analysing cluster keyword source documents for similarities proved futile due to the limited number of documents. Nonetheless, a few noteworthy keyword categorisations are deduced and confirmed within the analysis of literature. There are presented below:

i. Major overarching concepts highlighted in the keywords include 4IR, sustainability, sustainable development, digital transformation, digitalisation, the triple bottom line, innovation, circular economy, internet and socio-technical. These concepts are related to one other through the concepts of sustainability, STS and 4IR and are further highlighted in Section 4.1.3;
ii. Key industry applications include manufacturing, learning factories, production industries and systems, risk management, management practice, supply chain management, planning, logistics and environmental technologies. These are further discussed in Section 4.1.4;

iii. Main 4IR technologies found within keywords include internet of things (IoT) and cyber physical systems (CPS). These especially have links in the production and manufacturing applications. These are expounded on in Section 4.1.4;

iv. Other disciplines and related techniques include simulation and optimisation, systems engineering, information systems and economics; and

v. The methodologies highlighted in the network includes literature reviews, conceptual frameworks, and maturity models.

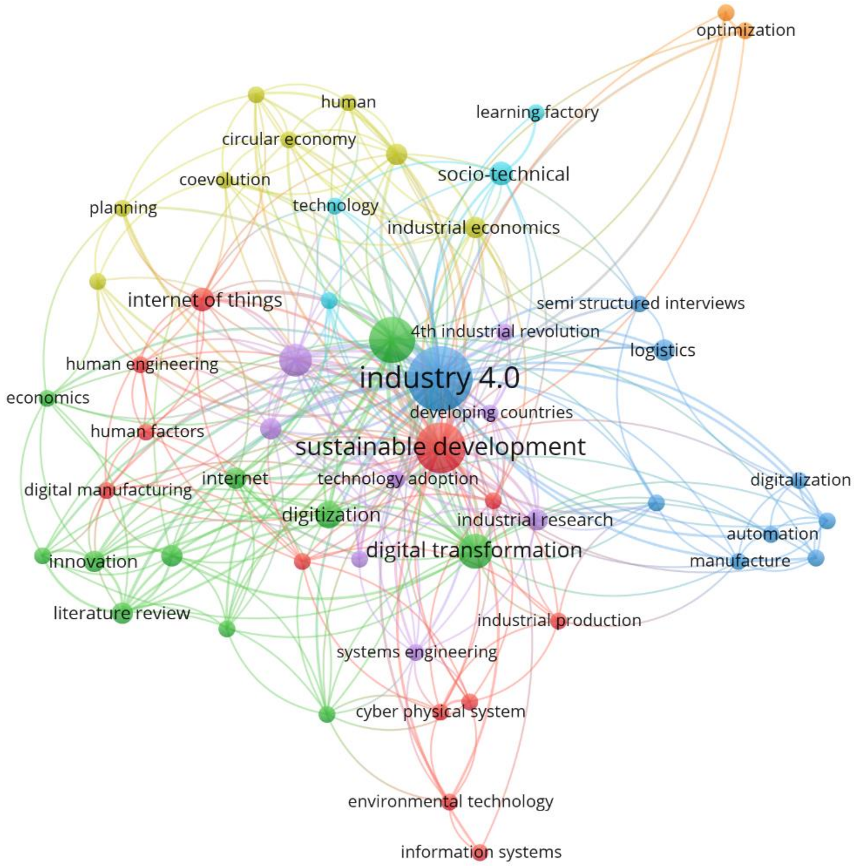

Figure 21: Keyword networks (created with VOSviewer)

For further understanding of the software, the author recommends reviewing van Eck & Waltman (2014, 2016) and Erasmus University Rotterdam (2019). Following this, content within the documents was analysed using ATLAS.ti software. All documents titles and their assigned codes in ATLAS.ti are presented in Table A.1 in the Appendix A. The following subsections highlights key findings from the analysis in ATLAS.ti.

4.1.1 STUDY METHODOLOGIES

Documents analysed present various methods for gathering data and output within their respective studies. Figure 22 and Figure 23 below show the various methodologies utilised within the scope of documents. As can be seen, case studies and literature reviews served as the most common methodologies for gathering qualitative input data for studies.

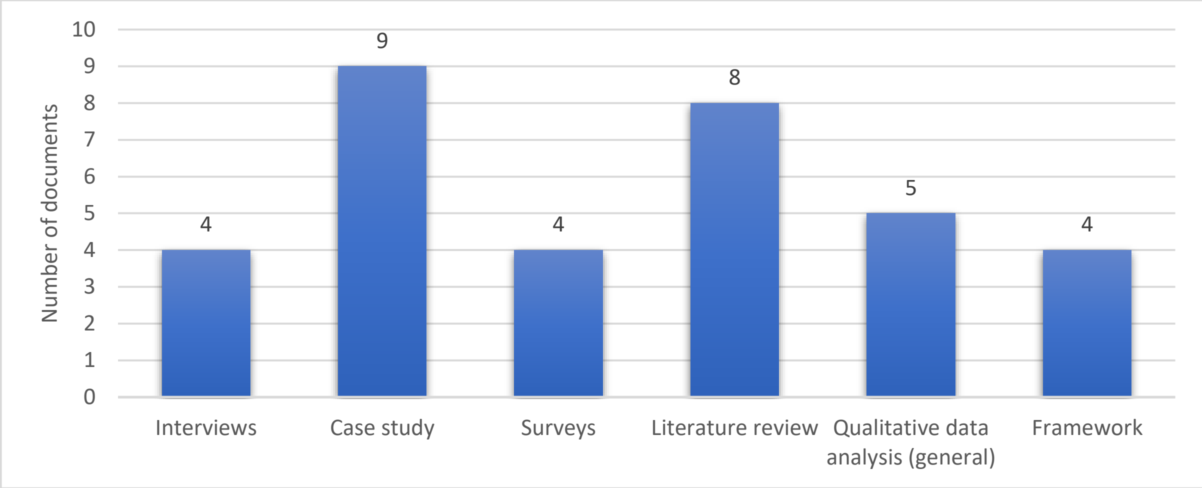

Figure 22: Literature input methodologies

The most common output from most studies is conceptual frameworks; constituting over 50% for all studies that gave output using a defined methodology.

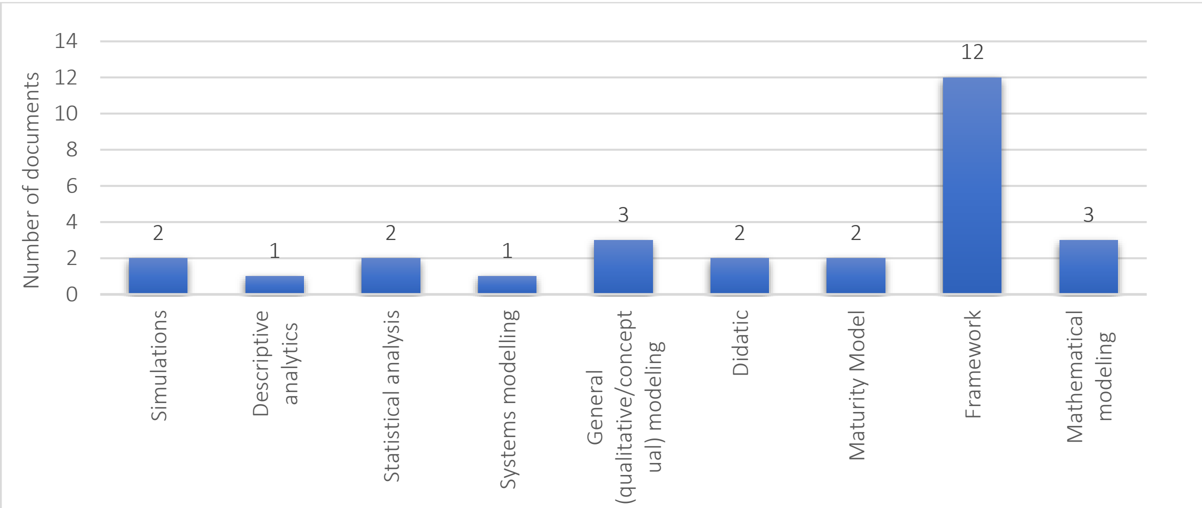

Figure 23: Literature output methodologies

Output frameworks constituted readiness assessment frameworks (Manavalan & Jayakrishna, 2019), policy frameworks for the adoption of 4IR technologies (Lin *et al.*, 2017), strategic frameworks for the implementation of 4IR technologies and concepts (Alrabhi, 2018; Brenner, 2018; Paravizo *et al.*, 2018; Villar-Fidalgo *et al.*, 2018), risk frameworks (Birkel *et al.*, 2019) and application of 4IR technologies and concepts within various industrial sectors and organisations (Bressanelli *et al.*, 2018; Martín-Gómez *et al.*, 2019; Mazzetto *et al.*, 2019; Nascimento *et al.*, 2019; Papetti *et al.*, 2018).

4.1.2 GEOGRAPHICAL REGIONS ANALYSED IN LITERATURE

Figure 24 below displays the regions assessed within the documents, where applicable. These include areas from which case studies are derived and areas in which interviews are conducted for the qualitative data derived for their respective studies.

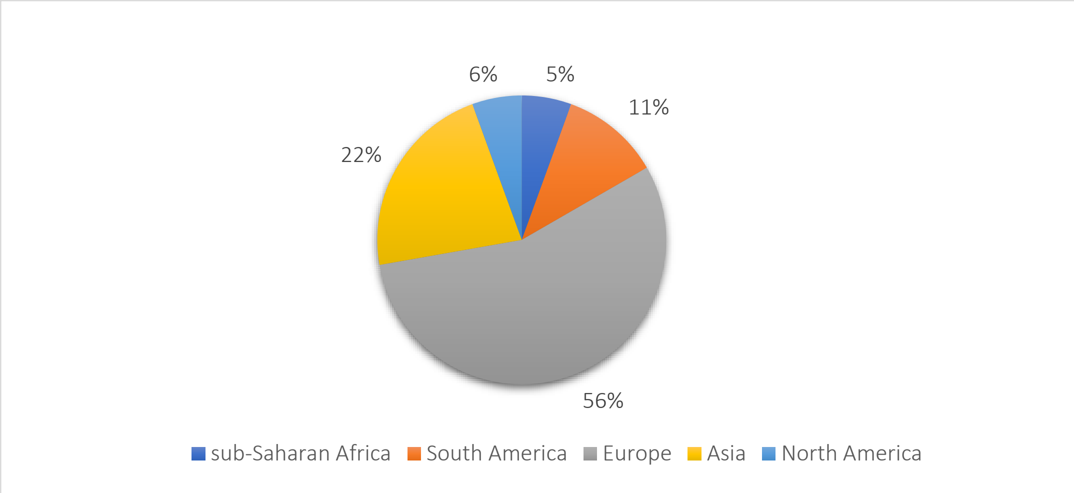

Figure 24: Regions assessed in literature.

It is observed that although literature presents a general gap for the analysis of STTs, STS, the 4IR, sustainability and sustainable development within all regions, there is a comparably larger need in all other regions outside of Europe.

4.1.3 KEY POINTS OF DISCUSSION

It was observed that various points of discussions are presented in the analysis of STTs, the 4IR, STS and sustainability/sustainable development. Table 11 presents key topics, their relation to the concepts of STTs, the 4IR, STS and sustainability/sustainable development, topic descriptions deduced from literature and references to documents that discuss the topics.

Table 11: Emerging themes in study concepts

Concept	Discussion point	Description	References
Sustainability/Sustainable development	Triple Bottom Line	Organisational or company perspective of the three dimensions of sustainability (People, Planet and Profit).	(Birkel *et al.*, 2019),(Savastano *et al.*, 2019)
	Circular economy	System design that aims at utilising products, components and materials for their highest value through closed loop cycles of reuse and recycling. Concept is prominently assessed and applied in literature within a manufacturing/industrial product perspective.	(Bressanelli *et al.*, 2018; Garcia-Muiña *et al.*, 2018; Martín-Gómez *et al.*, 2019; Nascimento *et al.*, 2019)
	SDGs	The 17 UN directives on achieving global sustainable development. Argued in literature as necessities for steering global economies towards achieving sustainability within its three dimensions.	(Paravizo *et al.*, 2018), (Garcia-Muiña *et al.*, 2018; Stock *et al.*, 2018)

Concept	Discussion point	Description	References
	Environmental sustainability	Conservation and preservation of the ecological system stemming from an awareness of the environment, the resources and human consumption dependent on it. Literature characterises activities within this dimension to have targets such as reduction of greenhouse gas emissions, pollution, waste, adoption of renewable energy sources.	(Birkel *et al.*, 2019; Bressanelli *et al.*, 2018; Garcia-Muiña *et al.*, 2018; Hidayatno *et al.*, 2019; Kayikci, 2018; Müller *et al.*, 2018; Nascimento *et al.*, 2019; Stock *et al.*, 2018; Świątek, 2019)
	Economic sustainability	Pertaining to upholding economic competitive advantage, value creation, efficient markets and profitability while conserving resources and increasing quality of life.	(Birkel *et al.*, 2019; Brenner, 2018; Garcia-Muiña *et al.*, 2018; Hamidi *et al.*, 2018; Hidayatno *et al.*, 2019; Mazzetto *et al.*, 2019; Müller *et al.*, 2018; Nascimento *et al.*, 2019; Papetti *et al.*, 2018; Rahman *et al.*, 2019; Stock *et al.*, 2018)
	Social sustainability	Meeting society's basic access needs safely and supporting good lifestyles across the various demographic categorisations.	(Birkel *et al.*, 2019; Garcia-Muiña *et al.*, 2018; Manda & Dhaou, 2019; Müller *et al.*, 2018; Nam, 2019; Nascimento *et al.*, 2019; Papetti *et al.*, 2018)
4IR	Digitalisation/ Digitization	These terms are used interchangeably in most literature. However, Savastano et al. (Savastano *et al.*, 2019) distinguishes between the two, describing digitisation as capturing analog information to digital formats and digitalisation as when the process of digitisation is leveraged for business process benefits. The processes of digitisation and digitalisation are used to describe the transformative effect of the 4IR in various fields.	(Garcia-Muiña *et al.*, 2018; Kayikci, 2018; Mazzetto *et al.*, 2019; Savastano *et al.*, 2019; Scharl & Praktiknjo, 2019)
	Digital transformation	Implementation stage in the processes of digitalisation/digitisation. Often described in literature as the implementation process of 4IR.	(Hamidi *et al.*, 2018; Kayikci, 2018; Müller *et al.*, 2018; Savastano *et al.*, 2019)
	Knowledge management	Transformation of raw data into useful information. Emerges within the 4IR due to Big	(Conrad *et al.*, 2019; Mazzetto *et al.*, 2019)

Concept	Discussion point	Description	References
		Data and Analytics, supported by existing Information Systems.	
	4IR Technologies	4IR focuses on the digitisation and digitalisation of end-to-end systems through various technologies. The main 4IR technologies presented include Internet of Things (IoT), Cyber Physical Systems (CPS), Big Data and Analytics, Smart "Things", Digital Twins, Cloud Computing and blockchain technologies. Literature highlights, analyses and discusses the potential of these technologies within a variety of industrial sectors.	(Alrabhi, 2018; Birkel *et al.*, 2019; Brenner, 2018; Bressanelli *et al.*, 2018; Garcia-Muiña *et al.*, 2018; Hamidi *et al.*, 2018; Kayikci, 2018; Lin *et al.*, 2017; Manda & Dhaou, 2019; Mazzetto *et al.*, 2019; Müller *et al.*, 2018; Nascimento *et al.*, 2019; Papetti *et al.*, 2018; Paravizo *et al.*, 2018; Savastano *et al.*, 2019; Scharl & Praktiknjo, 2019; Sjödin *et al.*, 2018; Wong *et al.*, 2018)
Socio-technical systems and transitions	T-O-P	T-O-P stands for Technology, Organisation, and People; and is an organisational socio-technical approach that underlines the interactions between people and technology as equally important and inter-dependent within an organisation.	(Conrad *et al.*, 2019; Reuter *et al.*, 2017)
	Transformations	Transformations in literature denote movements of systems from one [unsustainable] mode of operation to another [often more sustainable] mode of operation. Most of literature focuses on organisation/industrial business systems transformation through digital transformation or as a response to changes in technology and innovation (Brenner, 2018; Garcia-Muiña *et al.*, 2018). Conversely, technology transformations are also referred to in literature as either the introduction of newer technologies or digital transformation and as a business sustainability approach (Lin *et al.*, 2017; Manda & Dhaou, 2019; Martín-Gómez *et al.*, 2019). In fewer cases, transformation is referred to in cases of global systems towards the achievement of sustainable development (Manda & Dhaou, 2019).	(Brenner, 2018; Garcia-Muiña *et al.*, 2018; Hamidi *et al.*, 2018; Lin *et al.*, 2017; Manda & Dhaou, 2019; Martín-Gómez *et al.*, 2019; Müller *et al.*, 2018; Sjödin *et al.*, 2018; Stock *et al.*, 2018)

4.1.4 FIELD/INDUSTRY APPLICATION

It is observed that literature held mainly two levels of analysis within the research conducted. These levels are micro and macro level analyses. Micro level analysis refers to the perspective in which literature analyses the key concepts of sustainability, 4IR, STS and transitions thereof from a firm, organisational or specific industrial field level whereas literature that held a macro level analysis analysed and discussed the key concepts from a global or national systemic level.

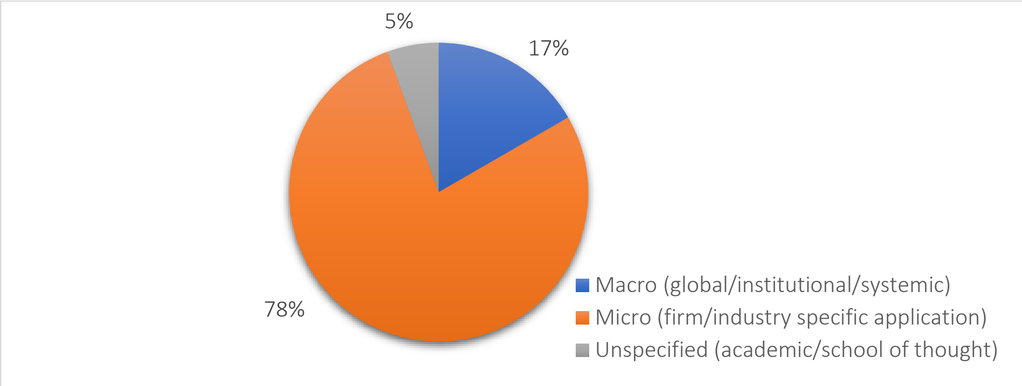

Figure 25: Level of analysis

As can be observed in Figure 25, a majority of the documents reviewed, analyse and discuss literature from a micro level or perspective. Various industrial sectors are considered within this perspective. Figure 26 below indicates all the various sectors (where defined) within which the published research is conducted and the number of documents pertaining to that sector. As can be observed and noted, a majority of the research conducted is within the manufacturing sector.

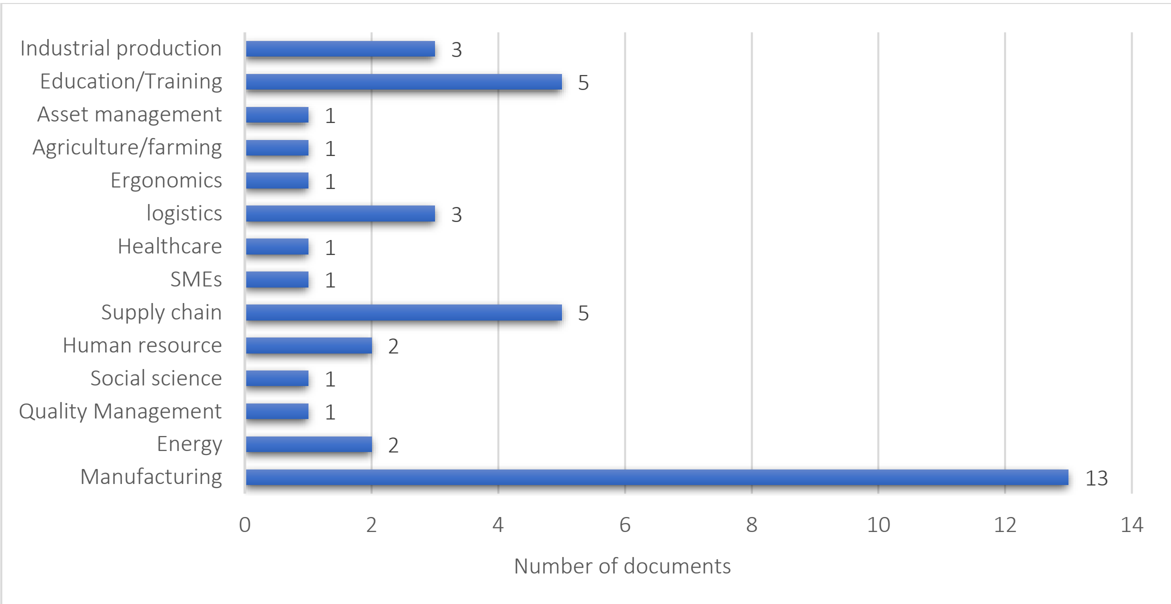

Figure 26: Industrial sectors relative to or applied in the study.

Furthermore, the potential of the various 4IR technologies is applied to some fields/sectors in literature. Table 12 below describes some of the technologies highlighted in the literature analysed. It is observed that a majority of the technologies analysed are within the manufacturing sector.

Table 12: 4IR related technologies identified and applied to industrial sectors within literature.

4IR Technology	Industrial field/sector applied	Reference
Cyber Physical Systems	Manufacturing	(Birkel *et al.*, 2019; Garcia-Muiña *et al.*, 2018; Papetti *et al.*, 2018; Paravizo *et al.*, 2018; Stock *et al.*, 2018)
	Supply chain	(Manavalan & Jayakrishna, 2019; Martín-Gómez *et al.*, 2019)
	Agriculture	(Mazzetto *et al.*, 2019)
	Asset Management	(Manda & Dhaou, 2019; Villar-Fidalgo *et al.*, 2018)
	Energy	(Scharl & Praktiknjo, 2019); Ergonomics (Papetti *et al.*, 2018)
Internet of Things	Manufacturing	(Bechtsis *et al.*, 2017; Bressanelli *et al.*, 2018; Garcia-Muiña *et al.*, 2018; Paravizo *et al.*, 2018; Stock *et al.*, 2018)
	Supply chain	(Manavalan & Jayakrishna, 2019)
	SMEs	(Hamidi *et al.*, 2018)
Big Data and analytics	Manufacturing	(Bressanelli *et al.*, 2018; Conrad *et al.*, 2019; Garcia-Muiña *et al.*, 2018; Müller *et al.*, 2018; Nascimento *et al.*, 2019; Stock *et al.*, 2018)
	Energy	(Scharl & Praktiknjo, 2019)
	SMEs	(Hamidi *et al.*, 2018)
	Supply chain	(Kayikci, 2018)
	Health care	(Wong *et al.*, 2018)
	Asset management	(Manda & Dhaou, 2019)
	Human resource	(Alrabhi, 2018)
	Logistics	(Alrabhi, 2018; Kayikci, 2018)
Smart "things"	Manufacturing	(Müller *et al.*, 2018; Savastano *et al.*, 2019; Sjödin *et al.*, 2018)
	Supply chain	(Kayikci, 2018)
	SMEs	(Hamidi *et al.*, 2018)
Digital Twins	Manufacturing	(Stock *et al.*, 2018)
Cloud computing	Manufacturing	(Stock *et al.*, 2018)
	Agriculture	(Bechtsis *et al.*, 2017)
	Supply chain	(Kayikci, 2018)
Additive manufacturing	Manufacturing	(Nascimento *et al.*, 2019)

4IR Technology	Industrial field/sector applied	Reference
Block chain technologies	Health care	(Wong *et al.*, 2018)

4.1.5 OTHER EMERGING TOPICS WITHIN LITERATURE

Furthermore, other topics of discussion emerge in literature within the micro and macro levels of analysis mentioned in Section 4.1.4. These are discussed in the following subsections:

4.1.5.1 POLICY

Policy within literature is addressed at a macro level. Literature highlights that policy is needed in light of 4IR towards the readiness, adoption and implementation of new technologies for systemic transformation. Governing bodies are urged to draft and enact policies that address concepts such as innovation management, investment and incentive allocation for innovation, legislation of cybersecurity and transparency, legislative reforms and readiness for technology adoption (Hidayatno *et al.*, 2019; Lin *et al.*, 2017; Manda & Dhaou, 2019; Scharl & Praktiknjo, 2019).

4.1.5.2 STRATEGY

Strategy is covered at both macro and micro levels and is addressed at the implementation of 4IR technologies towards achieving multiple sustainability targets and sustainable development goals. At a macro level, literature highlights the need for a national innovation strategy (Lin *et al.*, 2017) and the need for strategies for implementation in the various industrial sectors (Hidayatno *et al.*, 2019) to achieve sustainability within the three dimensions. It is urged that strategy should offer guiding points to governing bodies on how to respond to digital demands and needs (Manda & Dhaou, 2019). Furthermore, knowledge management is highlighted as a useful component in strategy (Hamidi *et al.*, 2018).

At a micro level of analysis (e.g., with firms or organisations), strategy is driven towards readiness and competitiveness for business sustainability. Literature, therefore, highlights business model innovation and innovation management as the main points for strategic differentiation in light of the 4IR paradigm (Hamidi *et al.*, 2018).

4.1.5.3 INNOVATION

At both macro and micro levels, 4IR presents various opportunities for product, process ad policy innovation (Lin *et al.*, 2017; Manda & Dhaou, 2019; Sjödin *et al.*, 2018). In themselves, technologies within the 4IR wave are regarded as technological innovations while they simultaneously create opportunities for innovations in various systems. Some literature argues that sustainability is a key driver for innovation and also conversely, innovations drive system transformation towards more sustainable states (Garcia-Muiña *et al.*, 2018; Nascimento *et al.*, 2019). These views are primarily held within the context of analysing technology with a circular economy perspective. Literature also acknowledges the interconnectedness between innovation and the external environment within which it occurs. This includes the labour force, academia, financial institutions and regulatory bodies (Brenner, 2018).

At a micro level, innovation is highlighted towards the achievement of organisational sustainability goals such as business sustainability through process innovation (Sjödin *et al.*, 2018), business model innovation for competitiveness and profitability (Brenner, 2018; Garcia-Muiña *et al.*, 2018; Nascimento *et al.*, 2019) and social/work place innovation for workers and employees (Liboni *et al.*, 2019; Nam, 2019; Papetti *et al.*, 2018; Paravizo *et al.*, 2018; Reuter *et al.*, 2017).

4.1.5.4 BUSINESS MODELS AND VALUE CREATION

Transformation of business models through innovation is a key highlight within literature. Literature suggests this is as a result of the changing technological environment and companies'/organisations' need to stay competitive and profitable in light of the changing economic climate. Regarding this, literature presents concepts such as servitization (which is described as the transformation of products from physical goods into a product-service offering (Brenner, 2018; Garcia-Muiña *et al.*, 2018)). This hinges off the opportunity to utilise a variety of technologies such as Big Data and analytics in order to improve service offering, meet customer needs and resilient revenue streams (Brenner, 2018; Bressanelli *et al.*, 2018; Garcia-Muiña *et al.*, 2018). Interestingly, some literature such as Bressanelli *et al.* (2018) and Garcia-Muiña *et al.* (2018) present this concept in tandem with a discussion on the concept of circular economy. Transformative capacity within organisations is argued for both as a result and driver for business model innovation which results in greater product and process innovations that effectively transpire into value creation and business sustainability for companies (Brenner, 2018; Müller *et al.*, 2018; Savastano *et al.*, 2019).

4.1.5.5 WORK AND EMPLOYMENT

The topic of jobs and employment formed part of the key discussions regarding the 4IR and sustainable development within the social dimension of literature analysed. The literature addresses and discusses concerns and speculation surrounding technologies within 4IR replacing human functioning within certain work-place environments and rendering certain jobs obsolete (Manda & Dhaou, 2019; Nam, 2019). However, counter-arguments emerge from at a micro-level of analysis, discussing the need to upskill or reskill the workforce and modify or re-orientate the workplace in order to favour and provide new opportunities for human employment given the new technological wave (Conrad *et al.*, 2019; Garcia-Muiña *et al.*, 2018; Hamidi *et al.*, 2018; Liboni *et al.*, 2019; Papetti *et al.*, 2018; Rahman *et al.*, 2019). Furthermore, 4IR technologies are also argued to have the potential for usefulness in creating safer environments for workers, especially in the manufacturing setting (Papetti *et al.*, 2018).

4.2 CONTENT ANALYSIS OF THE FINAL DOCUMENTS

In this section, a second part of the content analysis is presented. This part of the content analysis focuses primarily on the literature's understanding of the concepts of STTs and the 4IR to further answer questions Q2 and Q3 of the SLR. Documents included in this part of the analysis are the final SLR full text documents after quality criteria is applied. After reviewing all full texts obtained from the SLR search after exclusion criteria, quality criteria was applied as specified in Section 3.3.2. Six final full texts were identified whose content addressed the main concepts. The detailed selection of these 6 documents is presented in Table B.1 in Appendix B. The final 6 documents obtained are highlighted in Table 13 below.

Table 13: 6 Eligible documents for final full text analysis

No.	Title and reference	Authors	Document focus	Year	Type	ATLAS.ti Code
1	A cross-strait comparison of innovation policy under Industry 4.0 and sustainability development transition (Lin *et al.*, 2017)	Lin K.C., Shyu J.Z., Ding K.	Policy and strategy: a comparison of China and Taiwan's policies on Industry 4.0.	2017	Article	D2
2	Industry 4.0 as enabler for a sustainable development: A qualitative assessment of its ecological and social potential (Stock *et al.*, 2018)	Stock T., Obenaus M., Kunz S., Kohl H.	General manufacturing and industrial production.	2018	Article	D36
3	Industry 4.0 technology implementation impact to industrial sustainable energy in Indonesia: A model conceptualization (Hidayatno *et al.*, 2019)	Hidayatno A., Destyanto A.R., Hulu C.A.	Energy and manufacturing; focus on Indonesia as a case study.	2019	Conference Paper	D37
4	A holonic framework for managing the sustainable supply chain in emerging economies with smart connected metabolism (Martín-Gómez *et al.*, 2019)	Martín-Gómez A., Aguayo-González F., Luque A.	Supply chain management	2019	Article	D45
5	Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: A business model proposal (Nascimento *et al.*, 2019)	Nascimento D.L.M., Alencastro V., Quelhas O.L.G., Caiado R.G.G., Garza-Reyes J.A., Lona L.R., Tortorella G.	Manufacturing	2019	Review	D51
6	Responding to the challenges and opportunities in the 4th industrial revolution in developing countries (Manda & Dhaou, 2019)	Manda M.I., Dhaou S.B.	South Africa	2019	Conference Paper	D54

The resulting 6 documents included Lin et al. (2017), Stock et al. (2018), Martín-Gómez et al. (2019), Nascimento et al. (2019), Manda & Dhaou (2019), and Hidayatno et al. (2019).

Lin et al. (2017) focus on policy reviews, presenting a generic sectorial comparative study on Industry 4.0 policies between China and Taiwan. Lin et al. (2017) highlights innovation policy and utilises an innovation policy framework for the analysis. This is formed on the basis that Industry 4.0 is a technological innovation and thereby assessing policy frameworks within the Chinese and Taiwanese contexts gives a holistic view of the impact on these countries' national systems. (Lin *et al.*, 2017)

Stock et al. (2018) conduct a qualitative assessment study on the potential of value creation in Industry 4.0 from an industry/sector level perspective and organisation specific perspective. Stock et al. (2018) highlights that although value creation is predominantly an economic sustainability benefit from Industry 4.0, it has the potential to contribute to other sustainability dimensions. Stock et al. (2018) incorporates a basic socio-technical perspective while setting the article's premise. (Stock *et al.*, 2018)

Martín-Gómez et al. (2019) integrate various frameworks for the three sustainability dimensions within and through supply chain management. Martín-Gómez et al. (2019) provide insights into the relationships between social metabolism, the circular economy and a holonic paradigm while utilising Industry 4.0 as an enabler. Nascimento et al. (2019) also integrates sustainability with supply chain management and the use of technologies that drive Industry 4.0 such as additive manufacturing and cyber physical systems as enablers with circular economy practices (Martín-Gómez *et al.*, 2019; Nascimento *et al.*, 2019).

Manda & Dhaou (2019) discuss the challenges and opportunities for Industry 4.0 in developing countries, using South Africa as a case study. Manda & Dhaou (2019) sets their premise from an applied STS perspective. Finally, Hidayatno et al. (2019) present a casual loop diagram integrating the three sustainability dimensions with a technological factor. With this, the argument is presented that revolutions and global systemic shifts often happen with and due to technology and thus technology presents itself as the most significant social driver (Hidayatno *et al.*, 2019; Manda & Dhaou, 2019).

The above documents are comprehensively analysed on their consideration of the concepts of STTs and the 4IR both jointly and individually. Deductions made are presented in the following subsections.

4.2.1 OVERALL CONSIDERATION FOR SOCIO-TECHNICAL SYSTEMS TRANSITIONS

STTs and STS perspectives are mainly inferred in the documents and are presented from the basic argument of human interaction with technology as a key driver for shaping system configuration and transformation. For example, Stock et al. (2018) make the argument that current human interaction with technology is a key factor to the proper functioning of the system and align CPS technologies and their functioning to this argument (Stock *et al.*, 2018).

Manda & Dhaou (2019) define STS as an organisation of two independent yet correlating and interacting systems; the technical and social working in synergy (Manda & Dhaou, 2019). The technological system transforms inputs to outputs while the social system comprises of the people, society and the environment that use the technology. Manda & Dhaou (2019) argue that the failure of a technological system can be attributed to the behaviour of social elements within which it operates and the successful transformation towards targets or goals requires an understanding of the social and technical systems and the environments within which they operate (Manda & Dhaou, 2019). Martín-Gómez et al. (2019) further elaborate that management for sustainability is embedded in the holistic system that looks at technology within societal and organisational contexts (Martín-Gómez *et al.*, 2019).

In comparison to literature presented in the contextualisation, these arguments and sentiments hold a basic understanding of STS. Furthermore, STTs as presented in the contextualisation are not explicitly defined, discussed and analysed in these documents. However, there are a few noteworthy deductions from these documents on considerations for systems transitions. These are presented as follows:

i. Stock et al., (2018) make the argument that organisations and institutional systems should transform and adopt technologies that drive value creation sustainably. They set the argument that Industry 4.0 encompasses such technologies and hence can be an enabler for transformation within various organisations and systems;
ii. Lin et al. (2017), Stock et al. (2018) and Manda & Dhaou (2019) emphasize that innovation is a critical element for systems in transforming towards more sustainable states (Lin *et al.*, 2017; Manda & Dhaou, 2019; Stock *et al.*, 2018);
iii. Stock et al. (2018) also argue that the transformation process should be built on economic development within social equity and ecological boundaries (Stock *et al.*, 2018), thereby highlighting the need for a three-dimension structure for system transitions;
iv. Martín-Gómez et al. (2019) suggest that to analyse societal systems' transitions towards more sustainable states, indicators at national, regional and industrial sector levels must be assessed and thus give credit to the importance of incorporating SDGs towards global systems sustainability (Martín-Gómez *et al.*, 2019); and
v. Martín-Gómez et al. (2019) also highlight that creative working processes such as strategic planning and Research and Development (R&D) are important for successful transformation (Martín-Gómez *et al.*, 2019).

Although the sentiment is carried that systems need to transform in order to meet set goals, there is a lack of sufficient elaboration on the process and the definitive nature of these transformations and transitions as discussed in STTs literature such as Elzen *et al.* (2004), Farla *et al.* (2012), Fuenfschilling & Truffer (2016), Geels, Turnheim, *et al.* (2019), Hof *et al.* (2020), Ramos-Mejía *et al.* (2018), Schot & Kanger (2018), and Sovacool & Hess (2017).

4.2.2 FOURTH INDUSTRIAL REVOLUTION CAPABILITIES FOR SUSTAINABILITY AND SYSTEMS TRANSITIONS

It is observed that literature is well versed in the analysis of the 4IR. Lin et al. (2017) define 4IR as a technological paradigm in which computers and automation are integrated with machine learning and control systems with little input from human beings (Lin *et al.*, 2017). Nascimento et al. (2019) state that the advancement of the 4IR is underpinned by information and communications technologies developing into further technologies such as IoT, cyber physical systems, Big Data and analytics, cloud computing and additive manufacturing (Nascimento *et al.*, 2019). These sentiments are aligned and similar to the core 4IR literature presented in the contextualisation.

However, it is also observed that literature focuses on the 4IR defined as Industry 4.0. (refer to Section 2.3). This implies a predominant focus on industrial and manufacturing systems. Regardless of this, literature unanimously agrees that Industry 4.0 holds the potential to positively impact global industrial systems and processes. Industry 4.0 is credited with improved technological efficiency, optimized resource usage, flexibility, increased system capacities and enlarged value creation networks which in turn produce varied quality product and service offerings to the customer or consumer, cleaner technologies, product life cycle management and renewable energy (Lin *et al.*, 2017; Stock *et al.*, 2018). All these are presented as positive contributions within the three dimensions of sustainability. Furthermore, it is argued that society can maximize on these benefits by transitioning towards the achievement of sustainability targets (Stock *et al.*, 2018). However, literature also specifies key concerns for the adoption and implementation of Industry 4.0 technologies that may negate efforts toward achieving these targets. These are summarised in Table 14 below.

Table 14: Concerns for implementation of Industry 4.0 (Lin *et al.*, 2017; Manda & Dhaou, 2019)

Social	Ecological	Economic
Automation of jobs which leads to simplification of jobs by tech systems resulting in extortion and exploitation and/or replacement of human labour. Increased cyber-dependence which increases risk for cyber-attacks leading to concerns for transparency and privacy issues. Anticipated rising inequalities and social gaps between emerging and developed countries or communities	Initial increased material and energy usage in the implementation of new technologies	Intense capital implications for the adoption resulting in hesitancy. Need for upskilling workers and a need for future skills some of which are not existent at the moment. ICT infrastructure still poor in most developing countries which may render technologies inefficient or further increase equality disparities.

Lin et al. (2017) and Manda & Dhaou (2019) specify drivers for successful implementation of Industry 4.0 technologies within current systems. These are presented in Figure 27 below.

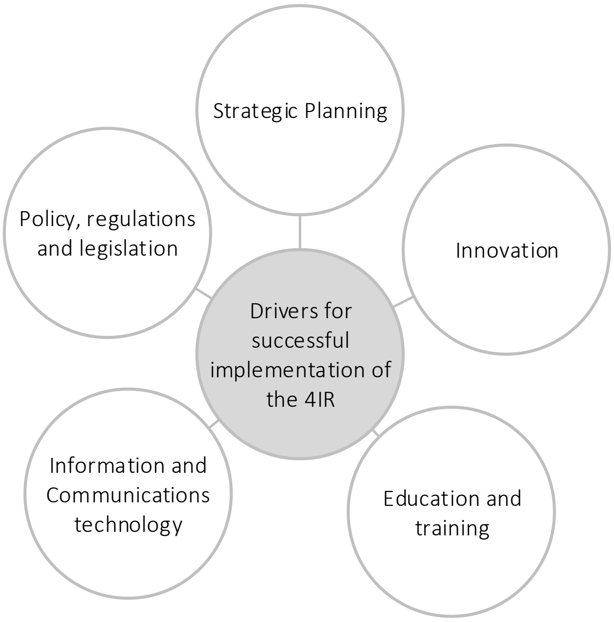

Figure 27: Drivers for successful implementation of Industry 4.0 (Lin *et al.*, 2017; Manda & Dhaou, 2019)

Strategic planning is suggested for the successful implementation of companies and for achieving set targets (Lin *et al.*, 2017; Stock *et al.*, 2018). Lin et al. (2017) and Stock et al. (2018) specify strategies for achieving systemic sustainable development targets within the contexts they address. These may be applied broadly within this context and are displayed in Figure 28 below with the inferred sustainability dimension within which they are applied.

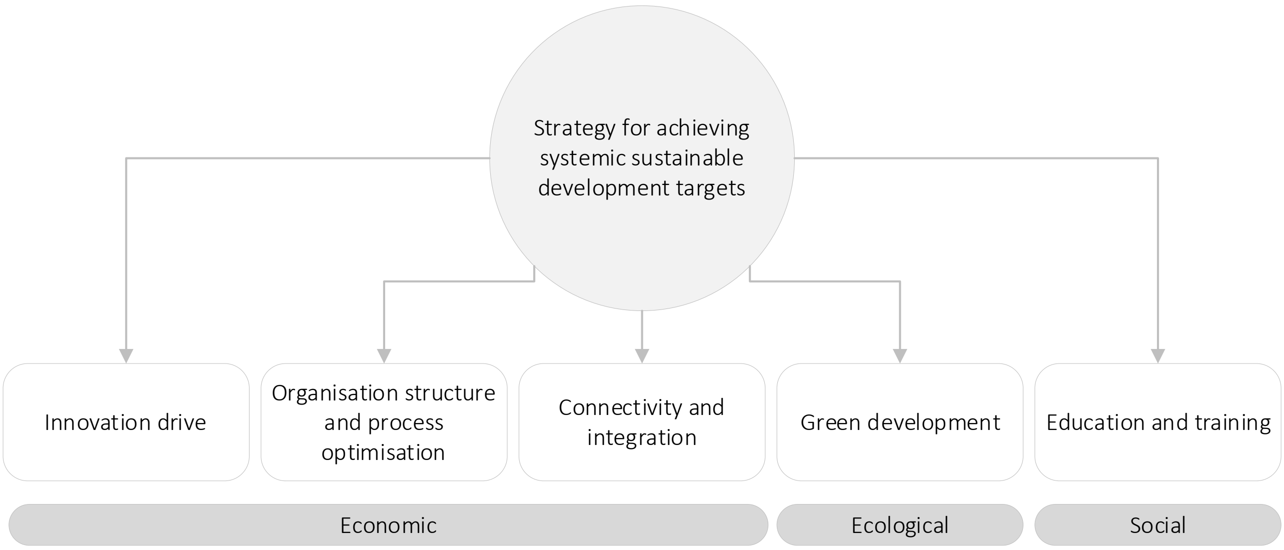

Figure 28: Strategy for achieving sustainability targets (Lin *et al.*, 2017; Stock *et al.*, 2018)

In the economic sustainability dimensions; innovation drive is highlighted as a key driver for the adaptation to technological shifts. Martín-Gómez et al. (2019) further highlight managerial strategy as important towards organisational structure and process optimisation towards organisational sustainability (Martín-Gómez *et al.*, 2019). Stock et al. (2018) highlights product life cycles, business model innovation and quality improvements as key. Connectivity through information systems, leveraging data and integrating various fields and sectors is also highlighted as a key strategy towards achieving economic sustainability (Stock *et al.*, 2018). Within the ecological dimension, establishment of green development is presented as a key strategy to achieve targets such as reductions in waste, reduction in material and resource usage, reduced energy consumption and scaled renewable energy initiatives (Stock *et al.*, 2018). Nascimento et al. (2019) and Martín-Gómez et al. (2019) propose the incorporation of a circular economy – which is described as a system that is restorative and regenerative – as a strategy for achieving combined ecological and economic targets (Martín-Gómez *et al.*, 2019; Nascimento *et al.*, 2019). Within the social dimension education and training through upskilling and reskilling of workers are viewed as key components for combating the social concerns with new technological paradigms. Furthermore, Martín-Gómez et al. (2019) state the need for both vertical (systemic) and horizontal (organisational processes) integration of technologies within the drive towards sustainability while Lin et al. (2017) presents these integrations as key within the policy, regulation and legislative driver for 4IR implementation (Lin *et al.*, 2017; Martín-Gómez *et al.*, 2019).

As mentioned, and as can be observed above, the analysis of 4IR in this literature focuses on specific industrial fields such as manufacturing or industrial production processes, computer sciences, information systems and infrastructure development. Stock et al. (2018) and Nascimento et al. (2019) hold a dominant manufacturing view, Martín-Gómez et al. (2019) look at sustainable supply chain management whereas Hidayatno et al. (2019) look at energy within a manufacturing context.

4.3 GAP ANALYSIS

From the contextualisation of STTs and the 4IR presented in Chapter 2 and the SLR findings presented through the content analysis, it is observed that gaps and disconnects exist between the contextualisation and SLR literature. Gaps identified highlight important content absent in the joint analysis of the concepts of the 4IR and STTs. Disconnects highlight differences between the contextualisation and SLR literature in how they analyse STTs and the 4IR. The gap analysis thereby presents both gaps in and disconnects between the conceptual literature and the SLR literature content in the analysis of the 4IR and STTs. The gaps and disconnects are later translated into deductions as a construct guidance for the envisaged research product.

4.3.1 OVERALL GAPS IN LITERATURE

Gaps identified in literature are deduced from the conceptual literature as well as the literature analysed from the SLR. These are presented below:

4.3.1.1 OVERALL LACK OF A CONSOLIDATED INTEGRATED ANALYSIS OF SOCIO-TECHNICAL TRANSITIONS AND THE FOURTH INDUSTRIAL REVOLUTION IN LITERATURE

In terms of a joint consideration for both concepts, inferences are drawn from content analysis within the contextual background of sustainability and sustainable development. These include:

i. Sustainability targets such as SDGs are relevant and important considerations or drivers for the adoption, implementation and utilisation of technologies and innovations, and are important targets or performance indicators for STS (Lin *et al.*, 2017; Manda & Dhaou, 2019; Nobre *et al.*, 2017; Paravizo *et al.*, 2018; Stock *et al.*, 2018);

ii. Current systems need to consider transitioning to attain the above-mentioned sustainability targets or SDGs. Furthermore, strategies towards these targets and utilisation of 4IR technologies need to be holistic, in that they consider various fields and sectoral inputs, at different levels (from micro to macro or organisational to global levels) within all dimensions of sustainability (i.e., economic, social and ecological) (Brenner, 2018; Manda & Dhaou, 2019; Stock *et al.*, 2018); and

iii. Industry 4.0 and therefore the 4IR encompass multiple technologies that possess a multitude of functionalities that affect and influence various facets of contemporary global socio-economic and systemic structures. Understanding this paradigm is thus imperative as it poses a multitude of opportunities and challenges to address some of the grand societal challenges faced today (Lin *et al.*, 2017; Manda & Dhaou, 2019; Müller *et al.*, 2018; Savastano *et al.*, 2019).

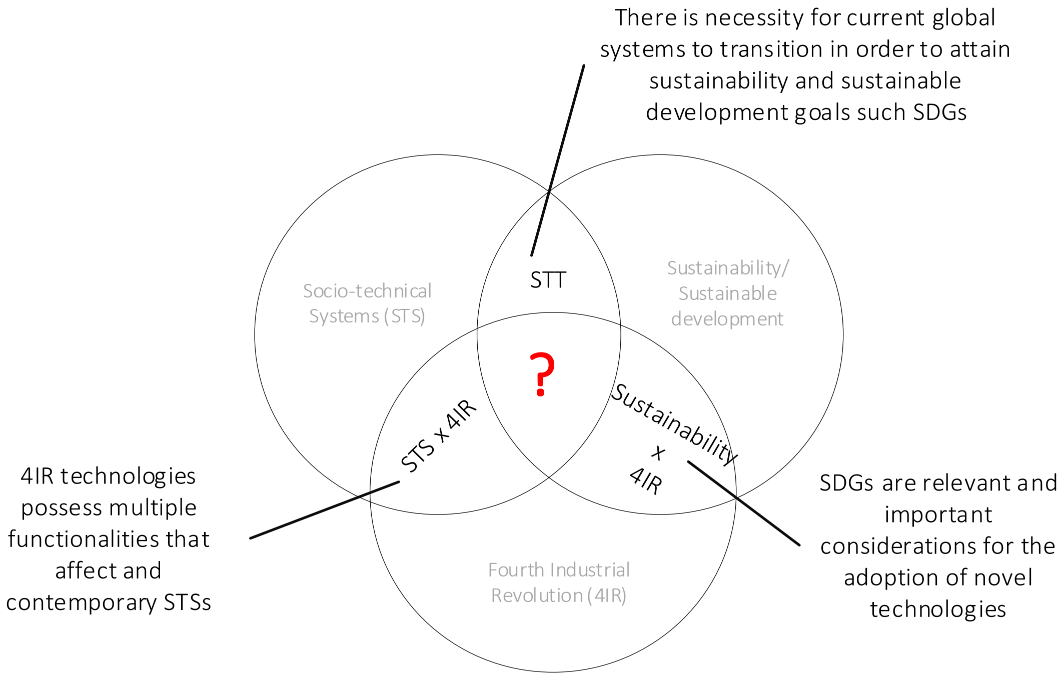

Figure 29: Literature's joint consideration of the main concepts

However, a definitive integrated analysis of the 4IR and STTs, as they are presented in Chapter 2, is largely missing in literature. There is an overall lack of a descriptive or conceptual relationship between the 4IR and STTs. The 4IR not only possess a multitude of opportunities to solve some of the contemporary societal challenges, but also continues to affect and influence various societal structures on a global spectrum (Li *et al.*, 2017). Incorporating the 4IR within STTs provides a contemporary and applicable context to the dynamics of STTs. Furthermore, an orientation of the 4IR with STTs would enable a further understanding of contributions, challenges, hindrances and enablers that are brought into effect by neoteric technologies within STTs.

4.3.1.2 OPPORTUNITIES FOR FUTURE RESEARCH IN SOCIO-TECHNICAL TRANSITIONS LITERATURE

Core STTs literature highlights a few gaps in the theoretical analysis of STTs. These gaps present opportunities for exploitation within novel studies as a contribution to the body of knowledge. These include:

i. Previous studies on transitions have typically been conducted after transitions have occurred i.e., application and case studies in literature are retrospective (Elzen *et al.*, 2004). Although advantageous for analysis, this presents a gap in synthesis as studies conducted are limited in application to current systems due to constant and consistently shifting contexts;
ii. Emerging technologies with new sustainability capabilities are often under-utilised in analysis, hence new functionalities are not taken into consideration (Elzen *et al.*, 2004); and
iii. The need to analyse not just single technologies but combinations of multiple emerging and existing technologies or niches which bring about new dynamics for systems and their transitions (Köhler *et al.*, 2019)

Given the contemporality of the 4IR with contemporary societal systems, it is envisaged that an integration of the 4IR and STTs would benefit STTs literature in addressing the above opportunities for further research.

4.3.2 DISCONNECTS IDENTIFIED BETWEEN THE CONCEPTUAL AND SYSTEMATIC REVIEW LITERATURE

Additionally, following a contrast between the SLR content (refer to Sections 4.1 and 4.2) and the conceptual literature presented in the contextualisation (Chapter 2) disconnects between the literature are identified and presented in the following subsections:

4.3.2.1 LACK OF SUFFICIENT ELABORATION ON SOCIO-TECHNICAL TRANSITIONS

Although transitions/transformation language is inferred, utilised and highlighted in some of the SLR literature (such as Bressanelli *et al.*, 2018; Hidayatno *et al.*, 2019; Lin *et al.*, 2017; Manda & Dhaou, 2019; Martín-Gómez *et al.*, 2019; Paravizo *et al.*, 2018; Scharl & Praktiknjo, 2019), there is little to no employment of STTs theory. This limits the critical understanding of what transitions are, their designs, dynamics and implications for current systems. Consequently, there is a dearth of explorative analysis of the 4IR's orientation in STTs design and its impacts. A lack of a proper understanding, systemic integration and alignment of societal needs with technological shifts is detrimental to the global sustainability and sustainable development success (European Environment Agency, 2018).

4.3.2.2 LACK OF SUFFICIENT CONSIDERATION OF SYSTEMS ORIENTED TOWARDS SOCIETAL FUNCTIONS

Literature highlights that STS are designed to meet societal needs. Given the undeniable orientation of contemporary global systems as socio-technical, STS studies prove useful in understanding the current system dynamics as well mitigating arising challenges. Baxter and Sommerville (2011) argue that given the repercussions of human interactions with technology within systems, it is important to not merely analyse systems from socio-technical perspectives but to develop, evolve and transition these systems in order to meet system requirements, goals and targets (Baxter & Sommerville, 2011) which in this case, encapsulate sustainability and sustainable development goals .

The main distinction between STS and other systems where human beings generally interact with various forms of technology, is that STS are analysed in their orientation to fulfilling societal functions such as food, water, health, transportation, energy and communications (European Environment Agency, 2018). Literature thereby highlights this fact as a key factor in defining STS and STTs.

However, given the societal good imperative in STTs, literature analysed in the SLR appears to be overall lacking in this holistic perspective. This is mostly due to the dominant economic-related targets fuelled by analysing the 4IR as Industry 4.0 within the industrial or manufacturing setting limits to efforts towards holistic sustainability and sustainable developments targets for societal systems.

4.3.2.3 OVERALL DOMINANT SINGLE VIEW OF THE FOURTH INDUSTRIAL REVOLUTION AS INDUSTRY 4.0

Most literature analysed is applied to the manufacturing and industrial setting which mainly considers the Industry 4.0 component of the 4IR. Although valid, it is understood that the scope of the 4IR goes beyond Industry 4.0, which but is one facet of the larger context. 4IR technologies display potential for positive impact and contributions in other sectors, that need to be analysed, explored and incorporated in STTs.

Additionally, this view of the 4IR limits the academic analysis of 4IR in the SLR literature to production value chains, in the manufacturing and industrial production context. This limits the sustainability contribution to a dominant economic perspective which is a limited premise for transitions towards sustainability. Economic benefits of technology within an industrial setting do not generally imply the achievement of sustainability or sustainable development targets for a society (European Environment Agency, 2018).

Furthermore, the Industry 4.0 view limits studies in the SLR to a firm/organisation/industry level which in the wider global context maybe considered as a micro level perspective. The analysis of STTs should also account for macro level perspective in the analysis of contemporary systems (Geels & Schot, 2010).

4.4 CONSTRUCT GUIDANCE FOR THE RESEARCH PRODUCT’S REQUIREMENT SPECIFICATIONS

It is envisaged that the research product fills the gaps and addressed the disconnects identified in literature and presented in Chapter 4 Section 4.3. Therefore, the gaps and disconnects presented are utilised in the development of a strategy for the integration of both concepts by translating them to deductions for the strategy. It is envisaged that the inferred integration strategy incorporate the following deductions from literature presented in Table 15 below.

Table 15: Deductions for the framework

Deduction ID	Deduction	Section from Chapter 4 being addressed
D1	Sufficiently integrate and orient aspects of the 4IR and STTs.	Section 4.3.1.1
D2	Comprehensively draw on the analysis of transitions from an STS perspective.	Sections 4.3.2.1 and 4.3.2.2
D3	Analyse the 4IR within its wider context i.e., not just a single driving technology or only pertaining to the manufacturing and industrial production fields as Industry 4.0.	Sections 4.3.2.3 and 4.3.1.2
D4	Account for a transition to a more sustainable state with the 4IR aspects being employed	Section 4.3.2.2
D5	Ensure contemporality i.e., applicability of the research product should be to contemporary systems and transitions	Section 4.3.1.2
D6	Adequately standardize the research product for to accommodate varying societal systems and contexts.	Sections 4.3.2.1, 4.3.2.2 and 4.3.2.3. This is also a design consideration.

As may be seen in Table 15, the deductions above are coded for reference and are later incorporated and addressed with the requirement specifications presented in Chapter 5, Section 5.2. The above deductions answer Q6 of the SLR guiding questions and thus conclude the SLR.

4.5 LIMITATIONS OF THE SYSTEMATIC LITERATURE REVIEW

The SLR was conducted in the early stages of the research therefore any literature published after June 2019 is not included in this review. This may prove to be a constraint as it is noted that the body of knowledge on the 4IR and STTs is constantly growing. However, due to time limitations of this research, the author was unable to repeat the process in order to constantly evolve the review. Furthermore, the SLR is limited to literature obtained through the Scopus database. However, as highlighted in Section 3.1.2, Scopus was chosen on the basis that it edges out other databases in providing quality academic literature relevant for this research. Furthermore, despite the quantitative analysis giving validity to the research, the results of the review are particularly more important for the qualitative analysis on the extent of joint consideration of the concepts at hand.

4.6 CHAPTER 4 CONCLUSION

In this chapter a gap analysis mainly consisting of deductions from contrasting literature analysed in the SLR and the contextualisation is presented. Overall, it is observed that although the 4IR holds connections with STTs, the main gap existent within literature analysed is the lack of a definitive conceptual integration of the 4IR and STTs. Furthermore, the gap analysis also presented further gaps in STTs literature that may be filled with a joint conceptual integration of the 4IR and STTs and disconnects in the analysis of the 4IR and STTs between conceptual literature presented in Chapter 2 and the content analysed in SLR literature. These findings culminated in deductions for the development of the research product, thereby setting a foundation for the development process presented in the next chapter and answering Q6 of the guiding questions. In the next chapter, a development strategy for the research product is presented.

CHAPTER 5: DEVELOPMENT STRATEGY – APPROACH AND SPECIFICATIONS

In this chapter, an outline of the development strategy for the research product is presented. This chapter discusses the methodology employed in the development of said product in fulfilment of Research Objective 3. From the gap analysis presented in Section 4.3 , it is observed that there is first, an overarching need in literature to conceptualise the 4IR and STTs together. It is envisaged that the research product fulfils the aforementioned need. Furthermore, the research product should address other gaps and disconnects identified in literature as presented in Section 4.3.2. The chapter commences a discussion on the selection of the research product in Section 5.1, followed by the requirement specifications of the product in Section 5.2. Thereafter, the methodology utilised in developing the research product is presented in Sections 5.3 and 5.4.

5.1 RESEARCH PRODUCT SELECTION

Literature presents approaches that may serve as a structure to follow in developing an appropriate conceptualisation that would aid in the integration of the concepts STTs and 4IR as desired for this study. These include models, theories, frameworks (theoretical and conceptual), roadmaps, toolkits, blueprints, strategies and typologies (Kleynhans, 2020). It is observed from literature, that there is a close relationship between models, theoretical and conceptual frameworks in how they are applied to create abstractions and define relationships between concepts. However, theoretical frameworks often refer to the application of a theory or a set of concepts (Imenda, 2014) and models are often utilised to describe and/or represent a phenomenon as it is reflected in real life (Nilsen, 2015).

In contrast, conceptual frameworks are described as the "*end result of bringing related concepts together to explain a given event or give a broader understanding of the phenomenon of interest*" (Jabareen, 2009). Conceptual frameworks offer a structure through which a research can synthesize different concepts from different bodies of knowledge and therefore present an integrated way to look at a problem of interest (Imenda, 2014). This research seeks present an integration between STTs and the 4IR – which is largely missing in literature analysed (refer to Section 4.3.1.1) – in a structured manner that describes and demonstrates the conceptual relationships between the two. A conceptual framework is thus deemed to serve as the appropriate mode for building such a conceptualisation in comparison to other approaches. A detailed description of the different approaches adapted from Kleynhans (2020) utilised in their comparison and thereafter deliberation of this choice is presented in the Appendix C.

Furthermore, this research is also intended to contribute towards the operationalisation and institutionalisation of STTs as mentioned in Section 1.2.1. This research is also conducted from the engineering discipline, which often implies a need for practical utility of developed products. It is therefore envisaged that an operationalisation strategy of the framework is also presented alongside it to offer guidance for the framework's use (Nilsen, 2015). The strategy is a secondary research product and is a utility add-on to the framework.

5.2 REQUIREMENT SPECIFICATIONS

To develop the framework, it is necessary to first consider the requirement specifications that are necessary for its development. Van Aken *et al.* (2007) specify four kinds of specifications for problem solving that are utilised in the development of the framework. These are:

i. Functional requirements: these elaborate on the performance demands of the object to be developed;
ii. User requirements: these are specific to the user i.e., specification considerations from the viewpoint of the user;
iii. Boundary conditions: these are specifications that are to be met unconditionally. May also refer to the constraints; and
iv. Design restrictions: these refer to the preferred solution space i.e., the domain boundaries of the framework.

The development and utilisation of these specifications is further discussed in the subsections below:

5.2.1 FUNCTIONAL REQUIREMENTS (F)

Functional requirements elaborate on what the product to be developed ought to do performance-wise. These specify requirements for the optimal performance of the research product. As discussed in Section 4.4, it is envisaged that the framework resolve the gaps and disconnects highlighted in Section 4.3 in an effort to make a positive substantial contribution to fulfilling the aim of this research given the findings from literature. Functional requirements for the framework include the following:

i. The framework should sufficiently integrate and orient aspects of the 4IR and STTs together;
ii. The framework should employ STTs from an STS background context for the integration;
iii. The framework should incorporate an understanding of the 4IR within its holistic context; and
iv. The framework should be applicable to contemporary societal system contexts.

5.2.2 DESIGN RESTRICTIONS (R)

Design restrictions denote the preferred solution space of the framework. Core STTs studies generally hold an advanced research acumen and are mostly conducted from a multi-disciplinary perspective. However, given the author's academic discipline, it is envisaged that the framework is developed with following restrictions:

i. The framework is developed from an Industrial Engineering (IE) perspective as it is this research's academical discipline. Expounds from other disciplines may be progressively added by SMEs in those disciplines;
ii. The framework does not provide new meaning or theory around STTs and the 4IR. However, it integrates both concepts using theory and examples provided in literature;
iii. The framework takes descriptive and explorative approaches towards conceptualizing the integration of the 4IR and STTs;
iv. The framework exclusively takes an STTs perspective towards sustainability transitions; and

v. The framework analyses sustainability and sustainable development from a macro level of analysis.

5.2.3 BOUNDARY CONDITIONS (B)

According to Van Aken *et al.* (2007), boundary conditions stipulate the restrictions that are to be met unconditionally for the product to work as developed. The framework is developed as a high-level introductory discussion into the analysis of the integration of 4IR and STTs and is therefore aims to pioneer in further research presenting inquiries, criticisms, insights, and developments in STTs with the 4IR. Given this premise, this research is therefore constrained to the following boundary restrictions:

i. The framework is most appropriately applicable to societal systems such as health care, agriculture, energy, transport etc in the quest to fulfil societal functions, achieve sustainability targets and overcome grand challenges;
ii. The framework must be utilised by users with some basic prior knowledge of the concepts at hand;
iii. The framework cannot be applied directly without contextual additions by users; and
iv. The framework is exploratory in application and is therefore not to be used prescriptively in the analysis of STTs and the 4IR.

5.2.4 USER REQUIREMENTS (U)

As briefly described above, the user requirements specify considerations from the viewpoint of the user. Following Systems engineering guidelines for developing for a user (Library, 2001), it is envisaged that the framework adheres to the following user requirements:

i. The framework should be understandable and unambiguous;
ii. The framework should be clear and concise;
iii. The framework should be open ended to allow for exploratory discussion from various disciplines and contexts; and
iv. The framework should be accompanied by some practical utility as it developed from an engineering perspective.

In summary, all requirement specifications for the envisaged framework as well as motivations for their employment are presented in Table 16 below:

Table 16: Requirement specifications for the framework

Requirement ID	Requirement	Motivation
Functional requirements		
F1	The framework should sufficiently articulate an integration and orientation of aspects of the 4IR and STTs together.	The need for the framework mainly stems from the lack of a sufficient integration of the concepts 4IR and STTs in literature despite evident connections between the two concepts. The framework is developed to contribute to literature by integrating aspects of the two concepts The framework should

Requirement ID	Requirement	Motivation
		therefore fill this gap by jointly conceptualising an orientation of the two concepts and their dynamics. These aspects should be in line with literature as presented in Chapter 2. (refer to section 4.3.1.1 and Table 15 D1)
F2	The framework should employ STTs from an STS background context for the integration.	This research bases sustainability transitions analysis on an STS perspective as presented in Chapter 2. The framework should therefore employ and utilise STTs theory as such drawn from literature presented in Chapter 2, Sections 2.1 and 2.2. This is done to address the disconnect from literature on a lack of sufficient elaboration of STTs from an STS perspective (refer to Section 4.3.2.1. Table 15 D2).
F3	The framework should incorporate an understanding of the 4IR within its holistic context.	A key disconnect identified in the gap analysis between core literature on the 4IR and literature jointly analysing the 4IR and STTs, is that the latter has a dominant view of the 4IR as Industry 4.0 (refer to Section 4.3.2.3). This has led to analysis that is dominated by manufacturing and industrial production fields, and hence 4IR technologies that are applied there such as CPS, 3D printing and digital twins. While such technologies may have applications in other sectors such as agriculture, food production, health, transportation and energy; it is envisaged that the proposed framework employs the 4IR technologies with the motive of demonstrating a holistic view of the technologies as they are applied to meet sustainability and sustainable development targets across all sectors, especially those that pertain to systems that fulfil societal functions for the greater good. Furthermore, the framework should incorporate the 4IR and its concepts holistically and not just through the lens of Industry 4.0 and the manufacturing context. This is due to the dominant view of the 4IR in literature as Industry 4.0 (Section 4.3.2.3). It is envisaged that the 4IR affects society beyond the scope of Industry 4.0. The framework should therefore elaborate on the sustainability impacts of the 4IR on other societal systems. (refer to Section 4.3.2.3 and Table 15 D3).
F4	The framework should be applicable to contemporary societal system contexts.	The framework should demonstrate an integration of the concepts of the 4IR and STTs as they pertain to contemporary societal contexts. The framework is therefore non-specific on a single technology or industry but should be generically applicable to any societal system of interest (refer to Table 15 D5).

Requirement ID	Requirement	Motivation
Design restrictions		
R1	The framework is developed from an industrial engineering perspective as it is this research's academical discipline. Expounds from other fields may be progressively added by SMEs in those fields.	It is also acknowledged that other disciplines such as social sciences form part and contribute towards the holistic understanding of STTs and that conversely, the 4IR affects multiple sectors around the globe outside of the technical realm. However, the background of this research stems from a systems or industrial engineering perspective, which is inherently more technically inclined. The framework, therefore, is developed using systems engineering and industrial engineering principles for systems thinking. However, it should also not be constrained to the industrial engineering field and should be developed to allow input from other fields for transdisciplinary and trans-sectoral input as applied to STTs (refer to Table 15 D6)
R2	The framework does not provide new meaning or theory around STTs and the 4IR. However, it integrates both concepts using theory and examples provided in literature.	The intent of developing the framework is not to create new theory and meaning around STTs studies or the 4IR. The framework is intended as an approach towards demonstrating integral links between STTs and the 4IR and helping the user understand the integration using already existing theory and examples that already exist and are provided in literature.
R3	The framework overall takes descriptive and explorative approaches towards conceptualizing the integration of the 4IR and STTs.	The framework is designed to explore the relationships between the 4IR and STTs and describe the relationships to as they pertain to integrating STTs and the 4IR.
R4	The framework exclusively takes an STTs perspective towards sustainability transitions.	While other transitions perspectives such as socio-economic, socio-ecological, sectoral systems of innovations and innovation systems have been acknowledged, this research focuses on STTs and therefore the framework exclusively takes an STTs perspective with main focus on society and system functions towards the greater sustainability good. Detailed effects on other spheres such as the environment and economy may be added in future work on the framework.
R5	The framework analyses sustainability and sustainable development from a macro level of analysis.	This research emphasizes an integration of the 4IR and STTs within the contextual background of sustainability and sustainable development. The 4IR by itself is technological revolution with multiple technologies affecting various societal systems. However, it is observed in literature that STTs are focused on sustainability or sustainable development from a societal or common good context i.e., towards fulfilling societal function. It is therefore imperative to investigate the impact of

Requirement ID	Requirement	Motivation
		the 4IR's technologies with societal systems towards STTs beyond economic sustainability of said systems. This is so as to avoid advocating for mere technological transitions which do not necessarily imply a transition to sustainability equally focused on all three sustainability dimensions, or that addresses the grand societal challenges. (refer to Section 2.3.4 and Table 15 D4)
Boundary conditions		
B1	The framework is most appropriately applicable to societal systems such as health care, agriculture, energy, transport etc in the quest to fulfil societal functions, achieve sustainability targets and overcome grand challenges.	Given that the research takes an STTs perspective, the framework is applicable to societal systems designed and oriented to fulfilling basic societal functions such as health care, agriculture, energy, transportation and mobility. Due to their inherent functioning, these systems are typically faced with grand sustainability challenges and would hence benefit from the envisioned integration in the quest towards sustainability and sustainable development.
B2	The framework must be utilised by users with some prior knowledge on the concepts at hand.	Given that the framework builds on literature's discussion on STTs and the 4IR and explicitly focuses on their integration, it is proposed that users of the framework should have some prior knowledge of the concepts at hand in order to effectively utilise it in analysis. Furthermore, a basic understanding of systems thinking is advantageous is understanding the framework.
B3	The framework must not be utilised without contextual additions by users.	It is understood from literature that the STTs and the 4IR are not homogenous in application. Different STTs contexts and scales of analysis may have varying implications to be considered. Context may be related to specific societal systems and how they are influenced by factors such as geographical location, socio-economic context, political context, and other technological development and adoption. Furthermore, these contexts have various scales and levels of analysis from organisational to global scales (refer to Figure 6). Therefore, the framework should account for various STTs contexts and scales of analysis. Where a specific context/unit of analysis is applied, the framework does not use such context-specific input prescriptively but only as a demonstration of the integration of the 4IR and STTs. Therefore, where needed, it is beneficial for users to have some contextual knowledge for a more applicable utilisation of the framework (refer to Section 2.3.4 and Table 15 D6).

Requirement ID	Requirement	Motivation
B4	The framework should not primarily be used prescriptively in the analysis of STTs and the 4IR.	The framework is developed to explore and understand the integration and relationships between STTs and 4IR in a given societal system context for the sole purpose of understanding these relationships. The framework should therefore not be applied as-is to solve any context-specific contemporary STTs and 4IR issues or prescribed as a solution in itself. It is envisaged that through the utilising the framework insights may be drawn from which meanings and practical implications may be developed that may aid in solving context-specific problems (refer to Table 15 D6). Furthermore, the author does not claim that the framework is the ultimate framework or the "be all end all" in the integration of the 4IR and STTs. However, given the novelty of the subjects at hand and the gaps identified in literature at the time of the research, the framework offers an approach, of which many more may be developed as literature advances.
User requirements		
U1	The framework should be understandable and unambiguous.	The framework should be easy to follow and understand especially for users that are not familiar with STTs.
U2	The framework should be clear and concise.	Details and explanations should be comprehensive yet brief.
U3	The framework should be open ended to allow exploratory discussion from various disciplines and contexts.	The framework should be usable by people from various fields and disciplines as the applicability of the concepts at hand pertains multiple fields (refer to Sections 4.1.4).
U4	The framework should be accompanied by some practical utility.	The framework is developed from an engineering perspective which requisites practical utility to academic products. The framework itself is not developed to directly address this, however, a tool should be presented alongside it to guide users on navigating implications for practical insights drawn from the framework for their respective fields/sectors.

The above requirement specifications are utilised in the development of the framework as later presented in Chapter 6, Section 6.1. Furthermore, an evaluation of the framework against the above requirement specifications is later presented in Chapter 7, Section 7.4.

5.3 GUIDING PRINCIPLES FOR THE FRAMEWORK'S DEVELOPMENT

Given that the framework is aimed at a conceptual integration of the 4IR and STTs that pertain to contemporary societal systems and from the industrial engineering domain; the author utilises the system's thinking principles to guide their approach in the integration of both concepts. Arnold & Wade (2015) describe Systems

Thinking as a holistic perspective that recognises the relationship between system components to be an important factor to how the system operates.

Arnold & Wade (2015) present a Systems Thinking Systemigram which summarises and synthesis of definitions from literature on Systems Thinking. The Systemigram highlights connections that are important for consideration in applying Systems Thinking principles. The Systemigram is adapted for development of the framework and is presented in Figure 30 below. Elements of the Systemigram are translated into four guiding principles which follow in sequence as shown in Figure 30.

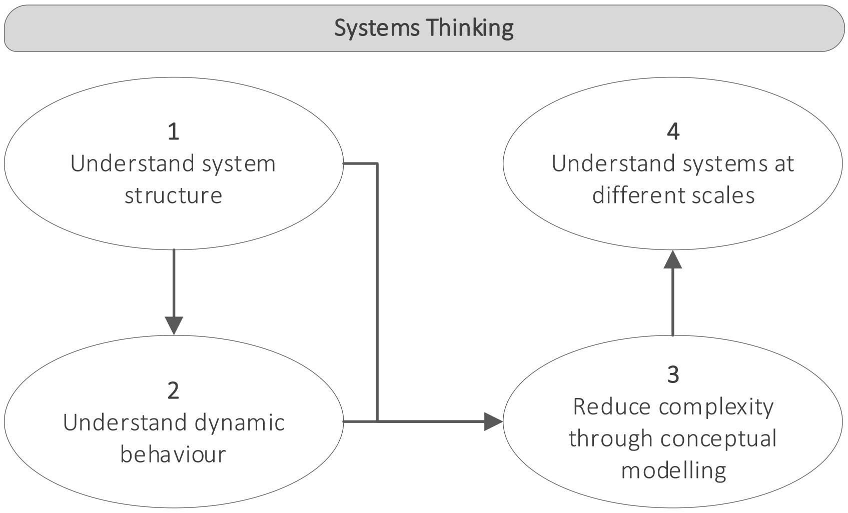

Figure 30: Systems Thinking guiding principles for the framework's development. Adapted from Arnold & Wade (2015)

The principles as applied to the framework development are elaborated on in the subsection below:

5.3.1 PRINCIPLE 1: UNDERSTAND SYSTEM STRUCTURE

According to Arnold & Wade (2015), a systems structure consists of aspects and interconnections between these aspects. An understanding of this structure facilitates how the system behaves. In the context of this research, aspects of STTs and 4IR are analysed for their integration through different perspectives and aspects.

5.3.2 PRINCIPLE 2: UNDERSTAND DYNAMIC BEHAVIOUR

According to Arnold & Wade (2015) dynamic behaviour within a system results from the interaction of different variables in the system and how they relate. In the context of this research, variables are translated to aspects for the integration of aspects of STTs and the 4IR. It is envisaged that relationships between these aspects demonstrate dynamic behaviour between STTs and the 4IR (Lake & Wright, 2020).

5.3.3 PRINCIPLE 3: REDUCING COMPLEXITY THROUGH CONCEPTUAL MODELING

Arnold & Wade (2015) describe reducing complexity as the ability to view a system from different perspectives, simplify its analysis and yet allow for the interpretation of greater complexity without excess detail. In application to this research, this principle is utilised in the development of a conceptual representation of the proposed framework. This is to fulfil user requirements U1, U2 and U3 (refer to Section 5.2.4 and Table

16) i.e., to develop a framework that is clear, concise, understandable, unambiguous and sufficiently generic to allow user inputs from other fields.

5.3.4 PRINCIPLE 4: UNDERSTANDING SYSTEMS AT DIFFERENT SCALES

Lastly, Arnold & Wade (2015) recommend the understanding of different scales of analysis in systems and a recognition of a system of systems perspective in analysis.

Systems Thinking is widely applied within Industrial Engineering and Systems Engineering (Du Preez *et al.*, 2009). Furthermore, the fundamentals of Systems Thinking are very closely linked to the design of STS and thus applicable to contemporary societal in the analysis of STTs (Baxter & Sommerville, 2011). The author utilises the Systems Thinking principles presented above as a guidance approach in conceptualising the envisaged framework and its operationalisation strategy. Furthermore, the application of Systems Thinking is in fulfilment of the framework's design requirement R1 i.e., developing the framework from an Industrial Engineering or Systems Engineering perspective. The application of the above principles in the framework and its operationalisation strategy's development is presented throughout Chapter 6.

5.4 OVERARCHING DEVELOPMENT PROCESS

This research employs Van Aken *et al.* (2007)'s general framework for design processes displayed in Figure 31 below, as the methodology for the development process of the framework. Van Aken *et al.* (2007)'s model for design process management is a process-step model where the process of developing an intended object (in this case, a framework) is broken down into vital process steps while work in each step is controlled by the process management. Process steps do not follow a fixed sequence in the framework's development but are conducted iteratively to explore steps and modify the framework as needed. This ensures flexibility and agility within the development process (Van Aken *et al.*, 2007).

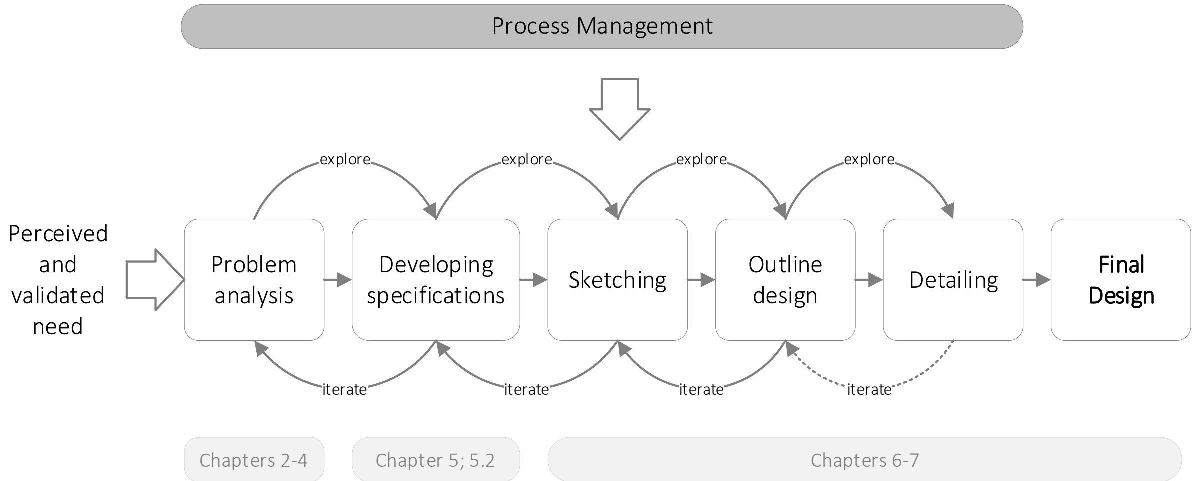

Figure 31: General model for a development process (Van Aken *et al.*, 2007)

The process begins with a validated and perceived need as its input. In this case the need and case for the framework has been detailed and presented in the preceding chapters (refer to Chapter 1, Section 1.2 and Chapter 4, Section 4.3). The process then initiates with a problem analysis. In this case, the problem at hand has been fully elaborated on in Chapters 2-4 of this document. The process model proceeds to 'developing specifications' as the next step. Requirement specification as set out by Van Aken *et al.* (2007) are developed and presented in Section 5.2.

The next steps in the process are sketching, outline design and detailing. All three pertain to the iterative and explorative development of the framework. Although the sketching step is informal and is therefore not presented in this document, it serves as an important step in formulating initial ideas of the framework. The outline design step, however, produces more a formalised product and also details decisions with respect to key development conundrums (Van Aken *et al.*, 2007). Van Aken *et al.* (2007) further specify that the outline design should be robust, in that the detailing step is carried out with minimal iterations (hence the dotted arrow on the iterating between the outline design and detailing steps). To the outline and detail design steps, four sub-steps are utilised in the development of the framework. These are shown in Figure 32 below.

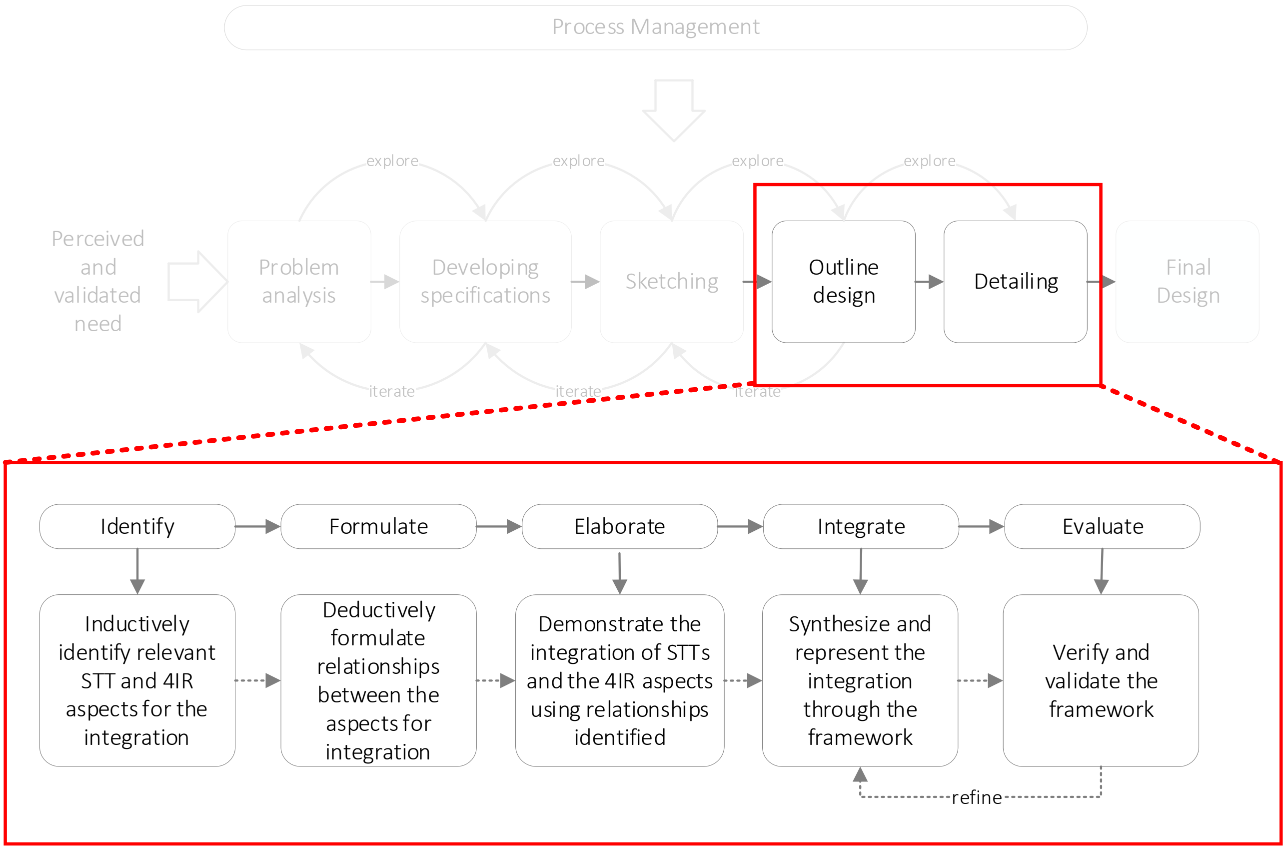

Figure 32: Framework development process (Van Aken *et al.*, 2007)

The first sub-step is to identify STTs and 4IR concept aspects for the integration. Thereafter, the aspects are synthesized together. As a synthesis is conducted and need for more aspects is identified for coherency, the process of identifying and integrating aspects is re-iterated. After synthesizing, relationships are formulated to demonstrate an integration. The relationships are elaborated on through descriptively synthesizing and exemplifying the concepts integration from literature. This process is done iteratively with the formulate step. Finally, the framework is evaluated through a verification and validation processes. This process may either yield a redesign of the framework in which case the development process is restarted from the beginning or a refinement where additional aspects are added, if necessary, or those identified are refined. Verification and validation processes are done with SMEs and a case application in line with Research Objectives 3 and 4. The final result of this process is a developed and validated framework.

5.5 CHAPTER 5 CONCLUSION

In this chapter, the integration strategy detailing the development process of the research product is presented. A framework is to be developed in an effort to contribute towards the integration of the 4IR with STTs. The framework's requirement specifications and development process have been presented in this chapter as well as a construct guidance from applied Systems Thinking. In the next chapter, the developed framework and its operationalisation strategy are presented.

CHAPTER 6: A FRAMEWORK FOR THE INTEGRATION OF SOCIO-TECHNICAL TRANSITIONS AND THE FOURTH INDUSTRIAL REVOLUTION

In this chapter, the developed framework for the integration of the STTs and the 4IR is presented. The chapter begins with a brief introduction of the final conceptual representation of the developed framework in Section 6.1 in which components of the framework which include perspectives, aspects and relationships are stated. Section 6.2 explores the framework's perspectives and introduces the aspects from STTs and the 4IR. Subsequently, Section 6.3 dives into relationships which ultimately demonstrate points of integration between the concepts of STTs and the 4IR. Lastly, the framework is accompanied by a strategy for its operationalisation referred to as the operationalisation strategy in Section 6.4. The operationalisation strategy aims to give practical utility to the framework as per user requirement U4 of the requirement specifications (refer to Chapter 5, Section 5.2.4 and Table 16).

6.1 THE I4IR-STT FRAMEWORK

From the beginning of this research, the importance of STTs and the 4IR's potential in the quest for global sustainability and sustainable development has been evidenced (refer to Chapters 1, 2 and 3). STTs analysis has been established as a key consideration for analysing cotemporary global systems in transition to more sustainable states. Furthermore, it has also been observed that the 4IR as a multifaceted and multi-technological paradigm, has several implications for sustainability and sustainable development within contemporary global systems. However, it has also been observed in literature that a conceptual integration of STTs and the 4IR is largely lacking (refer to Chapter 4). It is therefore proposed to develop a framework to demonstrate an integration between the concepts of the 4IR and STTs and facilitate an understanding of the ontological[2] integration of both concepts as they both evidently pertain to global systems and have an orientation to and implications for global sustainability and sustainable development (refer to Chapter 1, Section 1.2). This framework is named the I4IR-STT framework and is presented in this chapter.

In this section, the overarching outline design of the I4IR-STT framework is presented following the development process from Van Aken *et al.* (2007) as presented in Chapter 5, Section 5.4. Du Preez *et al.* (2009) highlight that the fundamentals of Systems Thinking are observing a system in its entirety while simultaneously trying to understand the parts within it. From this and the guidance provided by the System's Thinking principle – *understanding the system structure* – (Arnold & Wade, 2015), the framework attempts to express the integration of STTs and the 4IR. Furthermore, the framework's development draws from the requirement specifications as presented in Section 5.2.

[2] Showing the relationship between the concepts and categories in a subject area or domain (Oxford Dictionary, 2020).

The I4IR-STT framework is dual-modal[3] in its approach to the integration of the concepts of STTs and the 4IR in the sense that it considers both STTs and 4IR sides in demonstrating an integration between the concepts. From each side, aspects of each concept are drawn for the integration as elaborated on in Section 6.2. The I4IR-STT framework consists of three key elements utilised in the integration of the 4IR and STTs. These include transitions aspects, technology aspects[4] and relationships. Transitions aspects draw key features and characteristics of STTs presented in literature that are envisaged to cohesively integrate with aspects from the 4IR. Conversely, technology aspects are key features and characteristics of the 4IR deduced from literature that are envisaged to integrate with aspects of STTs. Relationships are thereafter used as an avenue to describe and demonstrate the integration of the STTs and the 4IR through their representative transitions and technological aspects. Relationships are further explored in Section 6.3. A diagrammatic conceptualisation of the I4IR-STT framework outline is presented in Figure 33 below. The rationale behind this representation is the application of Principle 3[5] of the Applied Systems Thinking (refer to Section 5.3.3) which is to reduce complexity through conceptual modelling (Arnold & Wade, 2015).

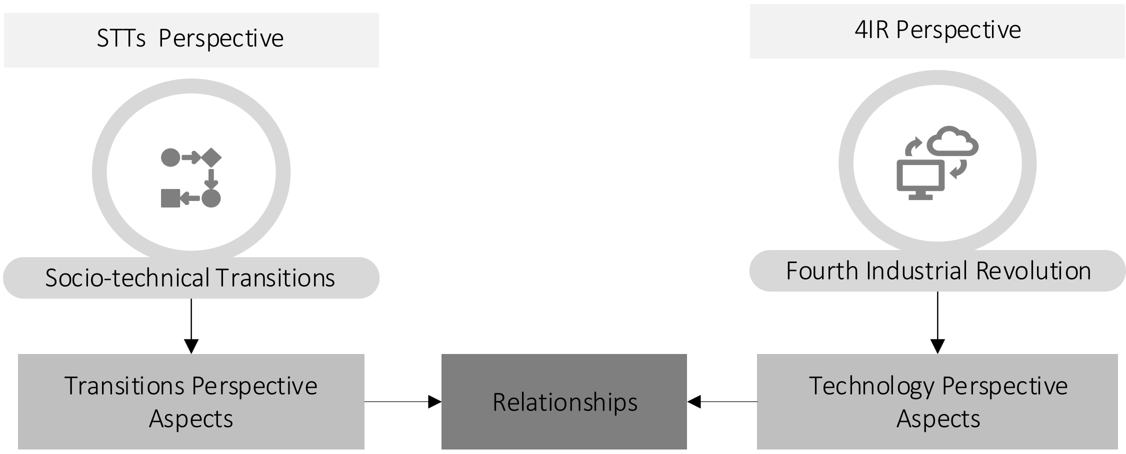

Figure 33: I4IR-STT framework outline

The framework as presented in Figure 33, conceptually structures and summarises the arrangement of its elements. As diagrammatically demonstrated, transitions and technology aspects are effectively channelled into the relationships element to demonstrate the integration.

Lastly, the framework's elements are conceptualised in such a way that the requirement specifications presented in Chapter 5, Section 5.2 are incorporated into their development. Table 17 below summarises the

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[3] The term 'dual-modal' is utilised to mean the approach to which the integration is expressed (modal) and in reference to the sets of twos i.e. two perspectives from which several aspects and relationships emerge (Oxford Dictionary, 2020).

[4] The use of the terms 'technology' and 'transition' in application to 4IR and STTs aspects is primarily for the framework's conceptualisation and does not imply exclusivity of the terms to the respective concept.

[5] In the development process of the framework, the author follows the sequence of the Systems Thinking principles presented in Figure 30. However, for the purposes of this document, each principle is presented in the relevant section where it was utilised. Therefore, although Principle 3 is sequentially the third step in Figure 30 it is presented in this section with the final framework.

requirement specifications and shows which framework element each requirement specification is applicable to. As can be seen in the Table 17, functional requirements and boundary conditions pertain to specific elements of the I4IR-STT framework whereas user requirements and design restrictions are applicable to all the elements of the framework.

Table 17: I4IR-STT Framework elements and corresponding requirement specifications

	Transitions Perspective	Relationships	Technology Perspective
Functional Requirements			
F1: The framework should sufficiently articulate an integration and orientation of aspects of the 4IR and STTs together.	X	X	x
F2: The framework should employ STTs from an STS background context for the integration	X	X	N/A
F3: The framework should incorporate an understanding of the 4IR within its holistic context.	N/A	X	X
F4: The framework should be applicable to contemporary societal systemic contexts.	X	X	X
Design Restrictions			
R1: The framework is developed from an industrial engineering perspective as it is the research's academical discipline. Expounds from other disciplines may be progressively added by SMEs in those disciplines.	X	X	X
R2: The framework does not provide new meaning or theory around STTs and the 4IR. However, it integrates both concepts using theory and examples provided in literature.	X	X	X
R3: The framework overall takes descriptive and explorative approaches towards conceptualizing the integration of the 4IR and STTs.	X	X	X
R4: The framework exclusively takes an STTs perspective towards sustainability transitions.	X	X	N/A
R5: The framework analyses sustainability and sustainable development from a macro level of analysis.	X	X	X
Boundary Conditions			
B1: The framework is most appropriately applicable to societal systems such as health care, agriculture, energy and transport in the quest to fulfil societal functions, achieve sustainability targets and overcome grand challenges.	X	X	X
B2: The framework must be utilised by users with some prior knowledge of the concepts at hand.	X	X	X
B3: The framework must not be utilised without contextual additions by users.	X	X	X
B4: The framework should not primarily be used prescriptively in the analysis of STTs and the 4IR.	X	X	X

	Transitions Perspective	Relationships	Technology Perspective
User requirements			
U1: The framework should be understandable and unambiguous.	X	X	X
U2: The framework should be clear and concise.	X	X	X
U3: The framework should be open-ended to allow exploratory discussion from various disciplines and contexts.	X	X	X
U4: The framework should be accompanied by some practical utility.	X	X	X

In Sections 6.2 and 6.3 below, aspects of the I4IR-STT framework elements are explored, in line with the detailing step of Van Aken *et al.* (2007)'s development process (refer to Figure 31).

6.2 CONCEPTUAL ASPECTS OF SOCIO-TECHNICAL TRANSITIONS AND THE FOURTH INDUSTRIAL REVOLUTION

As previously mentioned, the I4IR-STT framework is a conceptual demonstration of an integration of the concepts of the 4IR and STTs. For this study, the term 'integration' is defined as combining two concepts together, each with its particular characteristics (or aspects in this case), to form as a whole in the analysis (Cambridge Dictionary, 2020). Functional requirement F1 (refer to Section 5.2.1) states the framework should sufficiently integrate and orient aspects of the 4IR and STTs together. The framework draws aspects from each concept, i.e., the STTs and the 4IR from literature presented in Sections 2.2 and 2.3 for this purpose. Selected aspects for the concepts of STTs and the 4IR are presented in the subsections 6.2.1 and 6.2.2 below:

6.2.1 TRANSITIONS ASPECTS

STTs have been described in literature (refer to Section 2.2.1) to possess characteristics and aspects that distinguish them in sustainability and sustainable development research. These include:

i. Grand sustainability imperative: STTs are concerned with the transition of systems that fulfil societal functions such as mobility, energy, health care and agriculture from states of unsustainability to a more sustainable state for the common societal good through addressing these societal systems' grand sustainability challenges. (Geels, 2011; Geels & Schot, 2007; Sorrell, 2018);

ii. Multidimensionality and co-evolutionary: STTs require and possess change processes across different sectors and value chains in each societal system both simultaneously and continuously (Elzen *et al.*, 2004; Köhler *et al.*, 2019);

iii. Multi-actor involvement: STTs involve several actors from various social groups, sectors, industries and institutions with different interests and visions which raises the importance of issues such as values and bring in contestation on key sustainability visions and goals (Köhler *et al.*, 2019); and

iv. Normative directionality: STTs often require normative directionality through regulations, policy and strategy to normalise and steer transitions towards societal good and align the often conflicting values and interests of actors involved (Köhler *et al.*, 2019).

These characteristics, as shown in Figure 34 below, are proposed as integration aspects from an STTs perspective. It is envisaged that these aspects may be manifested in the unfolding of the 4IR and are hence utilised in demonstrating the 4IRs' integration with STTs. Furthermore, the above aspects are appropriately derived from STTs as with STS analysis is stipulated by functional requirement F2.

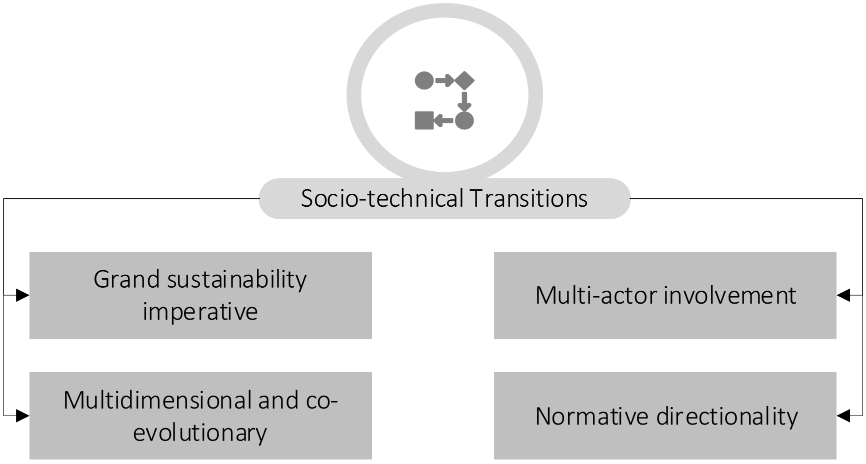

Figure 34: Transitions perspective aspects

6.2.2 TECHNOLOGY ASPECTS

The term technology in relation to the framework includes but is not limited to physical artefacts, systems, user practices/processes and knowledge (Val Dusek, 2006) that pertain to the 4IR and including technologies identified and listed from literature (refer to Section 2.3.1, Table 4, Page 30). It is proposed that the technology perspective takes a techno-centred approach and its aspects focus on technological integrational factors that cumulatively become responsible for steering and enacting the transitional process (Bond, 1999).

From literature (such as presented in Section 2.3), the scope of the 4IR is described as a fusion of technologies that cut across the physical, biological and digital domains and have various applications in different facets of society. Literature presented these technologies as the primary driving force behind the 4IR (refer to Section 2.3.1). These technologies are interconnected and possess interoperability which enables them to cut across various sectors, industries and value chains (Schwab, 2016). This key characteristic of the 4IR is proposed as the first aspect for the integration.

Furthermore, from the key issues and topics arising from the 4IR literature on sustainability and sustainable development as presented in literature (refer to Section 2.3.2). These issues and topics, listed below, are also identified and presented as inclusions for aspects as for integration:

i. Technological innovation and value creation: The advancement of 4IR technologies has furthered and been furthered by increased innovation. Literature specifies, however, that innovation must benefit the society and the economy and value must be added for the economy and transformed societal systems (Schwab, 2016; World Economic Forum, 2020);

ii. Strategy and policy: The advancement of the 4IR in society is dependent on the development of policies and strategies for innovation, implementation of technologies and transition management in order to ensure the successful achievement of set targets for societal good (Lin *et al.*, 2017; Schwab, 2016);

iii. Socio-political factors: A number of social issues are highlighted in literature concerning the 4IR such as jobs, skills, employment and social inequality. The advancement of the 4IR technologies brings into focus social concerns on the loss of employment due to some jobs being obsolete, the need for individuals to re-skill in order to stay competitive and advance in the 4IR era as well as the social inequality gap that is widened by the advancement of the technologies. Furthermore, the extent of the use of data by 4IR technologies and the advancement technology's autonomy present challenges concerned with ethics, security and identity which are key in the 4IR literature (World Economic Forum, 2019, 2020).

The above are proposed as aspects to demonstrate the 4IRs integration with STTs as presented in Figure 35 below. Furthermore, as per functional specification F3, the framework incorporates the 4IR from a wider perspective and is not restricted to Industry 4.0.

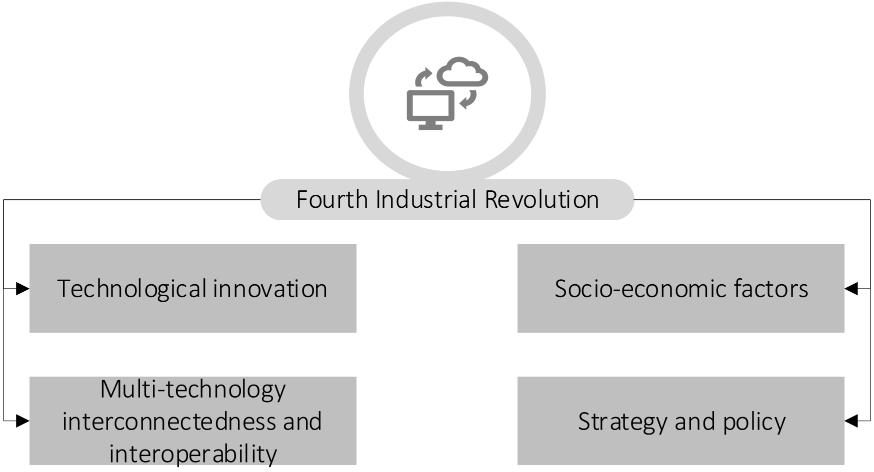

Figure 35: Technology perspective aspects

6.3 RELATIONSHIPS

The I4IR-STT relationships are proposed as themes that demonstrate a unification between aspects of the 4IR and STTs. The framework proposes three relationships to demonstrate the integration of the 4IR and STTs:

i. Purpose: This explores the integration of STTs and the 4IR based on aspects that are related to the core existence of STTs and 4IR;

ii. Systemic dependencies: This explores the integration of across aspects that relate to technical or structural nuances of the 4IR and STTs; and

iii. Actor engagement: This explores the integration with specific focus on actors, their involvement and the factors that affect them.

Relationships are explored in relation to both the STTs and 4IR aspects and are used to draw intersections between them. The demonstration of relationships draws from by the second principle of Systems Thinking as presented in Section 5.3.2 i.e., '*understanding dynamic behaviour'* (Arnold & Wade, 2015) which implies identifying and understanding relationships between the 4IR technologies and contemporary STTs which demonstrate their integration. (Arnold & Wade, 2015). This is also in fulfilment of design restriction R2 (refer to Table 16). These relationships are explored in the following subsections:

6.3.1 PURPOSE

The 'purpose' relationship denotes an integration between STTs and the 4IR through their intrinsic reasons for advancement. It has been highlighted that STTs are undeniably orientated towards the grand sustainability imperative in societal systems. On the other hand, the 4IR has been birthed and advanced out of the innovation and fusion of multiple technologies which are geared towards value creation in different systems. Therefore, as can be seen in Figure 36, the grand sustainability imperative aspect of STTs and technological innovation aspect of the 4IR are utilised in this relationship of the framework.

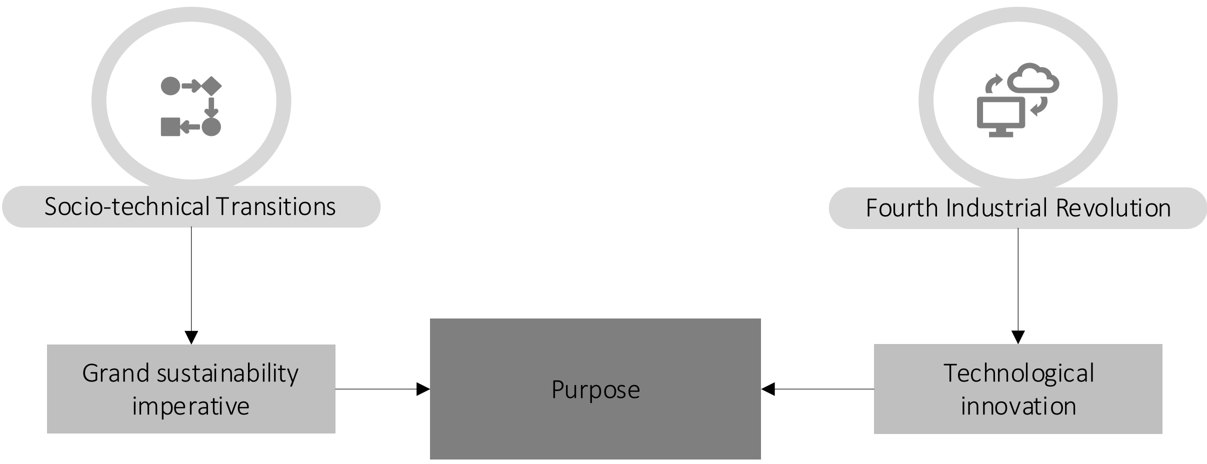

Figure 36: Purpose relationship aspects.

Through 'purpose', the framework demonstrates how the 4IR is integrated in the grand sustainability imperative of STTs and conversely how the 4IR's technological innovation and value creation are encompassed as key factors in STTs analysis.

6.3.1.1 GRAND SUSTAINABILITY IMPERATIVE

From an STTs perspective, contemporary societies are faced with multiple grand sustainability and sustainable development challenges such as climate change, global warming, long standing illnesses, epidemics and social inequality (United Nations, 2019). Geels (2011) highlights that a characteristic of STTs is that they are often goal oriented and purposive i.e., they are enacted in efforts to address such grand societal sustainability and sustainable development challenges for the greater societal good. Solutions to these challenges are largely embedded but not restricted to global and national directives and targets such as the SDGs (United Nations, 2019). Within STTs, sustainability and sustainable development targets and goals set to address grand sustainability challenges such as the UN SDGs are encompassed as guiding visions for transitions within contemporary societal systems (Geels, Sovacool, *et al.*, 2019; OECD, 2016, 2019a).

Literature analysed shows that a key connection between the 4IR and STTs is the quest towards sustainability (refer to Sections 2.2.3, 2.3.3, and 2.3.4). To further demonstrate the employment of the 4IR as part of sustainability imperative in contemporary societal systems, Table 18 displays various examples from grey literature where 4IR technologies are integrated in various societal systems, with the purpose of contributing solutions to grand sustainability challenges.

Table 18: Exemplification of the integration of societal systems and 4IR technologies through aspects of the I4IR-STT framework's perspectives.

Technology	Societal System	Examples of specific technology[6] utilised	Societal system's grand sustainability challenges	Sustainability solutions contributed to	Societal system's challenges for the utilisation of technology
Artificial Intelligence (AI) (Niestadt *et al.*, 2019; OECD, 2019a)	Transportation[7]: Specific applications in road transport.	Autonomous vehicles (AVs). Digital ride sharing platforms such as Uber that use AI algorithms.	Increased number of vehicles which still widely depend on fossil fuels leading to increased carbon emissions contributing to global warming. Efforts to improve or reduce mental, physical and emotional strain on road users. Reduction in the number of traffic-related accidents.	Traffic management leading to less traffic congestion and hence reductions in vehicle emissions. Enabling of ride sharing platforms contributes to the minimization of the number of cars on roads, resulting in reductions in traffic pollution. Improvement of road and rail safety through autonomous vehicles and trains which contributes to less crashes, and more human lives saved from accidents.	Legal, safety and ethical concerns from user data collection and its safety. Ethical concerns for AI having full autonomy in decision making and observation of safety regulations such as traffic rules. Workforce disruption for drivers in the transportation business. Lack of policy on the disposal or replacement of existing assets and infrastructure.
	Health systems.	Big Data and analytics for tracking and disease detection. Machine Learning (ML) and deep learning algorithms.	Long standing illnesses without cures for example non communicable diseases such as heart blood pressure and cancer. Emergence of global health issues such as pandemics. Lack of access to health care services in some areas of the world.	Enabling precision medicine. Fostering mobile health care; early detection of patient medical conditions; optimising clinical decision making. Accelerated discovery of new treatments and medications. Optimised management of health systems. Surveillance and alerts of disease breakouts	Concerns for data usage, its security and patient privacy. Large amounts of un-synthesized health data for decision support due to health systems operating in silos.
	Agriculture/Food production.	ML algorithms. Predictive Analytics. Agricultural robotics.	On the supply side: drought, plants and animal diseases and crop pests. The need for food production efficiency. On the demand side: food supply shortages due to drought and low agricultural yields.	Improving cognitive computing technologies on farms which identify crop readiness and diseases, thereby improving agricultural yields. Monitor crop and soil health and the impacts of environmental factors on existent yields for further yield optimisation.	Lack of adopted standards and interoperability of health systems.
IoT (OECD, 2016; Papetti *et al.*, 2018)	Energy (Motlagh *et al.*, 2020).	Sensors, actuators, and communication technologies (e.g., connectivity to the internet though Wi-Fi) attached to physical things for monitoring energy. These result in the formation of Smart "Things" e.g., smart-grid systems for electrical grids, smart buildings and cities, smart meters in homes and battery energy activation systems; Digital platforms for monitoring of energy usage.	Global warming from rising carbon emissions.	Reduction and optimisation of energy usage. Reduction of carbon emissions. Increasing efficiency of energy production.	Digital security and privacy risks or concerns with large amounts of data being collected from various sources.
	Transportation (Maciej Kranz, 2018)	Sensors, actuators and communication technologies embedded into various modes of transport to create "smart transportation". Digital platforms.	Global warming from rising carbon emissions	Reduce traffic congestion and air pollution hence reduction in carbon emissions; Reduction in energy wastes from current transportation modes.	Accountability, transparency and consent for data collected and used by institutions and authorizing bodies.

[6] Technologies presented here also fall under the scope of 4IR technologies but are broken down to the specifics of the technologies which may include processes, products or artefacts or systems (Sandén & Hillman, 2011).

[7] It is noted that the transport system has a wide scope of modes including rail, water and air transportation. However, literature shows that the use of AI is significantly more developed in road transport compared to other modes of transport such as air, rail and water. AI applications in these modes of transport is still under research and development (Niestadt *et al.*, 2019).

Technology	Societal System	Examples of specific technology[6] utilised	Societal system's grand sustainability challenges	Sustainability solutions contributed to	Societal system's challenges for the utilisation of technology
	Urban planning covering systems such as transportation, energy; and waste management (Maciej Kranz, 2018)	5G, Wi-Fi and other local or wide area networks linked with sensors, data analytics leading to other technology applications such as: smart water technology; automated street lighting; remote controlled irrigation; on-demand waste pick-ups; optimised bus routes.	Climate change and global warming. Pollution of from cities and urban living.	Reduce traffic congestion and pollution; Reducing and optimising water and energy usage; Optimised waste management	Policy development surrounding the development and use of some of these technologies.
	Public Health (Maciej Kranz, 2018)	Sensors and analytics for pollution	Air and water pollution	Reduce air pollution; Increasing quality of air and water resources for human living	
	Agriculture (Maciej Kranz, 2018)	Drones, cameras, sensors; tracking and analytics for precision agriculture. Sensors and Big Data analytics for waste elimination	Natural disasters such as drought; famine in some countries and need for food production efficiency.	Reduce consumption of resources such as water and fertiliser, thereby cutting out waste and increasing yields; Cutting out food wastage	
	Health systems (Maciej Kranz, 2018; OECD, 2018)	Sensors and robotic assistants for real time patient data or screening. Tracking and analytics	Improving health care service provision for patients.	Enabling precision medicine; Fostering mobile health care; Early detection of patient medical conditions.	
Digital Platforms (OECD, 2019b)	Health systems (Vital Wave consulting, 2012; Wyber *et al.*, 2015)	Digital platforms such as search engines like Google. Social media platforms such as Facebook, Twitter, etc Real time analytics Network analytics e.g., social network analytics and sensors obtaining data from various sources. ML Algorithms to analyse and interpret the data.	Need for faster response in health interventions to minimize fatalities and optimise health care delivery. Longstanding illnesses or diseases connected to lifestyle and habits; Sporadic disease outbreaks	Tracking of the spread communicable diseases such as flu, zika virus, Ebola etc and enabling development of intervention strategies. Combined visualisation of health and lifestyle data for holistic patient health views. Understanding of disease diffusion and spread e.g., during pandemics. Clinical decision support and optimising resource allocation.	Policy questions concerning personal data and the access to it. Lack of interoperable data for to effectively utilise the technology. Lack of interoperability of information systems. Fragmentation of health care facets e.g., lack of coordination and continuity within different facets of patient's wellbeing and lifestyle.
Big Data and Analytics	Transport (Stanley *et al.*, 2019)	Visualisation or analysis of real-time usage of transport networks through data from cameras, sensors, microcontrollers, GPS devices. Real time analytics; ML algorithms Digital platforms i.e., ride sharing platforms such as Uber.	Carbon emissions Traffic congestions Accidents and road fatalities	Optimise public transport to minimise congestion. Monitor emissions into the environment. Monitoring road user behaviour	Ethical considerations and uncertainties on privacy. Unreliability of data points. Government intervention
	Education (Vital Wave consulting, 2012)	Network analytics e.g., social network analytics and mobile analytics	Poor quality and access to education	Data to improve public sector understanding of education trends, needs and knowledge gaps in a population group.	
	Energy (Gupta *et al.*, 2018)	Real time analytics for example from applications for "smart" homes (connected to IoT)	Energy over consumption and high carbon emissions from fuel usage.	Enabling energy conscious environments.	
	Agriculture (Vital Wave consulting, 2012)	Analytics on trends on food or agricultural consumption and demand/supply dynamics. Use of mobile or financial applications for this.	Food wastage; Drought	Optimising the agricultural food supply chain i.e., from production to consumer, reduction of wastes and spoilage; identifying regions in agricultural stress or other agricultural needs for assistance.	

As can be seen in Table 18, 4IR technologies are envisaged to contribute to solutions to grand sustainability and sustainable development challenges such as climate change and global warming within the societal systems where they are being utilised. 4IR technologies are emerging in global societal systems as niche innovations and are taking advantage of windows of opportunity created by pressures from the landscape (Elzen *et al.*, 2004; Geels, 2011; Geels, Sovacool, *et al.*, 2019). For example, the global warming challenge creates pressure on regimes to reduce carbon emission and hence creates opportunities for the rise of 4IR technologies such as IoT and analytics in monitoring energy usage across different sectors. This exemplifies an alignment of the 4IR towards a grand sustainability imperative driven by STTs.

6.3.1.2 TECHNOLOGICAL INNOVATION

From a 4IR perspective, technological innovation is evidently a key marker of the revolution as innovative technologies are creating new products and processes for societal systems and creating avenues to add value to various businesses, industries and sectors (Pantuliano, 2020; World Economic Forum, 2020). As previously mentioned, STTs are described as processes that involve continuous processes of innovation in niche spaces (Geels & Kemp, 2012). 4IR technologies have emerged contingently into societal systems through the inherent continuous innovation process in multiple niche spaces across various sectors. This may be exemplified through the rise of the use of Big Data and analytics, ML and AI for business advantage. However, such emerging technologies also show potential for sustainability benefits for the societal systems they are being utilised or developed in. This may be exemplified in the adoption of ML, and Big Data and analytics in societal systems such as health systems to improve health care or AVs in transport (See Table 18 below).

STTs thrive on the continuous innovation processes in the niches, as the ultimate STTs involves the change from one incumbent technological system to another through niche innovations breaking through which triggers changes in the broader supply chain, infrastructure and policies (Geels, Sovacool, *et al.*, 2019). For example, in energy, contemporary 4IR advancements such as the development of IoT related devices have created opportunity for monitoring and optimisation of usage through the harnessing of energy data and visualisation through digital platforms and cloud computing (Motlagh *et al.*, 2020). This is encouraging shifts across the value chain i.e., in energy production process towards the advancement of national initiatives to cleaner or renewable energy sources, to the reduction in waste in the supply process through technology infrastructure such as smart grids and adjustments in consumer behaviour through the monitoring of their energy use (Motlagh *et al.*, 2020).

Although, the grand sustainability imperative by STTs may not necessarily be the overarching initiator for the development and adoption of the 4IR technologies, it is a key driver in how these technologies are advanced within society. Conversely, contemporary technological innovation with the 4IR is not always purposed by sustainability but the advancement of the 4IR is contributing to shifts in societal systems as the 4IR is continuously shaped by how society may harness it for the greater good (World Economic Forum, 2020). This evidences clear parallels between the STTs and the 4IR in terms of the overarching goals these two concepts are set to achieve in contemporary societal systems.

6.3.2 SYSTEMIC DEPENDANCIES

The system and process dependencies relationship explains the integration of the 4IR and STTs across aspects that describe the unique internal functioning of the concepts. Aspects of the I4IR-STT framework from each concept identified to contribute to this relationship include the multidimensional and co-evolutionary characteristic of STTs and the multi-technology interconnectedness and interoperability aspect of the 4IR as shown in Figure 37 below:

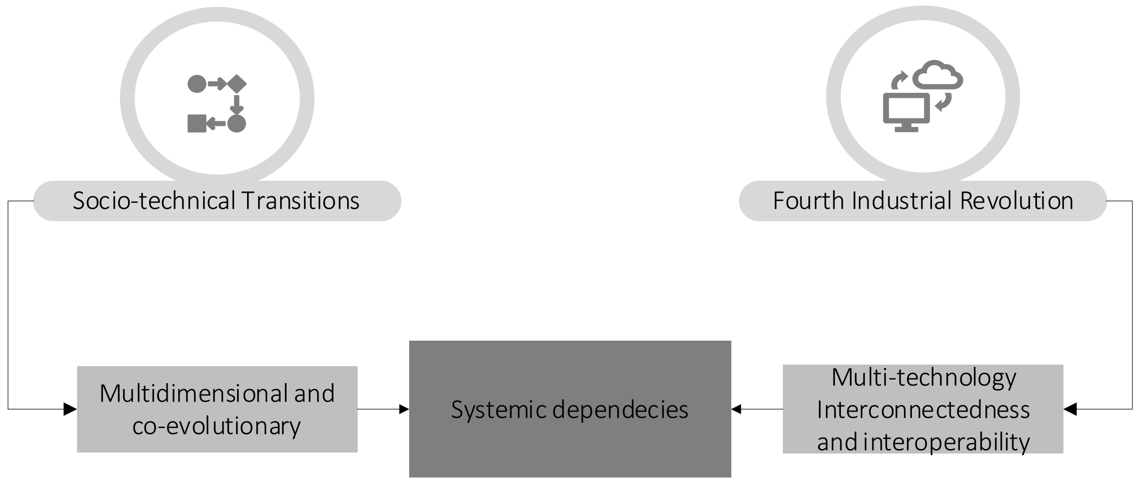

Figure 37: System and process dependencies aspects.

6.3.2.1 MULTIDIMENSIONALITY AND CO-EVOLUTIONARY

STTs are described as multidimensional and co-evolutionary as they consist of different aspects such as technologies, markets, user practices, knowledge, infrastructure and industrial structures changing simultaneously. They are not linear but involve multiple interdependent developments across these aspects. It is observed in literature (such as that exemplified in Table 18) that grand sustainability challenges cut across multiple societal systems for example global warming and rising carbon emissions are a challenge across transportation and energy systems. This is also as a result of these systems being functionally interconnected through other mutual technologies such as the use of fossil fuels (Sandén & Hillman, 2011).

6.3.2.2 MULTI-TECHNOLOGY INTERCONNECTEDNESS AND INTEROPERABILITY

A uniqueness of the 4IR is that it involves the fusion of multiple technologies which blur lines across digital, physical and biological domains for example the creation of IoT through the connection of network systems and physical artefacts or new materials emerging from the integration biotechnology with physical materials (Schwab, 2016). Furthermore, 4IR technologies are shown in literature to be functionally interconnected.

Furthermore, the relationship between the 4IR's driving technologies and the incumbent regime also plays a vital role in the adoption and utilisation of 4IR technologies within societal systems. For example, technology complementarities as described in STTs literature such as Sandén & Hillman (2011) suggest that technologies that arise symbiotically and are in support of the incumbent technologies to meet set targets may offer better support to the transition process within the societal systems where they are utilised as regime actors are given opportunity to "buy-in" to the technologies. This may be exemplified in the modular approach to the utilisation of AI in autonomous vehicles in the transport industry where the OECD describes a six-stage standard for the development of AVs, of which the first four stages are the incorporation of AV functionalities in current vehicle modes (OECD, 2019a).

The overall adoption and utilisation of multiple technologies within the same system towards similar function and/or sustainability or sustainable development targets may better support or reinforce the transition process within the societal system. This can be expected to create ripples that foster co-evolutionary dynamics across systems as pertains to STTs. At a macro level (such as global, national or sectoral levels), 4IR technologies are making small aggregable changes to multiple societal systems in the way they are structured, their policies, markets, user preferences and institutional focus which can be anticipated to retrospectively contribute to global transitions.

6.3.3 ACTOR ENGAGEMENT

The actor engagement relationship explains an integration of the 4IR and STTs based on similarities in how actors interact with and within the two concepts. As shown in Figure 38 below, aspects of this relationship include multi-actor involvement, values and normative directionality and open ended and uncertainty aspects of STTs as well as strategy and policy and socio-economic factors from the 4IR.

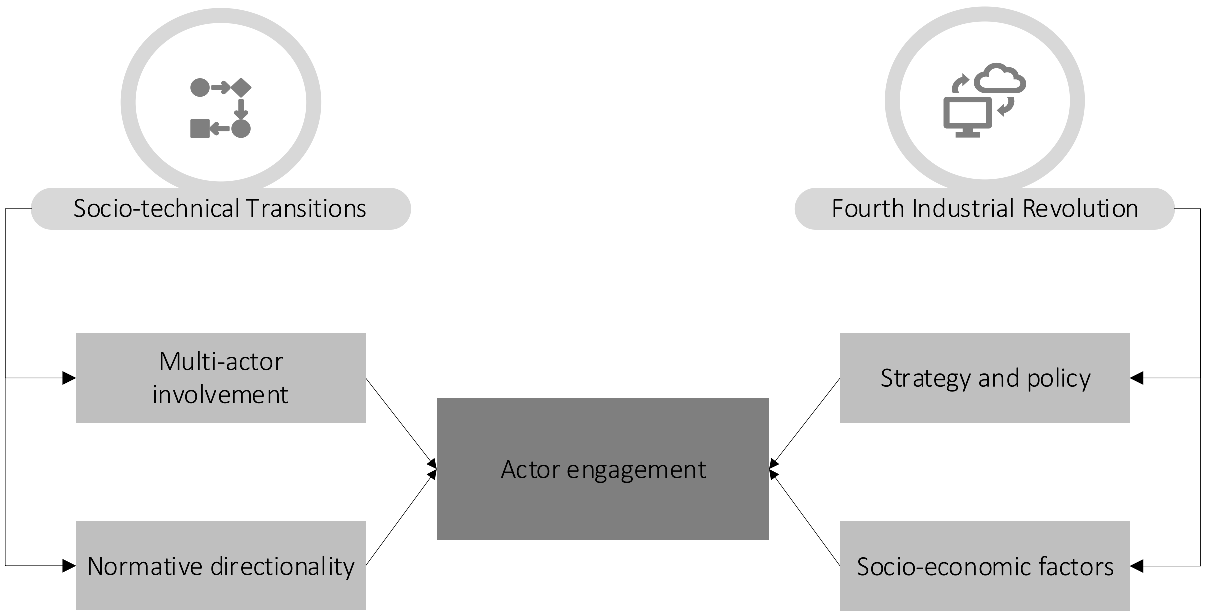

Figure 38: Actor engagement relationship aspects

6.3.3.1 MULTI-ACTOR INVOLVEMENT

STTs are described in literature to involve the interaction of multiple societal actors such as individuals, civil society groups, institutional and organisational networks, political figures and institutions, industry and business figures, academia and innovators (Farla *et al.*, 2012). These actors make up the fabric of society through and for which systems are designed to fulfil societal functions and that influence that functioning of said systems. Actors may be encompassed on either the supply or production side of a societal system or on the demand or user side of the same system (Geels, 2004). They also occupy the different dimensions of STTs i.e., they are found actively engaging in niches, for example academia, innovators, investors involved and invested in the innovation process; in the regime through actor networks actively engaged in political and economic institutions, organisations and market structures, and have influence through landscape shifts and changes such as social movements and protests. (Berkhout *et al.*, 2004)

Similarly, the 4IR involves multiple actors from different transitions dimensions, domains and fields. 4IR technologies have scalable usability from individuals use of digital platforms, to systems, product and process design and discussions within businesses, institutions, organisations and industries, and to government initiatives such as security (World Economic Forum, 2020). Actors from these different dimensions and domains are critically engaging in activity that analyses and shapes the 4IR within their contexts especially towards sustainability targets. (World Economic Forum, 2019).

Furthermore, within STTs, actors have different interests and values which influence the trajectories and pathways in which STTs occur. Global sustainability challenges such as climate change, global warming and social inequality have created guiding visions that civil and institutional actors are actively driving in the utilisation of 4IR technologies[8]. This, in part and from a 4IR perspective, is aided by technologies such as the use digital platforms, Big Data and analytics which enable the visualisation and analysis of data on various global social, economic, and environmental sustainability metrics. As shown in Figure 39 below, actors are thereby able to drive and advocate for agency and change where sustainability and sustainable development issues arise (Johansson & Scaramuzzino, 2019; World Economic Forum, 2019). Such action reinforces the 4IR through an increase in an innovative drive and the development of technologies in efforts to address such global sustainability issues (Müller *et al.*, 2018). This may further reinforce pressures, stress, and tensions on existing systems to transition and contribute to the further establishment of protective spaces for 4IR technological and market niches for such innovations to develop and break into the regime (Geels, 2004, 2005). As Berkhout *et al.* (2004) argues, actor visions towards sustainability are effective in seeding a transition through actors' engagement at the macro level where legislation and general opinion are defined, and are later channelled into market and regulatory signals which then in turn influence the adoption of technologies which originate at the niche micro-level.

Civil society engagement is observed at different scales in the contemporary world. For example, at a macro level, the United Nations Environment Programme (UNEP) lists over 600 civil society groups in various categories such non-governmental organisations, women groups, children and youth groups from over 60 countries across the globe (UNEP, 2020a). These groups are given observer status over the organisation's sustainability endeavours and are included in dialogue towards decisions making and policy formulation (UNEP, 2020b). At a micro level, other examples show communities taking matters into their hands and are reportedly initiating and building projects to meet sustainability needs such as renewable energy and enact transition processes in their local contexts (Ison & Langham, 2015) and/or using 4IR technologies to drive initiatives e.g., Omdena, a platform for global collaborative AI solutions development for grand sustainability challenges (https://omdena.com/projects/#running_challenges).

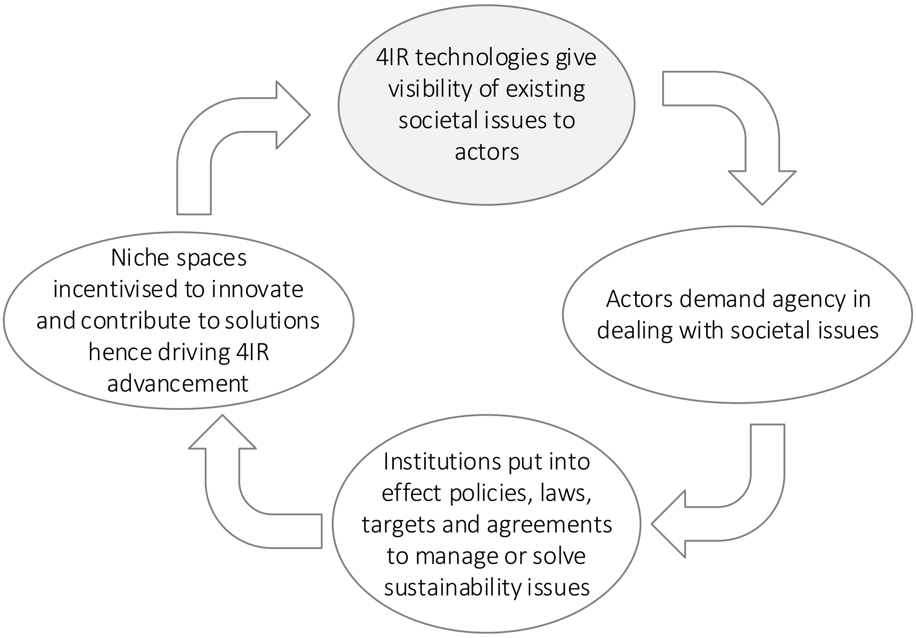

Figure 39: Exemplification of a reinforcing dynamic between the 4IR and STTs through actors in societal systems

However, as described with STTs, varying actor visions within regimes and niche spaces also cause internal conflicts towards stability and change. For example, a key value and vision in STTs is environmental sustainability which is largely reflected in literature on challenges such as climate change or global warming and the application of 4IR technologies towards combating such challenges (Best *et al.*, 2020; Köhler *et al.*, 2019; OECD, 2011; Stock *et al.*, 2018). It is envisaged that the long-term environmental sustainability gains may only effectively be realised when there is collective growth in the development and adoption of 4IR technologies towards sustainable targets across multiple aggregated societal systems (Schot & Kanger, 2018) Literature, however, also shows that there are growing debates on the overall sustainability potential of the 4IR through the evaluation of the negative impacts that 4IR technologies have on the environment (Best *et al.*, 2020). This may create conflicting social perceptions about 4IR enabled STTs where on the one hand, the 4IR is seen as an aid to solving grand sustainability challenges, yet on the other hand it may have a negative impact in solving these issues in the future. In the analysis of STTs, this may demonstrate an opening up of channels through which possible lock-ins and resistances from the regime may arise and which may in turn imply a longer time-span for the adoption of novel technologies and thus an even longer time before the sustainability gains from the adoption of 4IR technologies.

6.3.3.2 SOCIO-ECONOMIC FACTORS

Societal systems are often entrenched systems with locked in production and consumption patterns which make it difficult to embrace new technological innovations. Regime actors may be slower at adopting the technologies due to vested interests such as investments and consumption patterns with the incumbent technology and actors may struggle to abandon them and which creates stabilisation within the system and difficulty for the system to adopt new technologies (Geels, 2012; Geels & Kemp, 2007). An example of this is the adoption of autonomous vehicles (AVs) within the transport system. Consumers who already have non-autonomous vehicles may struggle to adopt AVs with immediate effect for sustainability contributions they have. Furthermore, such products due to having a smaller market share, are unable to achieve economies of scale yet, which makes it difficult for the everyday consumer to pay for the more sustainable product because of the higher cost price (OECD, 2019a). As mentioned, change that is necessary to achieve long-term sustainability visions for the greater good, although necessary in its aggregation, often only happens incrementally through small innovations and changes in practices in STTs (Berkhout *et al.*, 2004). Furthermore, resistances brought about by entrenched consumption patterns lengthen the adoption and establishment process of 4IR technologies and the consequent realisation of sustainability targets (Berkhout *et al.*, 2004).

Additionally, innovation is not always driven by visions towards grand societal sustainability. Technological innovations such as those in the 4IR are also driven by business cases such as profitability in their adoption and implementation and for their competitive advantage (Müller *et al.*, 2018). For example; contemporary actors in industries and business have needs to optimise and create efficient systems to save time and money. The use of technologies such as AI, ML and analytics offer innovative solutions to such optimisation challenges (OECD, 2016, 2019a), but they also present challenges for society such as the future of jobs and employment for workers (Nam, 2019). Another case may be observed through social digital platforms such as Facebook which are typically structured by monetization strategies that involve the selling of data to third-party companies to generate revenue. However, in such cases, the need to stay competitive often ripples into repercussions contrary to society’s desired goals such as combating security, political peace and long-term combating of social-inequality through fair justice and political systems (Kozlowska. Iga, 2018; Ur Rehman, 2019; World Economic Forum, 2019).

Furthermore, literature highlights a number of other hindrances and challenges actors are facing in the adoption and utilisation of the 4IR within contemporary societal systems. Some of these challenges and hindrances include:

i. Ethical concerns for the adoption of some of the technologies such as the development of AI, the use Big Data and analytics in systems such as health care;
ii. Lack of developed infrastructure to fully utilise technologies in some areas for example sub-Saharan Africa’s landscape is still too underdeveloped to adopt advanced technologies such as AI;
iii. Cyber security and safety concerns due to the involvement of people’s personal data across multiple platforms and the use of that data to advance technologies; and
iv. Concerns for the job security and the future of employment with the adoption of technologies.

Lastly, the above-mentioned factors are shown in research demonstrated by hype cycles (Gartner Inc., 2020a,b). The varying dynamics between envisioned 4IR technological potential, cyclical yet unpredictable user perceptions and values of these technologies and the trends in technology adoption and diffusion demonstrate the complexity of the 4IR within contemporary societal systems especially towards sustainability. This, STTs analysis describes, makes the transition process with 4IR unpredictable and uncertain and with the potential to span over decades before grand targets are achieved (Köhler *et al.*, 2019).

6.3.3.3 NORMATIVE DIRECTIONALITY, STRATEGY AND POLICY

4IR technologies are contemplated to influence a large part of social norms and require significant value shifts amongst users (Schwab, 2016). Social actors are not only enabled but are also required to behave and function differently in order to effectively utilise these technologies within societal systems in order to achieve envisioned sustainability goals. The need for normative direction on what transitions with the 4IR ought to achieve are therefore imperative, as although sustainability or sustainable development ensures public good for society and future generations, it is not always pursued by private actors who may hold conflicting interests (Köhler *et al.*, 2019). STTs involve change that includes normative frameworks that guide the production and consumption of technologies (Köhler *et al.*, 2019).

STTs describes directionality to be enacted through regulations, standards, policies and subsidies from the regime (Elzen *et al.*, 2004; Geels & Schot, 2010; Köhler *et al.*, 2019). 4IR literature highlights the need for directionality through policy and strategy in policy development at different institutional levels (refer to Sections 2.3.2, 4.1.5.1 and 4.1.5.2). STTs literature highlights frameworks that offer direction for public policy development including resistance strategies, technology diffusion strategies, process management and innovation policy; all of which may be relevant in the contemporary analysis of the 4IR (Bergek *et al.*, 2008; Frantzeskaki & de Haan, 2009; World Economic Forum, 2017).

In summary, through the I4IR-STT framework an integration of the concepts of the 4IR and STTs has been demonstrated. The framework proposed two perspectives i.e., a transitions and technology perspective to approach the integration. From each perspective, aspects of the respective concept from literature are identified and used as aspects of the framework for integration as shown in Figure 40 below. The framework then integrates the 4IR and STTs through these aspects. A summary of the integration is presented in Table 19 below:

Table 19: Summary of the I4IR-STT framework integration of STTs and 4IR

I4IR-STT framework relationship	Framework aspects	STTs and 4IR integration
Purpose	STTs: The grand sustainability imperative 4IR: Innovation	STTs are driven by a sustainability imperative which contemporary 4IR technologies are envisaged to contribute towards. The 4IR is driven by technological innovation which is encompassed in the analysis of STTs and plays a key role in how transitions occur.
Systemic dependencies	STTs: Multidimensional and co-evolution 4IR: Multi-technology interconnectedness and interoperability	STTs are multidimensional and co-evolutionary processes requiring the simultaneous change of technologies, markets, user practices, knowledge, infrastructure, industry and policy. The 4IR consists of a fusion of interconnected and interoperable technologies that cut across multiple systems and industries and are envisaged to effect changes across markets, user practices, infrastructure, policy and strategy as with STTs.
Actor engagement	STTs: Multi-actor involvement STTs: Values and normative directionality 4IR: Strategy and policy 4IR: Socio-economic factors	Both the 4IR and STTs involve multiple actors from all dimensions. Global actors in STTs are engaging with the 4IR are demonstrated to show similar behaviour and conundrums and having resulting effects on the 4IR trajectory as described in STTs analysis. Furthermore, the need for strategy and policy to foster the advancement of the 4IR towards sustainability targets is crucial to achieving set targets.

Figure 40 below presents the final design of the I4IR-STT framework in accordance with Van Aken *et al.* (2007)'s development process presented in Chapter 5, Section 5.4. It is important to note that the framework's purpose, systemic dependencies and actor engagement relationships are not mutually exclusive and thus possess interconnections. This is represented by the dotted lines in between the relationships in the I4IR-STT framework as shown in Figure 40. Given the aim of the framework i.e., to provide a premise for the integration of the 4IR and STTs; interconnections between the framework's relationships are not explicitly explored in this research but are acknowledged and suggested for further work. In the next section, an operationalisation strategy for the framework is presented.

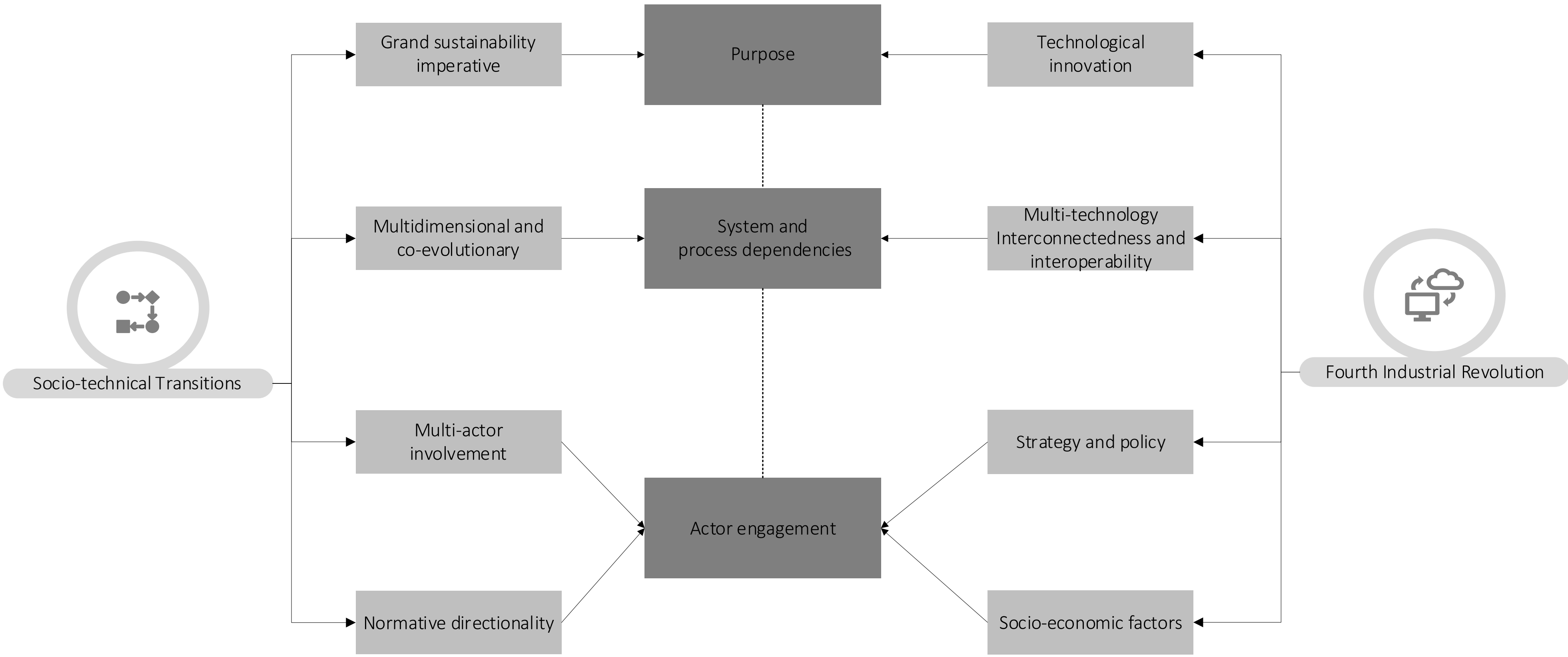

Figure 40: I4IR-STT Framework

6.4 OPERATIONALISATION OF THE I4IR-STT FRAMEWORK

The I4IR-STT framework is developed with the primary aim of demonstrating an integration between the 4IR with STTs within the global contemporary context. Through the I4IR-STT framework, distinct overlaps have been highlighted between STTs and the 4IR, which demonstrate an integration between the two concepts. However, it is also noted that the framework facilitates an understanding of the integration between the concepts and is thus not geared towards actioning any insights obtained from the framework towards a specific societal system context. It is on this premise that an operationalisation strategy is developed for the framework.

6.4.1 PURPOSE OF OPERATIONALISING THE I4IR-STT FRAMEWORK

The main aim of the operationalisation strategy is to enable one to apply the I4IR-STT framework in understanding the STTs and 4IR integration within a specific societal system of interest towards or within a transitions process. It is important to conceptualise the integration between the 4IR and STTs for the following reasons:

i. **Understanding the dynamics of change:** The 4IR has been described to be creating shifts on the global spectrum on how society defines itself and its functions (Schwab, 2016), and thus how societal systems are structured and operate. These shifts have become increasingly important within sustainability literature as the 4IR has implications for society and the technologies that drive it have demonstrated potential for contributing towards global sustainability initiatives. The analysis of STTs demonstrates a way of thinking about and addressing grand sustainability challenges in societal systems to bring about wide-scale global change. Overlaps between the two are key in understanding the contemporary change modern societies are undergoing;

ii. **Emphasis of agency:** A key factor to change within societal systems is the involvement of actors who demonstrate the ability to make individual or collective decisions that aggregately contribute to systemic transitions. STTs literature highlights that the transitions process may not be planned but it may be influenced (Elzen *et al.*, 2004; Köhler *et al.*, 2019; Markard *et al.*, 2020; Schot & Kanger, 2018) i.e., STTs may not be planned per se but actors have agency and may be able to influence aspects of transitions within their contexts. Furthermore, it is envisaged that the 4IR presents opportunities to influence the trajectory of agency within societal systems actors through the shifts the revolution presents.

Technologies play a key role in the transition process as transitions occur when new STS configurations are formed around technologies, replacing the old ones to meet a societal system’s needs (Köhler *et al.*, 2019) and hence developing intervention efforts to influence the transition process is of valuable contribution towards sustainability and sustainable development targets and goals. In this section, an operationalisation strategy for the I4IR-STT framework is presented. The operationalisation strategy is developed to enable practical utility of the framework and enable the user to apply the framework to develop an understanding of STTs and 4IR integration in a practical real-world/case.

6.4.2 DEFINING THE I4IR-STT FRAMEWORK'S USER

The I4IR-STT framework is designed to demonstrate an integration between the 4IR and STTs. Users, therefore, ought to have sufficient insight into both concepts in order to understand the conceptual integration of both of them as per the framework's boundary condition B2 (refer to Table 16, Section 5.2). Furthermore, the framework utilises systems thinking and industrial engineering tools and principles, of which prior basic knowledge would be beneficial to the user.

The operationalisation of the framework involves applying the framework's approach to the integration of STTs and the 4IR to a real-world societal system. Therefore, as a pre-requisite to operationalising the framework, a user ought to have sufficient knowledge of the system unit under analysis in order to effectively utilise the framework in understanding STTs and 4IR integrations within the system as stipulated with boundary conditions B3 of the framework's requirement specifications (refer to Section 5.2.3).

Given the above-mentioned specifications, potential users of the I4IR-STT framework and its operationalisation strategy may include but are not limited to:

i. Subject Matter Experts (SMEs) such as researchers and academics within the fields of the 4IR and STTs analysing both concepts and expanding on the body of knowledge;
ii. Practitioners in societal systems such as agriculture, energy and health care that are analysing the concepts of STTs and 4IR within their systemic context; and
iii. Various stakeholders engaged or interested in the sustainability for societal good such as innovators, strategists and policy enthusiasts; who are looking to expand their outlook towards sustainability targets with the 4IR and through an STTs perspective.

6.4.3 I4IR-STT FRAMEWORK OPERATIONALISATION STRATEGY

In this section, the operationalisation strategy for the I4IR-STT framework is presented. The operationalisation strategy is developed using a three-phased approach adapted from the Enterprise Engineering Process (EEP) provided in Du Preez *et al.* (2009). The EEP is adopted due its applicability within the industrial engineering domain and generic engineering design approach which allows for modification for different applications that coordinate strategic and operational demands (Du Preez *et al.*, 2009). In the context of this research, the EEP is used to structure the operationalisation strategy into a three-phased approach for guiding users in utilising the I4IR-STT framework to understand the integration between the 4IR and STTs in a societal system in analysis. The original EEP as shown in Figure 41 below has three phases i.e., an initiation, master planning and deployment phase, each of which has its respective stages as shown in the figure.

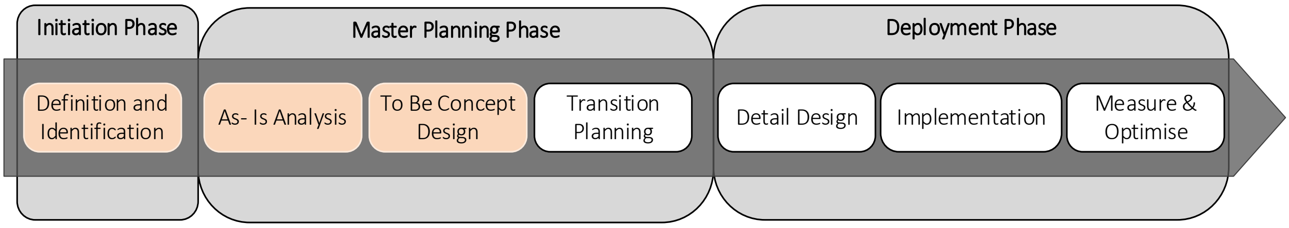

Figure 41: Enterprise Engineering Process. Source: Du Preez *et al.* (2009)

For the purposes of the operationalisation, the operationalisation strategy utilises the definition and identification stage in the initiation phase and the as-is analysis and the to-be concept design stages in the Master Planning phase. It is envisaged that the three stages i.e., definition and identification, 'as-is' analysis and 'to-be' concept design renamed are deemed appropriate for the operationalisation strategy. This is due to their orientation and alignment with the I4IR-STT framework in aiding users to understand a system under analysis towards specific goals (Du Preez *et al.*, 2009). The stages as used in the operationalisation strategy therefore are:

i. Definition and identification;
ii. 'As-is' state analysis; and
iii. 'To-be' state analysis.

These stages are envisaged to guide the user in:

i. Demarcating a societal system of interest to a specific unit of analysis and defining key informational points through the definition and identification stage;
ii. Understanding the integration of the 4IR and STTs in the current state of the system unit of analysis through the 'as-is' analysis stage; and
iii. Understanding and/or developing a future 'to-be' state for the analysed system unit's transition using the 4IR and STTs integration through the 'to-be' concept design stage.

Furthermore, at each stage, the operationalisation strategy is also presented with the following:

i. **Objective:** This describes what the operationalisation strategy aims to aid the user to primarily achieve at each stage in order to effectively utilise the I4IR-STT framework;
ii. **Supporting activities**: These aid the user in utilising the I4IR-STT framework effectively at each stage;
iii. **I4IR-STT application**: These are guidelines for the user on how to utilise the I4IR-STT framework aspects towards the understanding the 4IR and STTs integration within the system unit under analysis at each stage; and
iv. **Output:** Documented output from utilising the operationalisation strategy at each stage.

Furthermore, the operationalisation strategy also draws rationale from the applied systems thinking approach presented in Section 5.3 and from the requirement specifications as presented in Section 5.2. The operationalisation strategy and its stages are further explored in the subsections below:

6.4.4 STAGE 1: DEFINITION AND IDENTIFICATION

The objective of the definition and identification stage in the operationalisation strategy is to enable the user to demarcate the societal system of interest for analysis and define key informational points for the analysis. As Figure 42 below demonstrates, a societal system may be specified in its geographical context within which a sector encompassing the system's activities exist. Within each sector, there exist multiple industries, of which each industry has multiple value chains which may be further broken down to specific processes and activities. Given the macro level analysis approach the framework's user ought to identify at which level or unit of analysis they wish to analyse the societal system in order to apply the I4IR-STT framework through its operationalisation strategy.

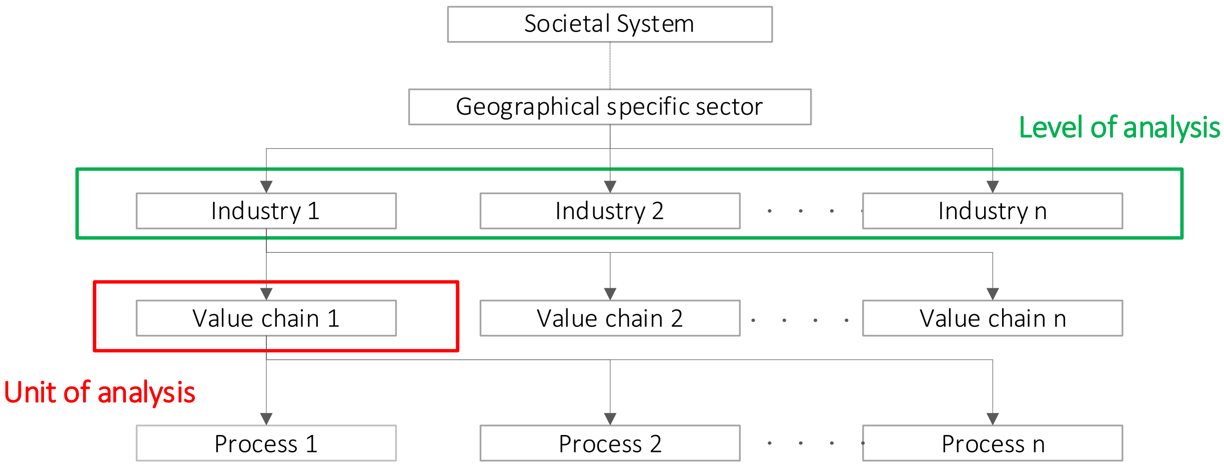

Figure 42: Societal system demarcation differentiating level of analysis and unit of analysis.

Once a system has been demarcated to a unit for analysis, the user may then utilise the I4IR-STT framework's technology and transitions aspects to identify and define the key informational points for the analysis. Du Preez *et al.* (2009) present a "what", "why" and "who" approach which is adapted for the operationalisation strategy as below:

i. The "what": The state of the system unit with regards to its sustainability and the state of the 4IR technological advancement within the system unit;
ii. The "why": Factors and drivers for the system unit's transition and transformation towards a more sustainable state;
iii. The "who": Various stakeholders in the system's unit of analysis, their needs and objectives towards achieving sustainability or sustainable development.

From this stage, the user may document the system demarcation and the identified "why", "what" and "who" in the analysis.

6.4.5 STAGE 2: 'AS-IS' STATE ANALYSIS

In the second stage of the operationalisation strategy, the primary objective is to aid the user in understanding the current state of the system unit under analysis in relation to the integration of the STTs aspects with 4IR aspects using the I4IR-STT framework. From the EEP, the as-is analysis stage involves describing current states and doing a critical analysis to identify problem areas (Du Preez *et al.*, 2009). In relation to operationalisation strategy, the user starts with supporting activity and first contextualises the system unit under analysis by identifying and understanding grand-sustainability related factors affecting the system unit. The user then utilises the framework to define and understand purpose, systemic dependencies and actor engagement relationships of the framework in relation to the system unit as below:

i. With the **purpose relationship,** the current state of the grand sustainability imperative and technological innovation aspects within the system unit are determined and highlighted. The grand sustainability imperative may include determining the sustainability challenges and proposed solutions within the system unit. Through the technological innovation aspect, the user may determine emerging and existing 4IR related technological innovations within the system and highlight 4IR technological efforts to address grand sustainability challenges as well as the effects of such technologies on the grand sustainability state of the system unit.
ii. With the **systemic dependencies relationship**, the user may determine systemic interconnections through the 4IR and their effects on the sustainability imperative of the system unit. Furthermore, the user may also determine factors that determine and demonstrate the interoperability between 4IR technologies and the system unit's incumbent technologies.
iii. With the **actor engagement relationship**, the user may determine actor perceptions of technology and socio-economic factors arising from the engagement with the 4IR and its driving technologies. Furthermore, the user may also determine contemporary system unit strategies and policies giving normative directionality towards the integration of the 4IR within the system unit towards its grand sustainability.

The above insights equip the user to understand the current state of the system unit of analysis and identify problem areas to be addressed in utilising 4IR technologies towards grand sustainability targets (Du Preez *et al.*, 2009) which are important for addressing in the third stage of the operationalisation strategy.

6.4.6 STAGE 3: 'TO-BE' STATE ANALYSIS

Lastly, with the third and final stage of the operationalisation strategy, the objective is to enable the user to understand and determine strategic recommendations for the analysed system unit, with the hope of addressing problem areas identified and contribute towards the system unit's transition process to a desired 'to-be' sustainable state. Using the I4IR-STT framework relationships, the user utilises the purpose relationship to highlight and identify the sustainability objectives of the desired 'to-be' state as well as proposed solutions to identified challenges. Furthermore, the user may identify or highlight proposed 4IR initiatives in response to sustainability challenges.

With the systemic dependency relationship, the user also identifies potential technological and systemic interconnections that may affect the desired 'to-be' state. Lastly, with the actor engagement relationship, the user identifies and understands stakeholder values from both the societal system unit and 4IR sides and potential socio-economic factors that may arise need to be addressed in the desired to-be state. Furthermore, the user also identifies proposed/possible strategies and policy for further 4IR integration within system unit towards the desired to-be state. From this stage, the user may document the objectives for of the ‘to-be’ state and learnings using the I4IR-STT framework relationships as guiding points.

This concludes the operationalisation strategy of the I4IR-STT framework. A consolidated I4IR-STT operationalisation strategy is presented in Figure 43 below. The framework and operationalisation strategy are demonstrated through a practical case application in Chapter 7 as part of the evaluation process.

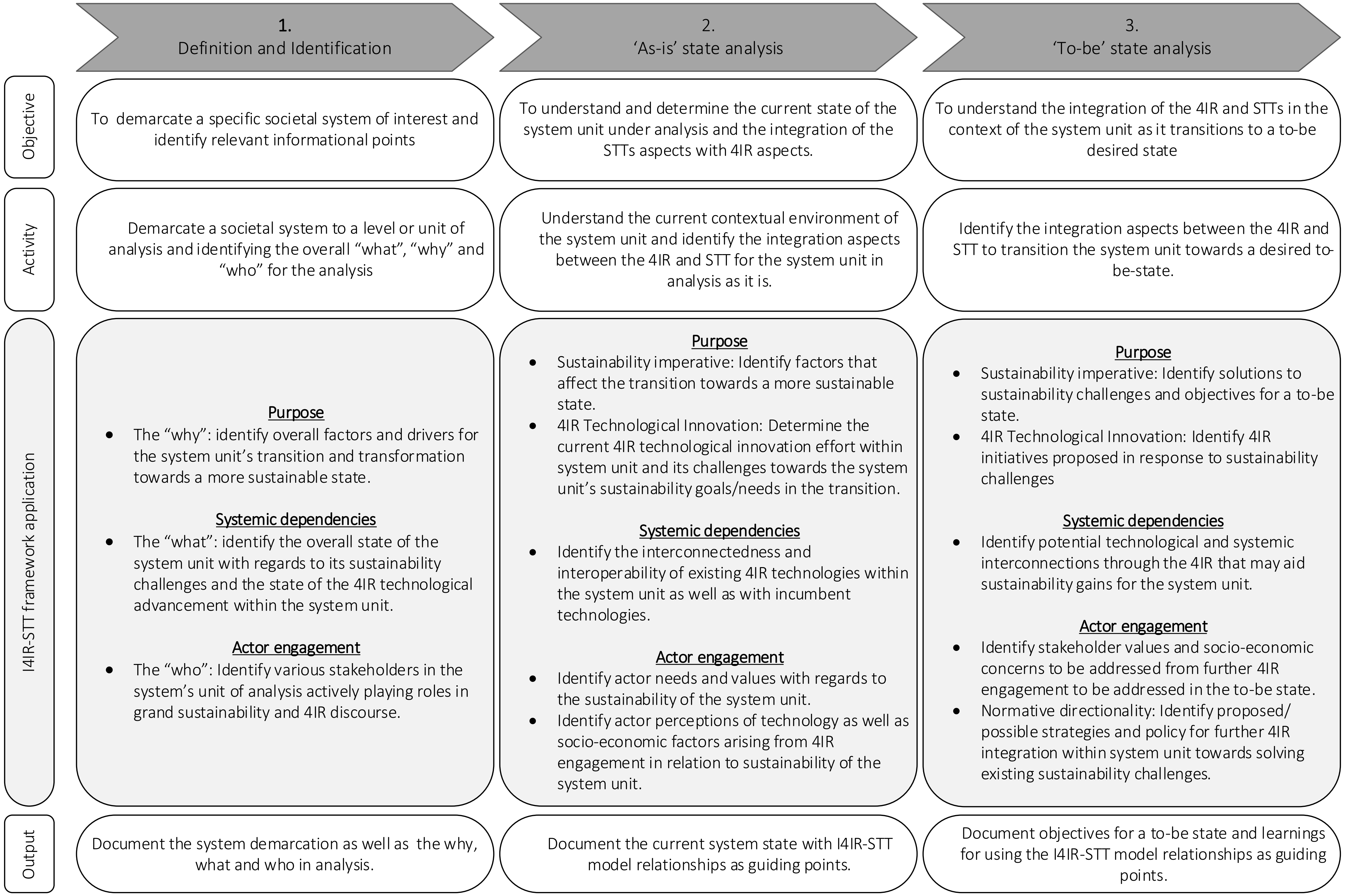

Figure 43: I4IR-STT operationalisation strategy

6.5 CHAPTER 6 CONCLUSION

In this chapter, the developed I4IR-STT framework and its operationalisation strategy have been presented. The framework utilises the aspects of the 4IR and STTs from literature as aspects for the integration. The framework considered two perspectives i.e., a transitions and technology perspective for the integration. From these perspectives, aspects are drawn for the integration from literature of the concepts through which relationships between the concepts are identified and demonstrated. The operationalisation strategy is presented to give practical utility of the I4IR-STT framework. The framework has been developed through the Van Aken *et al.* (2007)'s process management and the finalised design is presented in this chapter. The process of developing the framework was initiated with an informal sketching process formally presented through an outline design in Figure 33 and a detailed design elaborated on in Section 6.3 and diagrammatically presented in Figure 40. Furthermore, the framework and operationalisation strategy development employed an applied Systems Thinking approach as a construct guidance (refer to Section 5.3). Table 20 below summarises the applied Systems Thinking principles and where they are utilised in the development of the I4IR-STT framework and operationalisation strategy.

Table 20: Systems Thinking Principles as applied to the I4IR framework and operationalisation strategy.

Principle	Parts applied to in I4IR-STT framework or operationalisation strategy
1: Understand system structure	Perspectives and aspects of framework (Sections 6.2)
2: Understand dynamic behaviour	I4IR-STT framework relationships (Section 6.3) Operationalisation strategy system contextualisation (Section 6.4.5)
3: Reduce complexity through conceptual modelling	I4IR-STT framework representations (Figure 33 - Figure 40) Operationalisation strategy conceptual representation (Figure 43)
4: Understand system at different scales	Operationalisation strategy (Section 6.4.4)

In the next chapter, an evaluation of the I4IR-STT framework and operationalisation strategy is presented.

CHAPTER 7: EVALUATION OF THE I4IR-STT FRAMEWORK AND OPERATIONALISATION STRATEGY

In this chapter, an evaluation of the research and its products is presented. This chapter opens with an introduction to the evaluation process in Section 7.1 detailing the methodologies used to verify and validate the I4IR-STT framework and operationalisation strategy. Thereafter, Section 7.2 briefly elaborates on the verification of parts of the I4IR-STT framework conducted with some SMEs. Section 7.3 presents the verification and validation of the entire framework and operationalisation strategy with SMEs. Section 7.4 presents the author's self-evaluation of the framework's requirement specifications and lastly, a case study application of the framework and operationalisation strategy is presented in Section 7.5 preceding the chapter's conclusion. The evaluation process is conducted in fulfilment of research sub-objective 4.3 (refer to Section 1.2.1).

7.1 EVALU TION PROCESS: INTRODUCTION

The evaluation process consists of a verification process and a validation process. The verification process evaluates how well the framework meets the requirement specifications provided for its development as well as an evaluation of the theoretical consistency of the developed framework. Verification was conducted during the process of developing the framework and is specifically focused on the framework, its operationalisation strategy and the requirements specifications used to develop it. The verification process is conducted to confirm that the framework is built is correctly (Bekker, 2018) i.e., to ensure theoretical correctness of the framework's content and verify that the framework presents reasonable theory. Theoretical verification was conducted in three ways:

i. Through an evaluation of the I4IR-STT framework against the requirement specifications for its development;
ii. Through the verification of parts of the I4IR-STT framework; and
iii. Through an overall verification of the entire framework after it was developed.

The validation of the I4IR-STT framework is conducted in order to confirm whether the right framework has been built for its intended purposes. Validation therefore tests how well the framework jointly addresses and integrates the concepts of STTs and 4IR (Bekker, 2018). As specified by Bekker (2018), the framework's validation is done to achieve the following:

i. Operational validation: Ascertain whether the framework's conceptualisation of an integration of concepts of the 4IR and STTs is applicable to the real world through its operationalisation strategy;
ii. Credibility: Ensure that the end users have confidence in utilising the framework and its operationalisation strategy in understanding the integration of both concepts and applying this understanding to relevant real-world scenarios.

The validation process was aimed at testing whether the I4IR-STT framework and its operationalisation strategy fulfils the purpose of its development and provides confidence in the applicability and practicability of the developed framework and its operationalisation strategy. Validation was therefore conducted after the framework was developed and entails an evaluation of the I4IR-STT framework. The framework was validated using a case study. Case studies are described as investigations of a phenomenon within a real-life context using multiple sources of evidence (Saunders *et al.*, 2007). The case study demonstrates the usability of the I4IR-STT framework through its operationalisation strategy and is presented in Section 7.5 of this chapter.

Both the verification and validation processes were conducted with Subject Matter Experts (SMEs) in the fields of STTs and the 4IR to ensure comprehensiveness. Table 21 below details the profiles of the SMEs involved in the evaluation process with brief descriptions of their areas of expertise.

Table 21: SMEs Profiles

SMEs interviewed	Description	Date of discussion
SME 1: Dr. A	Dr. A is a senior lecturer at the Agrisciences Faculty at Stellenbosch University. Dr. A is also a key stakeholder at the Agri Innovation Hub at Stellenbosch University and is involved in research about the 4IR within the agricultural sector.	30 November 2020
SME 2: Dr. B	Dr. B is a consultant, researcher and an associate professor at Stellenbosch University. Dr. B has also co-founded a global policy-science initiative in support of knowledge and innovation for the SDGs.	15 December 2020
SME 3: Prof. C	Prof. C is a professor and chair of sustainable energy systems at Victoria University of Wellington in New Zealand.	17 December 2020
SME 4: Dr. D	Dr. D is the CEO of a company that consults in the realms of science, engineering, technology and innovation. Dr. D has expertise in conceptual modelling and operationalisation.	6 January 2021
SME 5: Prof. E	Prof. E is an associate professor and former chair of IoT at the Engineering faculty at Stellenbosch University.	12 November 2020
SME 6: Mr. F	Mr. F previously headed the innovation division at Stellenbosch University LaunchLab. Mr. F has years of experience in the incubation of start-ups developing technologies for various fields such as engineering, Agri-tech, food science and finance.	August 2020

SMEs 1-4 were involved in the overall evaluation of the entire framework and its operationalisation strategy detailed in Section7.3 and SMEs 5 and 6 were involved in theoretical verification of parts of the framework as presented in Section 7.2 below:

7.2 THEORETICAL VERIFICATION OF PARTS OF THE FRAMEWORK

During the design process, some of the ideas and examples from literature used in the development of parts of the framework were theoretically verified with SMEs. Within the context of the 4IR and its technologies, technologies are evolving and being utilised in the real-world context faster they are being documented in literature. Verification, therefore, was conducted to ensure that information obtained from literature is valid and factually sound in relation to what is happening on the ground in the contemporary 4IR technological environment. Parts in the framework that were verified include Table 18 presented in Section 6.3.1. Theoretical verification of this part was conducted with SMEs 5 and 6 respectively and was conducted through semi-structured interviews where SMEs were given a brief introduction to the research, then presented with preliminary copies of the framework's parts and thereafter a discussion ensued. Information that resulted in corrections and refinements for the above-mentioned framework parts was obtained through insights obtained through recommendations provided and indirectly through thoughts formulated from comments and insights given by the SMEs during the discussion. It should be noted that refinements are already included to the final presentation of the respective parts on page 88.

7.3 THEORETICAL VERIFICATION OF THE I4IR-STT FRAMEWORK AND OPERATIONALISATION STRATEGY

The I4IR-STT framework was verified by Subject Matter Experts (SMEs) in STTs and the 4IR through semi-structured interview discussions. Interviews were held with SMEs 1-4. Prior to meeting with the SMEs, SMEs were presented with an overview document of the research for comprehensive context of the research. Included in the overview document was the research's aims and objectives, highlights from the literature analysis conduct, an overview of the methodology undertaken including the requirements specifications and the I4IR-STT framework and its operationalisation strategy. The overview document presented to SMEs is included in the Appendix D.

A list of thematic questions was drawn up to guide the interview process, but the structure and course of the interview varied with each SME dependent on the flow of the conversation (Saunders *et al.*, 2007). The questions asked were aimed at ascertaining the following:

i. That the framework is based on reasonable and adequate theory in respect to the 4IR and STTs;
ii. That the framework's logic in integrating the 4IR and STTs is sound; and
iii. That the framework adequately addresses and represents a conceptual integration between the concepts of the 4IR and STTs.

The questions addressed three key areas i.e., the overall research, the methodology and requirements specifications and the framework and operationalisation strategy. These questions were presented to SMEs, in order to obtain meaningful feedback that addressed the above points and hence verified the framework. During the meetings, each of the SMEs was given a presentation on the research highlighting the background, problem statement and objectives, deductions from literature towards the I4IR-STT framework's development, the framework's development process and requirement specifications. The I4IR-STT framework was then presented highlighting its perspectives and their aspects alongside its operationalisation strategy. Thereafter, the SMEs were met with to discuss and conduct the evaluation process. Feedback from the discussions with SMEs is presented in Sections 7.2 and 7.3. The overall guiding questions and presentation given to SMEs can be found in Appendices E-G of this document. In the following subsections, general feedback and suggestions from the SMEs are presented and discussed below:

7.3.1 GENERAL FEEDBACK: VERIFICATION

Overall, the I4IR-STT framework developed, and the research received positive feedback from the SMEs. SME 1 expressed overall satisfaction with the approach of the framework and thinks that it is solid and meets its requirements specifications. The SME expressed confidence that the research will add value to both bodies of knowledge, stating that "*the framework is customizable and transferrable between sectors and the research can be expanded in its application*". SME 2 stated that the framework is a useful approach to understanding how the 4IR and STTs are interlinked. According to this SME, "*The framework is useful to unpack the salient elements of how literature is evolving. It is a useful tool for building on a more detailed analysis and a steppingstone for more comprehensive research. The research is robust to prepare the ground to answer how questions."*

SME 3 also expressed overall satisfaction with the framework and believes that the framework is a useful approach to understanding how the concepts of the 4IR and STTs can be interlinked. The SME stated that he did not see any glaring issues with the framework and agrees that the purpose of the framework is sound, and the framework accomplishes its stated purpose. SME 4 expressed positive sentiment towards the framework's contribution in connecting two areas that have historically been difficult to integrate; namely the social environment and the technological system. The SME expressed belief that every aspect of society can come together in a way that technology may harnessed to help society for the greater good and the framework contributes to such endeavours. The SME also believes that the framework can be "*quite powerful as an STTs framework in the context of many other things other than the 4IR for example the integration between STTs and Social Construct*". Furthermore, all SMEs expressed satisfaction with the framework's functional specifications.

All SMEs affirmed that the developed framework is based on reasonable theory in respect to the 4IR and STTs, that the logic in integrating the 4IR and STTs is sound and applicable to the contemporary societal systems. Regarding the adequacy to which the framework addresses and represents a conceptual integration between the 4IR and STTs, SMEs gave feedback and suggestions which are presented in the following subsections alongside the author's response.

7.3.2 SUGGESTIONS FOR THE FRAMEWORK AND REFINEMENTS

SMEs also presented their critiques and identified limitations of the research, I4IR-STT framework and operationalisation strategy during the discussions. SMEs' ideas and thoughts were engaged and converted into suggestions towards the refinement of the framework, its operationalisation strategy and the research in general. All suggestions accumulated from the evaluation process are summarised into four categories:

i. Suggestions that were incorporated into the framework's refinements coded "I";

ii. Suggestions that were not incorporated into the framework's refinements coded "NIL". These ideas were excluded due to limitations relating to the scope of the research;
iii. Suggestions that were given but not agreed with, coded "V". These suggestions were voided and not included in the refinements; and
iv. Additional refinement ideas which developed as thoughts that occurred to the author while engaging with SMEs, but that cannot be attributed to a specific statement or suggestion that was made by any particular SME during the verification process.

All suggestions and their respective addresses are discussed in the subsections below.

7.3.2.1 SUGGESTIONS INCORPORATED INTO THE I4IR-STT FRAMEWORK AND OPERATIONALISATION STRATEGY REFINEMENTS

SMEs provided a number of suggestions that the author incorporated into the framework refinements. These suggestions are divided into two types i.e., conceptual and structural suggestions. Conceptual suggestions pertain to the theoretical content of the framework, operationalisation strategy and the research; whereas structural suggestions pertain to the presentation and narrative of the framework, its operationalisation strategy and the research at large. Table 22 presents the suggestions made by each SME as well as their rationale, and areas where these suggestions have been incorporated in the framework and operationalisation strategy as presented in this thesis document.

Table 22: Suggestions utilised in the refinements

Type	SME	Suggestion	Rationale	Resolve
Conceptual	SME 1	I1.1: Include user perception of technology.	The SME highlighted that people's views of technology affects how it is diffused and utilised in society and argues that it is key to technology's success in achieving any targets it is intended for. Furthermore, that in line with SDGs and a macro level analysis of sustainability, the research should have a human-centred approach.	Added to framework through the Actor Engagement relationship. Refer to Chapter 6, Section 6.3.3.
		I1.2: State the stance on technology for the research i.e., does the research view technology as antagonistic or synergistic?	Following point I1.2 above, the SME argued that the research should define or state an initial stance on technology. The research implicitly indicates that 4IR technologies may be positively harnessed to aid and drive sustainability targets and therefore has a synergistic outlook. However, the antagonistic side should be acknowledged.	Included in Chapter 1, Section 1.3.2
		I1.3: Apply and test the framework to a sector system.	The SME argues that although the framework is theoretically sound, to test it with a case study would add practicability to it. The SME argued that the demonstration would also flesh out implications for sector demarcations such as value chains which add complexity to any societal system.	A case study/application is conducted and is presented in Chapter 7 Section 7.5
		I1.4: Clearly define and include the who, what and where for the framework's operationalisation strategy.	The SME advised that the operationalisation strategy should state who engages with the framework, at what point, for what system and purpose. He also further advised that if it is not explicitly defined in the operationalisation strategy or demonstrated in the case application, it should be acknowledged as the framework's limitation.	Included in the refined framework operationalisation strategy. See Chapter 6, Section 6.4.
	SME 2	I2.1: Acknowledge that as part of framework's limitations, it does not address contextual specifics such as value chain, geographical or sectoral specifics.	The SME stressed that STTs in such contextual additions dictate the nature of how 4IR technologies are being developed, diffused and adopted within societal systems. He advised that if such additions are not addressed directly	Included in the framework operationalisation strategy and acknowledged as limitations to the framework in Chapter 8 Section 8.2.

Type	SME	Suggestion	Rationale	Resolve
			by the framework, then they should be acknowledged as limitations and avenues for future works.	
		I2.2: Recognise that there are different frameworks that do not emerge in isolation such as sectoral systems of innovation. Position STTs approach in the research's narrative within the broach Systems innovation of transitions and transformations.	The SME stressed that STTs are not the only perspective or approach towards sustainability transitions. Literature's focus on the manufacturing sector should imply a sectoral systems innovation outlook towards sustainability transitions. Furthermore, the SME pointed out that the emergence of frameworks in STTs and other approaches such as sectoral systems of innovation are not in isolation i.e., there are multiple points of convergence and complementarities. The SME urged that this has to be acknowledged in the research introduction while stating the scope of the research.	The author includes these notes in Chapter 1.
	SME 3	I3.1: Facilitate and demonstrate the framework with a case study.	The SME also advocated for the application of the framework to a case study in order to demonstrate its usability.	A case study/application is conducted and is presented in Chapter 7, Section 7.5.
		I3.2: Clearly define what is meant by the term "societal system".	The SME suggested that there should be a clear definition for what the term "societal system" as utilised in the framework is, and boundaries for the term's usage.	Included in the framework's revision. See Chapter 1 Section 1.3.
		I3.3: Clearly define boundaries for analysis while using the framework i.e., level of analysis and/or unit of analysis.	The SME argued that without clear definition of the boundaries for analysis, the framework's user will be overwhelmed by the enormity of the process in analysing a system to understand its integration with the 4IR for sustainability transition. The SME argued that the framework requires a tool set to guide the user on where and how to use it.	The author agrees with the SME, and this validates the use of the framework's operationalisation strategy. The operationalisation strategy is thereby adapted to clearly give guidelines to the user on how to use the framework. See Chapter 6, Section 6.4.
	SME 4	I4.1: Express the framework's purpose as one that enables its user to better	The SME advised to explicitly state that the purpose of the I4IR-STT framework as one that helps its users understand and develop an integration	The author acknowledged these recommendations. Adjustments were made

Type	SME	Suggestion	Rationale	Resolve
		understand an integration between the 4IR and STTs.	approach between both concepts and is therefore descriptive in nature and maybe used as an understanding framework. The SME cautioned, however, to not over restrict the framework in terms of theory generation as the framework has the potential to be utilised in various contexts where new theory may be generated from its use.	to the research methodology in Chapter 1 Section 1.4 and Chapter 5 Section 5.2 in the requirement specifications to make the research and framework's purpose clear in this regard.
		I4.2: Revise the research scope and framework's position so as to reflect its suitability for a macro level of analysis and sustainability as that which affects the common societal good.	The SME pointed out that the framework and its operationalisation strategy would be more effective in a macro level of analysis such as at a global, national or sectoral level. He also highlighted that the framework might be too general for a micro-level analysis such as at an organisational level. The author agrees with the SME, given sustainability in the context of the research is towards the common societal good.	Adjustments were made to the scope and aim's narrative in order to clearly highlight this in Chapter 1. Furthermore, revisions were made to Boundary conditions that the framework is to be used for a high-level analysis. Refer to Chapter 5 Section 5.2.
		I4.3: Set the research scope and apply the framework at a high-level/macro level of analysis.	The SME advised that the framework would be most applicable at a macro level of analysis i.e., at a sector or industry level as opposed to micro level of analysis such as at or in an organizational setting. The SME advised that the micro-level setting may require more definition in variables and factors that affect the system compared to a macro-level setting, which may be beyond the scope of the research. Furthermore, the SME recommended that it is important to clearly define the level of analysis within the scope of research.	The author took note of this and followed as recommended in the case study application (refer to Chapter 7, Section 7.5.2). The research scope in Chapter 1, Section 1.3 is also set to match the same level of analysis as recommended.
Structural	SME 1	I1.5: Clearly state the aim of the framework is to integrate STTs and the 4IR	The SME stated that the aim of the framework was not explicitly clear to them in the overview document.	The author noted this and revised the document narrative to ensure clear communication of the framework's aim.
	SME 3	I3.4: Adapt the framework operationalisation strategy to a modular approach as opposed to a step-wise approach.	The SME argued that the step wise approach to the framework's operationalisation strategy is rigid and gives the perception that the application can only be done in the so-many steps provided. The SME recommended a modular approach, arguing that it allowed for more	The author revised and fleshed out the operationalisation strategy, as presented in Chapter 6 Section 6.4, to a more

Type	SME	Suggestion	Rationale	Resolve
			flexibility and gave the user a foundational building block base in utilising the framework, as opposed to a once-off prescription as with the step-wise approach.	comprehensive, modular-structured guide using IE methodology structure it.
	SME 4	I4.5: Change systems perspective to societal or transitions perspective.	The SME argued that both society, transitions and technology have systems elements to them and therefore recommended that the systems perspective be renamed to a societal or transitions perspective.	The author noted this, and “systems” element was renamed to “transitions” element (refer to Figure 33)

7.3.2.2 SUGGESTIONS NOT INCLUDED IN THE I4IR-STT FRAMEWORK AND OPERATIONALISATION STRATEGY REFINEMENTS

Some suggestions made by SMEs were not included in the framework and operationalisation strategy refinements. These, as mentioned in Section 7.3.2 include good ideas that were not included because of limitations due to scope and time as well as suggestions that the author did not agree with. Suggestions not included are presented in Table 23 below, including the author's reasons for exclusion.

Table 23: Suggestions not included in the refinements.

Category	SME	Suggestion	Reason for exclusion
Good ideas not incorporated (NIL)	SME 1	NIL1.1: Include a SWOT analysis of each technology, detailing its role in transitions' ecosystem as well as an overview of its development and adoption as documented in resources such as Gartner's hype cycles[9].	The author acknowledges that this would be good comprehensive context to the emerging 4IR technologies and their contemporary effect on the transitions landscape. However, due to scope and time limitations this was not included. However, it has been suggested as an avenue for future work (see Chapter 8, Section 8.3).
		NIL1.2: Include design thinking approaches in integrating technologies and societal systems while using the framework e.g., if the 4IR technology analysed is not well suited for a societal system, then iterations must be made to the framework in order to find fit. The reverse would also be true i.e., if a society system is not fit for a technology, an iterative approach can be taken to find fit.	The focus of this research and hence the framework is to demonstrate an approach towards the integration of the concepts of the 4IR and STTs. The SMEs suggestion NIL1.2, although helpful to a user in the operationalising the framework, poses as an extension to the operationalisation strategy as design thinking methodology requires prior understanding and training in its utilisation. This research is unfortunately limited, in such regard. However, this idea is added to suggestions for future work.
	SME 2	NIL2.1: Account for the business case in the adoption and development of technologies. Business case: as a factor for technologies to be adopted: either opposed or in tandem in the public good rationale. There has to be a business case rationale. Technology is driven by a business rationale. Market is not paying green products.	The business case is acknowledged in the framework's revision (see Chapter 6, Section 6.3.1) but not fully explored due to scope and time limitations. This suggestion has also been added to the recommendations for future work.

[9] Gartner's hype cycles are a graphical representation of the overview of how emerging technologies evolve over time, thereby giving their users insight for deployment of the technologies (Gartner Inc., 2020a)

Category	SME	Suggestion	Reason for exclusion
		NIL2.2: Explore the negative side of 4IR technologies and how that integrates or affects the transitions process for any societal system. This research assumes an optimistic outlook on the utilisation and effects of the 4IR technologies on societal systems which is one sided.	The author acknowledges that this is a good point. Due to scope and time limitations, the negative perspective of 4IR technologies is not explored in this research. However, it is recommended as an avenue for future work.
		NIL2.2: Analyse the environmental and social implications of the 4IR technology production chain.	The author is aware of this; however, it was excluded due to the scope of the research. This is included in the recommendations for future pr further studies.
	SME 3	NIL3.1: Differentiate between individual vs collective behaviour towards technology	SME 3 argued that individuals may behave differently and hold different attitudes towards technology in an individual capacity compared to when they are part of a collective or institution. The author acknowledges this; however, the idea is not widely explored in the research due to scope limitations.
		NIL3.2: Include a nature's perspective to the framework	The author does not address nature's perspective due to scope limitations. However, it is added to the recommendations for future work.
Suggestions not agreed with (V)	SME 1	V1.1 Demonstrate the framework using a single technology and its effect on the societal system	In line with addressing the gap in literature about the need to analyse the effects of multiple technologies combined as opposed to a single technology (refer to Chapter 4, Section 4.3.1.2), the author maintains the multiple technology narrative as opposed to diving into one single technology under the 4IR umbrella.
	SME 2	V2.1: Acknowledge that a limitation to the research, STTs are not the sole addresser of sustainability transitions.	The author acknowledges the fact that STTs are not the only approach that addresses STTs. Furthermore, the author acknowledges the complementariness between STTs and other perspectives to sustainability. However, the scope and premise of the research were originally set at STTs specifically, hence other studies are excluded from the start.

Category	SME	Suggestion	Reason for exclusion
		V2.2 The framework does not sufficiently address the convergence of and complementarities between technologies. Technological innovation also occurs on a large scale when there are changes in the business innovation e.g., through business framework innovation.	The author acknowledges the validity of this suggestion; however, a deeper dive into technological convergence and complementarities would require an exposition beyond the scope and requirements of the research. The author maintains that the highlights presented in the framework to demonstrate technology's interconnectedness and its effects on societal systems are enough to demonstrate the framework's aim.

7.3.2.3 REFINEMENTS MADE THAT ARE NOT DIRECTLY CONTRIBUTED BY SMES

Lastly, while engaging with SMEs during the evaluation and reflecting on the evaluation process post engagement, a couple of ideas occurred to the author which were utilised in the I4IR-STT framework and operationalisation strategy refinements. These ideas could not be traced back to anything in particular that the SMEs had said but were directly triggered through the engagement in the evaluation process and are therefore credited as such. Furthermore, these refinements were particularly made to enhance the connection between literature analysed in the first phases of the research and the framework developed, as well as to simplify the framework's integration of the 4IR and STTs concepts. These refinements included the following;

i. Primarily utilising characteristics and aspects of the 4IR and STTs for the integration (refer to Chapter 6, Section 6.2) from literature analysed (refer to Chapter 2): In the previous version of the framework, aspects of the 4IR and STTs were independently developed and loosely connected to the literature analysed and presented in Chapters 2 and 3. However, given that the aim of the framework is to demonstrate an integration between the 4IR and STTs, the author decided that it would be best to ground aspects of the 4IR and STTs for the integration in existing academic and grey literature. This creates a bridge between existing literature and what the framework and operationalisation strategy aim to achieve.

ii. Aggregating and condensing relationships demonstrating the integration into three main themes as presented in Chapter 6, Section 6.3; The I4IR-STT framework initially contained six observed relationships demonstrating integration points between the 4IR and STTs which were deduced from literature. However, on re-assessment, the author observed that there were three overarching themes across the six initial observed relationships. This prompted the author to simplify and aggregate the framework's relationships to the final three i.e., purpose, systemic dependencies and actor engagement. The author envisaged that the final relationships would simplify the integration and generalize the framework in a non-destructive way that would be more palatable for various users. This generalisation further enabled the development of a more comprehensive operationalisation strategy for the user.

iii. Changing the final product from a model to a framework: the initial research product for evaluation was presented as a model. However, after some deliberation, the author determined that a framework is the best suited mode for the product given its structure and intent. The reasoning behind the decision is presented in Section 5.1.

Following the above presented suggestions and recommendations, final refinements were made to the framework and operationalisation strategy. The final version of the I4IR-STT framework and its operationalisation strategy is presented in Chapter 6 of this document.

7.4 SELF-EVALUATION OF THE REQUIREMENT SPECIFICATIONS

The verification process also entailed checking that final I4IR-STT framework and its operationalisation strategy meet the requirement specifications for its' development as presented in Section 5.2. The methodology followed for this process was adapted from previous academical research studies such as Kennon (2017), de Kock (2020), and Ungerer (2015). A total of seventeen specifications are provided in Table 16 for the framework's development within four categories i.e., functional requirements (F), design restrictions (R), boundary conditions (B), user requirements (U) as specified by Van Aken *et al*. (2007).

Specifications in each category were allocated to parts of the framework (refer to Table 17 in Section 6.1) and are therefore self-assessed against those respective parts. Tables 24-27 below present the self-evaluation. Self-evaluation is conducted through a descriptive address or tick mark as applicable. A descriptive address is provided where the requirement specifications may be non-obvious and requires some elaboration. A tick mark given for each requirement specification where the fulfilment is regarded as obvious and is displayed against each specification's respective aspect to confirm that the aspect meets the requirement stipulated against it. Table 24 below presents a self-evaluation of the fulfilment of functional requirements through the I4IR-STT framework's applicable aspects.

Table 24: Functional requirements verification

Code	Description	Transition Aspect	Relationships	Technology Aspect
F1	The framework should sufficiently articulate an integration and orientation of aspects of the 4IR and STTs together.	The framework utilises aspects from STTs and the 4IR as obtained and presented in Chapter 2.		
F2	The framework should employ STTs theory from an STS background context in the integration.	✓	✓	N/A
F3	The framework should analyse the development and understanding of the 4IR within its holistic context.	N/A	✓	✓
F4	The framework should be applicable to contemporary contexts.	The framework is applicable to contemporary societal systems. It is non-specific to a single technology or sector. Users are given various examples of STTs and 4IR connections from literature which ultimately widen their perspective on the applicability of the framework.		

Table 25 below presents a self-evaluation of the fulfilment of the design restrictions through the I4IR-STT framework's applicable aspects.

Table 25: Design restrictions verification

Code	Description	Transition Aspects	Relationships	Technology Aspect
R1	The framework is developed from a systems or industrial engineering perspective as it is the research's academical discipline. Expounds from other disciplines may be progressively added by SMEs in those disciplines.	The framework is developed using industrial and systems engineering principles such as systems thinking and process management steps and provides a structure through which STTs and the 4IR can be integrated. The framework has been designed to be generic enough to incorporate expounds and utilised by other disciplines such as Social Sciences can be added.		
R2	The framework does not provide new meaning or theory around STTs and the 4IR. However, it integrates both concepts using theory and examples provided in literature	The framework draws from literature to structure and exemplify the integration of the 4IR and STTs.		
R3	The framework takes descriptive and explorative approaches towards conceptualizing the integration of the 4IR and STTs.	✓		
R4	The framework exclusively takes an STTs perspective towards sustainability transitions.	✓	✓	N/A
R5	The framework analyses sustainability and sustainable development from a macro level of analysis.	The framework incorporates grand sustainability and sustainable challenges as they are pertinent to STTs and the 4IR. This inherently denotes the focus of the integration as from a macro level of analysis.		

Table 26 below presents a self-evaluation of the fulfilment of the boundary conditions through the I4IR-STT framework's applicable aspects.

Table 26: Boundary conditions verification

<table>
<tr><th>Code</th><th>Description</th><th>Transition Aspect</th><th>Relationships</th><th>Technology Aspect</th></tr>
<tr><td>B1</td><td>The framework is most appropriately applicable to societal systems such as health care, agriculture, energy, transport etc in the quest to fulfil societal functions, achieve sustainability targets and overcome grand challenges.</td><td colspan="3">The framework draws applications and examples from literature that support this requirement. Furthermore, the case study application demonstrates the use of the framework for a relevant societal system.</td></tr>
<tr><td>B2</td><td>The framework must be utilised by users with some prior knowledge on the concepts at hand.</td><td colspan="3">The framework does not offer a contextual background on the 4IR and STTs but builds on it through this research. It is recommended that users have some basic understanding of the concepts which is conveniently provided through this research.</td></tr>
<tr><td>B3</td><td>The framework must not be utilised without contextual additions by users.</td><td colspan="3">The framework is designed as generic and non-specific to any societal system or 4IR related elements. The user, however, is guided on how to practically contextualise and utilise the framework through the operationalisation strategy. Furthermore, demonstrates the correct applicability of the framework and operationalisation strategy in this regard.</td></tr>
<tr><td>B4</td><td>The framework should not primarily be used prescriptively in the analysis of STTs and the 4IR.</td><td colspan="3">The framework focuses on demonstrating the integration between the 4IR and STTs. In itself, it does not offer solutions to challenges faced by societal systems. Furthermore, users are guided on how to apply the framework to primarily understand the integration of the 4IR and STTs in a system of interest.</td></tr>
</table>

Lastly, Table 27 below presents a self-evaluation of the user-requirements in the I4IR-STT framework

Table 27: User requirements verification

<table>
<tr><th>Code</th><th>Description</th><th>Transition Aspect</th><th>Relationships</th><th>Technology Aspect</th></tr>
<tr><td>U1</td><td>The framework should be understandable and unambiguous</td><td colspan="3">✓</td></tr>
<tr><td>U2</td><td>The framework should be clear and concise.</td><td colspan="3">✓</td></tr>
<tr><td>U3</td><td>The framework should be open ended to allow exploratory discussions from various disciplines and contexts.</td><td colspan="3">The framework is developed to be conceptually generic enough to be applicable to other disciplines outside of engineering. The fulfilment of this requirement is demonstrated through the case study which conducted on the agricultural sector in conjunction with an SME from the agriscience discipline.</td></tr>
<tr><td>U4</td><td>The framework should be accompanied by some practical utility.</td><td colspan="3">An operationalisation strategy has been presented alongside the I4IR-STT framework’s user practically utilise it.</td></tr>
</table>

Each requirement specification as initially presented in Chapter 5, Section 5.2 has been addressed in fulfilment of the self-evaluation. This concludes the self-evaluation process of the requirements specifications. In the next Section, a case study is presented to further validate the I4IR-STT framework and operationalisation strategy.

7.5 A CASE STUDY ON THE SOUTH AFRICAN WESTERN CAPE AGRICULTURAL SECTOR

An illustrative case study was conducted to demonstrate the applicability, practicability and usability of the I4IR-STT framework to a real-world case. Robson (2002:178) defines case study as *'a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real-life context using multiple sources of evidence'.* Given that this research pertains to STTs and the 4IR which are of contemporaneous nature, it is envisaged that applying the framework to a contemporary societal system would aid its user and enhance practicability and usability of the developed framework and its operationalisation strategy.

The framework is envisaged to be applicable to any societal system or sector. The agricultural sector in the Western Cape is chosen as an illustrative case study which is presented below:

7.5.1 INTRODUCTION: THE WESTERN CAPE AGRICULTURAL SECTOR

South Africa's Gross Domestic Product (GDP) is valued at US$283 billion. The Western Cape (WC) contributes about 14% to SA's economy and 3–5% of this is contributed by its agricultural sector (Partridge *et al.*, 2020). Although the agricultural sector contributes a small share to the country's GDP, it is important for the creation and provision of jobs, economic stability, food security and inputs to other industries such as manufacturing and processing. (USB, 2017).

The Western Cape's agricultural sector has recently seen a decline in its gross value added to South Africa's economy by 13% in 2019 following the prolonged effects of the drought (Partridge *et al.*, 2020). Furthermore, the agricultural sector is experiencing various disruptions from drivers for transformation within the sector. These include (Ungerer *et al.*, 2018):

i. Emerging technological innovation such as smart agricultural technologies, biotechnology and advanced manufacturing;
ii. New consumer preferences and increased societal awareness for health and sustainability causing changes in demand to more personalised products;
iii. Changing value chain configurations, growing change towards horizontally and vertically integrating offerings; and
iv. Climate change.

From the above, the unique sustainability challenges faced by the agricultural sector in the Western Cape in conjunction with emerging technologies within the 4IR are positioning the agricultural sector in the WC as a potential case for a societal system in transition or transformation. This qualified the societal system to be this research's case study.

This case study has been conducted in conjunction with SME 1 in order to obtain contextual additions as stipulated in requirement specifications, boundary condition B3. Furthermore, the SME also co-authored Ungerer *et al.* (2018), a report on the future of the Western Cape's agricultural sector in the context of the 4IR. The report is used as a primary source of information for the case study. Conducting the case study with the SME also doubled as a verification and validation of the framework's operationalisation strategy and case study application. As presented in Section 6.4.3 and in utilising the I4IR-STT framework operationalisation strategy, the author followed through each stage of the operationalisation strategy and output from the analysis is presented in the subsections below:

7.5.2 DEFINITION AND IDENTIFICATION

In this section, WC's agricultural is demarcated and the why, what and who in analysis as corresponding to the purpose, systemic dependencies, and actor engagement relationships of the I4IR-STT framework are identified.

7.5.2.1 SYSTEM DEMARCATION

As can be seen in Figure 44 below, the agricultural sector or societal system may be demarcated into industries such as livestock and animal farming, horticulture, wine industry and crop husbandry, which in turn may be demarcated into value chains such as production/farming, processing, distribution, and end use (Kuschke & Geyer, 2016); which can then be further split into various processes within the system and so forth. However, as per the recommendation of SMEs (refer to Table 22, point G4.3) and limitations due to scope (refer to Section 1.3) and time, the case study is conducted at a macro-level of analysis and analyses the Agricultural sector in the Western Cape at a value chain level , taking the primary production value chain (also referred to as farming) as the unit of analysis. As can be seen in Figure 44, the definition and identification stage is applied to this unit, proceeding from which, 'as-is' and 'to-be' state analyses are conducted using grey and academic literature as well as input from SME-1.

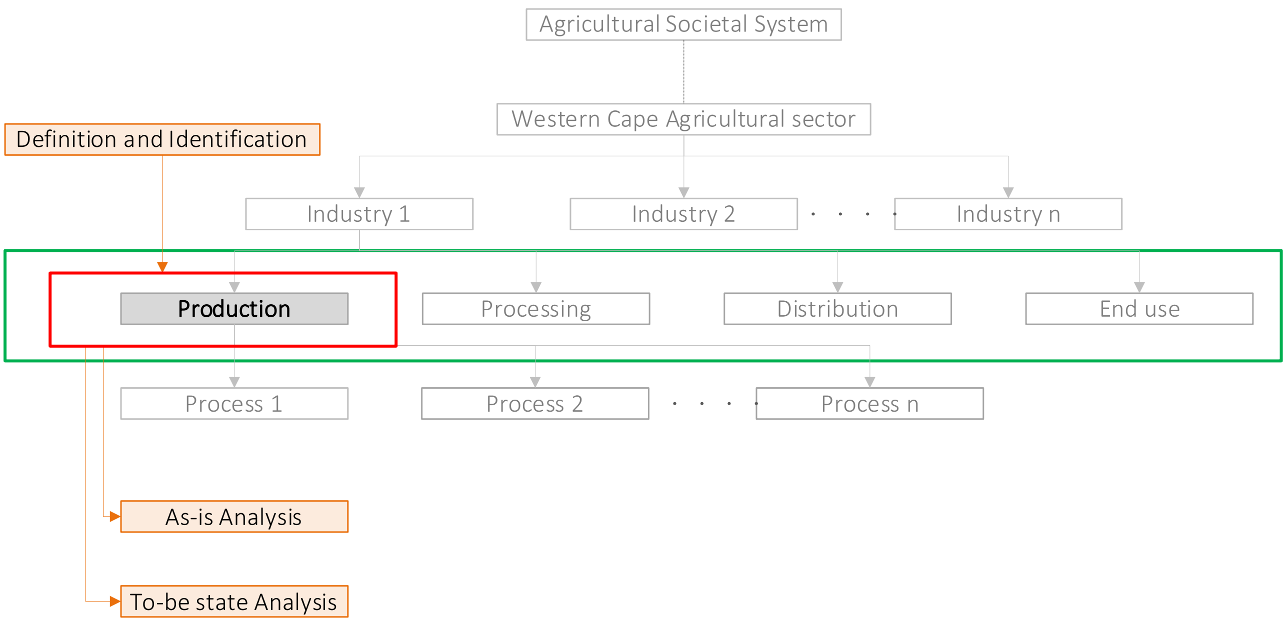

Figure 44: System demarcation – case study unit of analysis highlighted

7.5.2.2 PURPOSE: THE "WHY"

As previously mentioned in the introduction, the agricultural sector in the Western Cape has experienced substantial grand sustainability challenges within the last decade (Partridge *et al.*, 2020). The recent drought left the sector with water shortages, which prolonged over time has negatively affected yield gains. Furthermore, the drought has led to increased regulations and restrictions on the quantity and quality of water for farmers, heightening the resource usage challenge. Additionally, global climate change is presenting a challenge for current farming practices with steadily increasing global temperatures (Ungerer *et al.*, 2018). Lastly, consumers are increasingly aware of global sustainability challenges and are therefore pushing for most sustainably produced products (Ungerer *et al.*, 2018). These pressing contemporary developments (among others), are at the heart of the sustainability discourse within the context of the agricultural sector in the Western Cape (Ungerer *et al.*, 2018).

The rise of the 4IR presents the agricultural sector in the Western Cape with the unique opportunity to pursue an "agricultural renaissance" as Ungerer *et al.* (2018) puts it. While disrupting the agricultural sector, emerging technologies are envisaged to contribute to solving the sector's sustainability challenges and simultaneously making contributions to improvements to productivity and efficiency within the sector. According to Ungerer *et al.* (2018), 4IR driving technology is emerging within the agricultural sector and although not fully developed, the use of digital technologies includes smartphones, tablets, infield sensors, drones and satellites which are "*widespread in agriculture, providing a range of farming solutions such as remote measurement of soil conditions, better water management and livestock and crop monitoring, enhanced analytics, affordable devices and innovative applications are further contributing to the digitalisation of farming*." (Ungerer *et al.*, 2018: 9)

7.5.2.3 SYSTEMIC DEPENDENCIES: THE "WHAT"

The identification of the "what" in analysis is a proponent of the systemic dependencies relationship of the I4IR-STT framework. In relation to the WC's agricultural sector, this entails the identification of key driving forces towards that are creating dynamism within the sector in the change towards sustainability with the 4IR. According to Ungerer *et al.* (2018), megatrends driving change in the sector with the Western Cape include but not limited to:

i. Climate change with changing weather patterns affecting soil quality and crop yields;
ii. Emerging new agricultural technologies and biotechnology triggering improvements to existing crop varieties, higher yields and cost reductions;
iii. Changes in society demand for resource intensive agricultural food products;
iv. A growing and rapidly urbanising population, with projected population growth of 10 million or more people by 2050, 67% of whom currently reside in town areas; and
v. Globalised trade and international regulations.

7.5.2.4 ACTOR ENGAGEMENT: THE "WHO"

The identification of the "who" in analysis is a proponent of the actor engagement relationship of the I4IR-STT framework. This entails identifying key actors in the WC's agricultural sector. According to the University of Stellenbosch Business School (2017), key players in the production value chain include:

i. Farmers who are looking to increase the yield and improve production systems;
ii. Research institutions such as universities and science councils providing ground-breaking research and know-how in the development of new technologies and improvement methodologies for farmers;
iii. Labour organisations protecting the rights and liberties of agricultural workers;
iv. Innovators and small start-ups developing new technologies under the 4IR banner and looking to create sustainable business ventures for themselves while solving societal issues; and
v. Government agencies which provide policy and strategy for social, economic and technological engagement and development in the agricultural sector.

7.5.3 'AS-IS' STATE ANALYSIS

In this section, the 'as-is' analysis of the WC's agricultural sector is presented in application of the I4IR-STT framework and operationalisation strategy. Purpose, systemic dependencies, and actor engagement relationships of the I4IR-STT framework are explored in relation to the sector.

7.5.3.1 PURPOSE

One of the most significant sustainability challenges of the Western Cape's agricultural production is resource usage (Ungerer *et al.*, 2018). The drought experienced in the Western Cape region in the early 2010s left constraints on water usage, as mentioned in Section 7.5.2. In addition to water, land usage also poses a challenge to the system's sustainability. The Western Cape is faced with high levels of migration and growing populations which bring pressure for development and changes to land use. A growing population exerts pressure and strain on the food production system of which the agricultural sector is the main contributor (Ungerer *et al.*, 2018). The Western Cape agricultural sector is also aligned to the National Development Plan's strategy for employment in creating opportunities for growth and jobs for its population (Ungerer *et al.*, 2018). Farmers are grappling with diminishing yields and returns due to changes in climate and resource scarcities. Therefore, sustainability issues causing pain to farmers (USB, 2017) include, but are not limited to:

i. Growing population leading to demand for higher agricultural output to avoid food shortages and posing challenges with land-use;
ii. Recent drought–water crisis which has left a water shortage; and
iii. Climate change.

On a farming or production level, the agricultural sector is looking to improve its systems so as to be able to use manage resource usage, provide higher yields for the growing population and navigate the global climate change issue. These challenges present the Western Cape's agricultural sector with unique pressure to employ more sustainable methodologies in order to meet current goals and yet be sustainable for the society in the region for the future.

The 4IR brings with it digital technologies that are currently spreading widely in the agricultural system globally. These technologies are envisaged to provide a wide range of solutions for farming such as measurement and management of resources (water and soil), better monitoring of crops and livestock, improved working conditions for farmers and reduced environmental impacts of agriculture (Ungerer *et al.*, 2018). For example, technologies such as IoT and robotics are providing the means to measure relevant agricultural parameters; cyber physical systems are enabling the networking between various types of equipment in farming and processing values chains and digital platforms are enabling better synergy between consumer needs and farmers planning; all of which are helping to enhance the agricultural sector's efficiency and effectiveness (Ungerer *et al.*, 2018). The implementation of 4IR technologies and their benefits towards agricultural sustainability are currently being seen in countries such as the United States of America, Israel, China and the Netherlands (Ungerer *et al.*, 2018).

However, the potential for digitalised technologies – although generally recognised – has not yet been fully realised in the Western Cape, South Africa. (Ungerer *et al.*, 2018). For example, most agricultural production technologies currently used in the Western Cape are analog and not all farmers and/or laborers are aware of the benefits of digital technologies nor do they have access to them (Ungerer *et al.*, 2018). Furthermore, where digital technologies are progressing (such as in back offices, and experiments with R&D from researchers and small innovative start-ups) these capabilities lack maturity and do not yet have significant investment at a large scale yet (Ungerer *et al.*, 2018). Additionally, costs to import new [mature] technologies from oversees are often very high (Ungerer *et al.*, 2018).

7.5.3.2 SYSTEMIC DEPENDENCIES

The agricultural sector in the WC is highly interdependent, so value chains do not operate in silos but consistently communicate in a push-pull manner. For example, shifting consumer expectations and demands for different types, amounts and quality of food directly correlates to production shifts necessary within the farming and production value chain. The use of 4IR digital technologies such as digital platforms, Big Data and analytics and IoT present producers with opportunities to closely measure and optimise yields in order to match demand. Conversely, changes in production practices due to new technologies are envisaged to ripple through other value chains (Ungerer *et al.*, 2018).

However, a big challenge is the Western Cape agricultural sector's low positioning on digital maturity (Ungerer *et al.*, 2018). Agricultural production in the Western Cape is highly dependent on agricultural equipment, which as previously mentioned is mostly analog. (Ungerer *et al.*, 2018). According to (Ungerer *et al.*, 2018), there is a lack of digital leadership, awareness and skills. Digital capabilities currently develop in silos, do not attract significant investments and are not widely accessible to most farmers or agricultural producers (Ungerer *et al.*, 2018).

7.5.3.3 ACTOR ENGAGEMENT

4IR digital technologies have shown potential to help agricultural producers meet their production requirements and optimise processes. However, changes in technology require changes in the skillset of farmers and other workers in the production value chain, most of whom are technologically semi-skilled or unskilled (Kuschke & Geyer, 2016; Partridge *et al.*, 2020). A big societal concern in the development, adoption and deployment of 4IR technologies is job security. As of 2015, 232000 people employed in the Western Cape Agricultural sector (USB, 2017) making up 3.6% of the Western Cape's 6.84 million people population (Partridge *et al.*, 2020). In light of this and South Africa's high unemployment rate (Manda & Dhaou, 2019), the introduction of technologies such as AI robotics and IoT – which may automate certain processes such as product harvesting, agricultural vehicle manoeuvring and pest or disease control which human labour fulfils – presents producers with challenges and scepticism towards the adoption of such technologies (Ungerer *et al.*, 2018).

Furthermore, researchers, innovators and entrepreneurs developing and exploring 4IR technologies and applications which provide solutions to farmers have to do so whilst simultaneously working towards creating business sustainability for their endeavours. However, given that these innovations currently lack significant investment and incentives, 4IR innovations in the Western Cape's agricultural production value chain lack significant economies of scale which would accelerate deployment, maturity and overall gains towards sustainability. Government agencies look to fulfil national development strategies and policies to alleviate socio-economic challenges such as unemployment and yet incentivize and develop strategies for the adoption and deployment of new technologies for the greater societal good (Ungerer *et al.*, 2018).

7.5.4 'TO-BE' STATE ANALYSIS

In this section, a 'to-be' analysis of the WC's agricultural sector is presented in application of the I4IR-STT framework and operationalisation strategy.

Ungerer *et al.* (2018) highlight that following global 4IR technological trends, a transition in the Western Cape's agricultural sector is inevitable. The 4IR is envisaged to inevitably disrupt the agricultural system and its industries as it has with multiple other systems and industries across the globe. 4IR technologies showing potential to disrupt the agricultural production chain include biotechnology, AI through autonomous vehicles, robotics and computer vision as well as IoT through smart sensors. In addition to these technologies' disruptive potential, they also show potential to offer significant contributions to the agricultural production's sustainability issues such as water scarcity, soil management, and climate monitoring. SME 1 emphasized that a distinguishing factor in the success of a transition towards sustainability is the Western Cape's readiness for the 4IR since pressing sustainability issues such as climate change and resource management are on-going and predicted to be prevalent in the near future of the Western Cape (Ungerer *et al.*, 2018).

It is imperative, therefore, that the agricultural production chain in the Western Cape is better prepared for the advancement of the 4IR and harnesses technological advancement to address some of the system's current sustainability challenges. Concepts such as sustainable farming are a promising 'to-be' state for agricultural systems. Furthermore, 4IR technology innovation is also contributing to development and use of alternative and efficient energy sources, alternative sources for food production, water and land use efficiency and precision agriculture (USB, 2017).

The 4IR shows potential to also contribute solutions to challenges for its implementation. For example, although 4IR technologies are currently being developed in 'silos' in the Western Cape's agricultural sector, they do not operate the same way. As a case in point, the deployment of IoT and AI towards precision agriculture gives way to smart sensing, monitoring and control of agricultural activities. These applications are further interconnected to the use of Big Data allowing for smart planning and analysis which also link to cloud computing (Ungerer et al., 2018). Technologies such as Big Data and analytics, digital platforms, IoT and AI are more extensively developed and used in other systems such as manufacturing, transportation and retailing. It is envisaged that 4IR technological advancements in such systems and value chains may give more workers in the Western Cape exposure to digital technologies which creates a skills advancement ripple effect within society. In the long run, as more people in society are exposed to digital technologies in other facets of life, the more acumen is developed for workers and producers within the agricultural production value chain. (Ungerer et al., 2018) Furthermore, there is exist technological strategies to progressively overcome some of the challenges with digitalisation such as the concept of "partial-digitalisation", where Bluetooth, sensors and GPS systems are being used to digitalise legacy machinery (Ungerer *et al.*, 2018). Symbiotic relationships between existing technology and the 4IR can ease the transformation, hence ushering farmers into the 4IR in a more effective way.

In addition, strategy and policy need to be developed in order to economically incentivise innovators and agricultural producers to develop and adopt new technologies respectively. For example, policy should be linked to the provision of directives and technological support to farmers where reforms require modifications in farming practice such as for resource usage (Ungerer *et al.*, 2018). Additionally, the transition to newer technologies as with the 4IR requires upskilling for producers and workers. According to (Ungerer *et al.*, 2018), farmers need to use new technologies to improve and extend their technological competence. Labour policy in alignment with National Development Plans and strategies may inform the perceptions and adoption of technologies such as AI in robotics and automated vehicles, (Ungerer *et al.*, 2018). Therefore, shifts in emphasis and awareness of upskilling may further drive technological innovation and adoption within farming in the Western Cape while simultaneously aiding the alleviation of unemployment which is a socio-economic challenge in the sustainability of the Western Cape's society.

7.5.5 CASE STUDY CONCLUSION

From the case study, it is observed that there is clear integration between changes in the agricultural sector, particularly with the production value chain and the advancement of the 4IR. This denotes the existence of an STT within the sector concurrent with the 4IR. In applying the I4IR-STT framework through the operationalisation strategy, the user is able to identify key factors and drivers for the system unit's transitions, key systemic dependencies and how actors are engaging with sustainability and the 4IR within the system unit. Furthermore, the user is able to identify and analyse the system unit in its contemporary as-is state and for the future to-be state.

As demonstrated by the case study, the I4IR-STT framework is applicable to contemporary societal systems and is generic enough to be customised to a system of interest regardless of field or discipline. Furthermore, the operationalisation strategy gives the framework practical utility and enables a user to practically apply the framework in a real-world context. Lastly, it is demonstrated through the operationalisation strategy that the framework is usable given the guidelines the strategy provides for applying the framework and the successful demonstration of the case study presented above.

The author acknowledges the value of receiving input from SME 1 to provide contextual background on the Agricultural Sector. Furthermore, the SME gave structural direction and feedback for information obtained from literature used in the case study. This demonstrates the importance of adhering to the I4IR-STT framework's Boundary Condition B3 i.e., "*The framework must not be utilised without contextual additions by users*" as presented in Chapter 5 Section 5.2.3. This concludes the validation process of the framework.

7.6 CHAPTER 7 CONCLUSION

In this Chapter, the evaluation of the I4IR-STT framework has been presented. This consisted of a verification process to ascertain the theoretical consistency and correctness of the study and framework. The verification process was focused on the requirement specifications and the I4IR-STT framework. Furthermore, the evaluation process included a validation of the I4IR-STT framework and operationalisation strategy to ascertain that the right framework has been built for its intended purposes. As part of the validation process, a case study demonstrating the applicability, practicability and usability of the I4IR-STT framework was also presented. The final designs of the framework and operationalisation strategy after evaluation are presented in Chapter 6.

CHAPTER 8: RESEARCH CONCLUSION

In this chapter, this research is concluded. A summary of the research is presented, and the attainment of the research objectives are assessed and discussed. Limitations of the research are discussed, and future work and recommendations are presented.

8.1 RESEARCH SUMMARY

Contemporary societal systems are faced with grand sustainability challenges that increasingly heighten the need for more sustainable configurations. The 4IR and STTs evidently demonstrate the potential to contribute to grand sustainability vision of contemporary societal systems. To this end, it was envisaged that these concepts are related, and their integration is important for analysing contemporary societal systems in their transition to more sustainable configurations.

The aim of this research was to contribute towards the contemporary societal systems transitions towards more sustainable configurations through the integration of the 4IR and STTs. The primary objective of the research was to investigate the extent to which literature has jointly analysed the 4IR and STTs and inferred their integration. It was found that the envisioned integration was largely at miss in the literature analysed. The research, thereafter, embarked on presenting a framework for the integration of the 4IR and STTs which was named the I4IR-STT framework. The I4IR-STT framework was presented with an operationalisation strategy, which was developed to enable a user to utilise and apply the framework in a real-life case. Table 28 below presents an assessment of the research objectives and their fulfilment as presented in this thesis.

Table 28: A review of the achievement of the research objectives

Research objectives and sub-objectives	Chapter	Research objective's achievement review
RO 1: Contextualise the STTs and the 4IR as presented in their core literature and as pertaining to this research		
N/A	Chapter 2	A review of literature pertaining to STTs and the 4IR was presented in fulfilment of Research Objective 1. STTs literature was presented with a review of literature on STS for contextual background. Literature on STTs included an overview of the STTs process and frameworks utilised in the analysis of STTs. The 4IR was introduced highlighting the technologies that drive it. Furthermore, sustainability research surrounding the 4IR was presented as well as the potential of 4IR technologies in contributing towards sustainability. It was noted that STTs are inherently oriented towards sustainability and a brief motivation of their necessity was given in this chapter. Furthermore, given the sustainability discussions on the 4IR and potential for contribution towards sustainability targets, the author made the argument for a plausible connection between the STTs and the 4IR observed from their respective literature.

Research objectives and sub-objectives	Chapter	Research objective's achievement review
RO 2: Investigate the extent to which STTs and the 4IR have been jointly considered within academic literature to confirm or refute the apparent lack of integration of both concepts previously mentioned.		
RO 2.1: Conduct a bibliometric analysis examining the literature landscape	Chapter 3	In order to fulfil Research Objective 2, a SLR was conducted to investigate the extent to which STTs and the 4IR have been jointly considered with literature. As part of the overarching SLR methodology undertaken, a bibliometric analysis was conducted to examine the literature landscape on both concepts in partial fulfilment of Research Objective 2. The SLR identified forty-two documents that fulfilled the search algorithm requirements. All forty-two documents were included in the bibliometric analysis. Results showed that both the 4IR and STTs are fairly new in academic research and have a higher traction in science fields such as engineering but lack a comprehensive coverage on the research scene outside of Europe. This presented the research with a valid and relevant case into the investigation of both concepts. After the bibliometric analysis, the forty-two articles obtained were taken through a selection process with exclusion/inclusion and quality in order to identify eligible articles for the next step in the SLR. This process was also presented in Chapter 3 of this document. The results of this process yielded six eligible articles.
RO 2.2: Conduct a content analysis examining how the concepts are jointly addressed and analysed in literature.	Chapter 4	Following the bibliometric analysis, a content analysis in order to determine how literature jointly presents and discusses the 4IR and STTs. The analysis highlighted methodologies, geographical areas of analysis, key industry applications in literature from all forty-two documents initially identified. Furthermore, main topics and themes of discussion within the literature were also highlighted. Lastly, the final six documents from the SLR selection process were also analysed to investigate how the 4IR and STTs were jointly considered therein. Synthesised results showed a dominant manufacturing or industrial production contextual focus with steered sustainability research to a focus of a micro-level of analysis. Hence research engages issues related to topics such as strategy, innovation and employment from a business organisational context. It was observed that STS (and by implication STTs) were inferred and 4IR analysis was unidimensional in application.

<table>
<tr><th>Research objectives and sub-objectives</th><th>Chapter</th><th>Research objective’s achievement review</th></tr>
<tr><td>RO 2.3: Conduct a gap analysis to compare literature obtained to the 4IR and STTs contextualisation and thus identify the gaps and disconnects to be addressed in this research.</td><td>Chapter 4</td><td>Lastly, a gap analysis was conducted in fulfilment of RO 2.3. The gap analysis contrasted literature studied and presented in the contextualisation in Chapter 2 to the literature obtained from the SLR. Results showed that there existed gaps and disconnects between the two sets of literature in the conceptual and analytical representation of both concepts as pertaining to the research problem. Furthermore, it was found that an integration of the 4IR and STTs was largely missing in academical literature. The gaps and disconnects found were translated into a construct guidance through deductions which were further translated into requirement specifications for the research product.</td></tr>
<tr><td colspan="3">RO 3: Articulate a development strategy from which the research product is to be designed and developed.</td></tr>
<tr><td>RO 3.1: Develop requirement specifications for the research product.</td><td>Chapter 5</td><td>In Chapter 5, the research focused on developing a strategy for the development of its research product. A conceptual framework was selected as the research product. A development strategy was presented as a means for developing the framework and fulfil RO 3.1. The strategy incorporated deductions from the gap analysis as construct guidance for the research product. These deductions were incorporated into the requirement specifications for the development of the framework. requirement specifications were categorised into four parts i.e., functional specifications, design restrictions, boundary conditions and user requirements. These specifications provided a baseline for the framework’s development in guided the author in developing conceptual content for the framework.</td></tr>
<tr><td>RO 3.2: Present the methodology employed for the development of the research product.</td><td>Chapter 5</td><td>The methodology employed for developing the I4IR-STT framework was also presented in Chapter 5 in fulfilment of Research Objective 5. Systems’ Thinking principles applied as construct guidance for the framework were presented. Furthermore, Van Aken et al. (2007)’s general model for design process was employed to develop the envisaged framework, and the process steps undertaken to develop the framework were elaborated on.</td></tr>
<tr><td colspan="3">RO 4: Develop the framework to demonstrate an integration between the 4IR and STTs.</td></tr>
</table>

Research objectives and sub-objectives	Chapter	Research objective's achievement review
RO 4.1: Develop the envisioned research product.	Chapter 6	A conceptual framework named the I4IR-STT framework was developed for the integration of the 4IR and STTs and was presented in Chapter 6. The framework consisted of three key elements utilised in the integration of the 4IR and STTs i.e., transition aspects, technology aspects and relationships. Transition aspects were drawn from characteristics of STTs as presented in literature and technology aspects were drawn from 4IR characteristics. Furthermore, the framework drew on examples from literature to highlight the relationships between the 4IR and STTs.
RO 4.2: Develop an operationalisation strategy for the research product.	Chapter 6	An operationalisation strategy was developed alongside the framework in Chapter 6 to give practical utility and enable the framework's user to apply the framework. The operationalisation strategy consisted of three stages i.e. definition and identification, as-is analysis and to-be concept design which were adapted from the Enterprise Engineering Process provided by Du Preez *et al.* (2009). The operationalisation strategy presents objectives for each stage and guides a user in analysing the integration of the 4IR and STTs in societal system of interest through activities in each stage to accomplish the set objectives.
RO 4.3: Evaluate the proposed research product with subject matter experts (SMEs).	Chapter 7	In fulfilment of this sub-objective the I4IR-STT framework and operationalisation strategy were evaluated i.e., verified and validated. The evaluation of the framework and operationalisation strategy was conducted to ascertain that the right framework was built for its intended purpose and that the framework exhibits theoretical correctness and was consistent with existing theories and literature on the 4IR and STTs. The evaluation process was mainly conducted with SMEs in both the fields of STTs and the 4IR to ensure comprehensiveness. Feedback from SMEs was obtained through semi-structured interview discussions with SMEs. SMEs feedback was categorised and incorporated into the framework's refinements. Furthermore, the I4IR-STT framework was evaluated against the requirement specifications for its development to ensure that framework's solution space was consistent with the identified gaps within literature.

Research objectives and sub-objectives	Chapter	Research objective's achievement review
RO 4.4: Conduct an illustrative case research to evaluate the research product.	Chapter 7	An illustrative case study was presented in Chapter 7 to demonstrate the applicability and usability of the I4IR-STT framework. The Agricultural Sector in the Western Cape was chosen as the societal system of interest which was consistent with an initial need identified in the content analysis for literature analysing the 4IR and STTs in other geographical contexts outside of Europe (refer to Section 4.1.2). Case study material was obtained from literature and validated with SME 1. From the case study, the integration of the 4IR and STTs with the example of the Western Cape Agricultural sector was demonstrated. Following the case study application, it was concluded that the I4IR-STT framework fulfilled its intended purpose and addressed the research problem as envisioned.

8.2 LIMITATIONS OF THE RESEARCH

Limitations of the research are presented and discussed below:

i. It is acknowledged that literature obtained for the SLR was limited at the time the review was conducted. This may be attributed to the neoteric nature of STTs and the 4IR. However, the 4IR and STTs' bodies of knowledge are growing considerably. As of the November 2021, the Scopus search algorithm used for the bibliometric analysis yielded two hundred and forty-three documents which is over six times the forty-two articles initially obtained when the bibliometric analysis was conducted. Although literature was limited, the initial deductions from the research indicated a body of knowledge with potential for growth and the relevance of the research are accentuated with the growth in literature;

ii. The research scope was limited to social and technological perspectives towards sustainability and sustainable development. As a result, ecological and economic perspectives, although incorporated to some extents, were not explicitly and extensively addressed in the research;

iii. The I4IR-STT framework was limited to a macro level of analysis which limited its operationalisation of the I4IR-STT framework to a high-level analysis of societal systems. SME 4 also concurred that the framework is most applicable at a macro level of analysis (global, national, sectoral high-level systems setting) as opposed to a micro level (e.g., at an organisational level). The SME advised that the micro-level required more granularity in the identification and definition stage of the operationalisation strategy;

iv. The I4IR-STT framework's generic format requires contextual additions on the system by users, which may expose the framework's applicability to the subjectivity of its users; and

v. Restriction to the industrial or systems engineering disciplines limits the operationalisation of the developed framework to Industrial Engineering tools and methodologies. Future work has the potential to incorporate approaches from other fields such as social impact analyses prevalent in social sciences or cost benefit analyses from economics and management sciences. This would ultimately pave the way to explore the framework from the perspective of other disciplines.

8.3 RECOMMENDATIONS FOR FUTURE WORK

The following recommendations are identified as viable options for future work expanding this research:

i. Expand the research to the application of the framework in other societal systems such as energy, transport and health systems and present case studies on the integration of the 4IR and STTs therein;
ii. Expanding the I4IR-STT framework to include other system demarcations such as value streams and supply chains interactions;
iii. Expanding the research to examine the negative impacts of the 4IR and its technologies on society and how this may affect STTs.;
iv. Expand the application of the framework to further engage with research on the ecological and economic perspectives in the integration of STTs and the 4IR to account for the impact on nature and the business case in adopting and utilising 4IR technologies;
v. Exploring the interconnections between the framework's relationships as discussed and suggested in Section 6.3, page 97.
vi. Expand the I4IR-STT framework's operationalisation strategy to provide the user with an outlet for exercising strategic intent with from the understanding developed by utilising the framework in analysis. STTs theory presents analytical frameworks such as the MLP, TIS, SNM, and TM frameworks (presented and described in Section 2.2.2) that are helpful in the shaping an approach towards identifying, understanding and strategizing efforts to influence transitions. Future work may incorporate such frameworks to give the user a premise for formulating strategic intent in the integration of the 4IR and STTs for a societal system under analysis;
vii. SME 3 recommended investigating and aligning the research to the deep transitions' framework. Deep transitions describe the unfolding of modern societies through industrial modernisation and from the STTs perspective (Kanger & Schot, 2018). This research's analysis and integration of the 4IR to STTs may be explored and aligned to the deep transitions' framework in future work; and
viii. The research does not include a granular analysis of technology but rather takes a broader approach. Technology is described in the literature as a combination of artefacts, systems, processes and/or products at different hierarchies (Sandén & Hillman, 2011). Technologies are made up of subsystems for example an engine in a car; and they form into sub-systems of a higher order within a systemic view such as cars within automobiles in a transport system (Sandén & Hillman, 2011). The framework does not distinguish these boundaries in its description of 4IR technologies. Such granularity may be explored in future work.

8.4 RESEARCH CONTRIBUTION

The primary contribution of this research is the I4IR-STT framework presented in Chapter 6. The framework presents a basis on which the 4IR and STTs are integrated. As previously discussed in Chapter 4, this integration was mostly missing in literature and the developed framework is envisaged to fill this research gap. Furthermore, it is observed that much of the research conducted on STTs and 4IR is fairly recent (refer to Chapter 3). This reflects the evident contemporaneous nature of these concepts. This research therefore aimed to further contribute to the 4IR and STTs bodies of knowledge through:

i. Simplifying the integration of these concepts and providing a premise to help others understand how they are mutually reinforcing; and
ii. Making the integration of the 4IR and STTs practical and applicable to contemporary societies; and
iii. Providing a premise for developing new perspectives and approaches towards modern day STTs.

Furthermore, in line with existing literature, this research may thus prove useful in the following manners:

i. In continuously demystifying the disconnect between technical systems engineering, innovations, human interaction and the effects on fulfilling societal functions (Baxter & Sommerville, 2011);
ii. In providing insights at system and strategy levels that further addresses concerns for the adoption of new technologies or technological paradigms; and
iii. In providing strategic insights for how new technologies, innovations or technological paradigms may be utilised to address sustainability issues and influence social systems towards achieving sustainability and sustainable development targets.

8.5 CONCLUDING REMARKS

STTs and the 4IR demonstrate the complexity of contemporary societal systems. The 4IR poses complexity through its interconnectedness and how that affects societal systems that utilise technologies within its scope. STTs are also complex because it is not just a technical transition, social factors and human behaviour influences the change towards sustainability. A significant part of the 4IR is the integration of all societal spheres which implies that a significant part of the STTs and 4IR integration is the way society interacts with technology. Society influences technology as much as technology is envisaged to impact society. SMEs argued that collective societal behaviour is challenging to predict and is often better captured retrospectively. Furthermore, advanced sociological nuances towards technologies pose complexity to analysing collective behaviour towards technologies for example people may behave differently in individual capacities than they do at collective/institutional levels. This may present contrasting or reinforcing results in the adoption and utilisation of technologies and add complexity to societal engagement towards sustainability goals.

However, the uniqueness of the 4IR is that through the technologies therein, the revolution presents opportunities to harness, map and improve societal patterns and functions at an unprecedent scale and speed compared to previous technological revolutions. This presents the unique opportunity to measure, monitor and manage global systems for different targets at an unprecedent scale than has not been previously available. Although the 4IR is still in its infancy stage, it is predicted to be inevitable and studies such as this provide a premise to further exploit the potential of the technologies therein in hopes to solve the global society’s grand sustainability challenges.

This research has provided an integration to the concepts of STTs and the 4IR and provided a baseline for which future work and research exploring the 4IR and STTs. Furthermore, it is envisaged that the research contributes to the wider sustainability discussions from a systems and industrial engineering perspective.

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APPENDIX A: SYSTEMATIC LITERATURE REVIEW

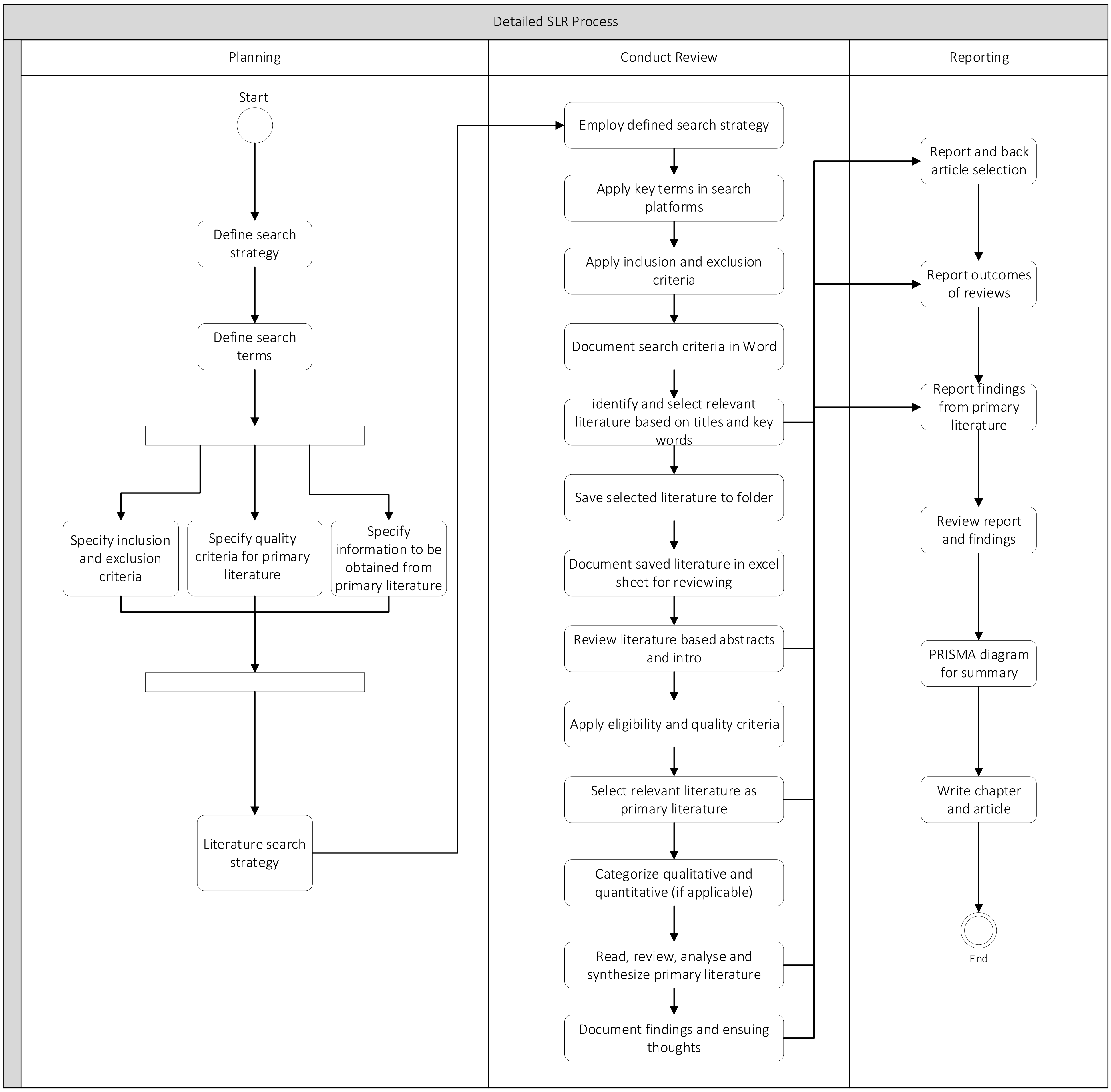


Figure A.1: Detailed SLR Process

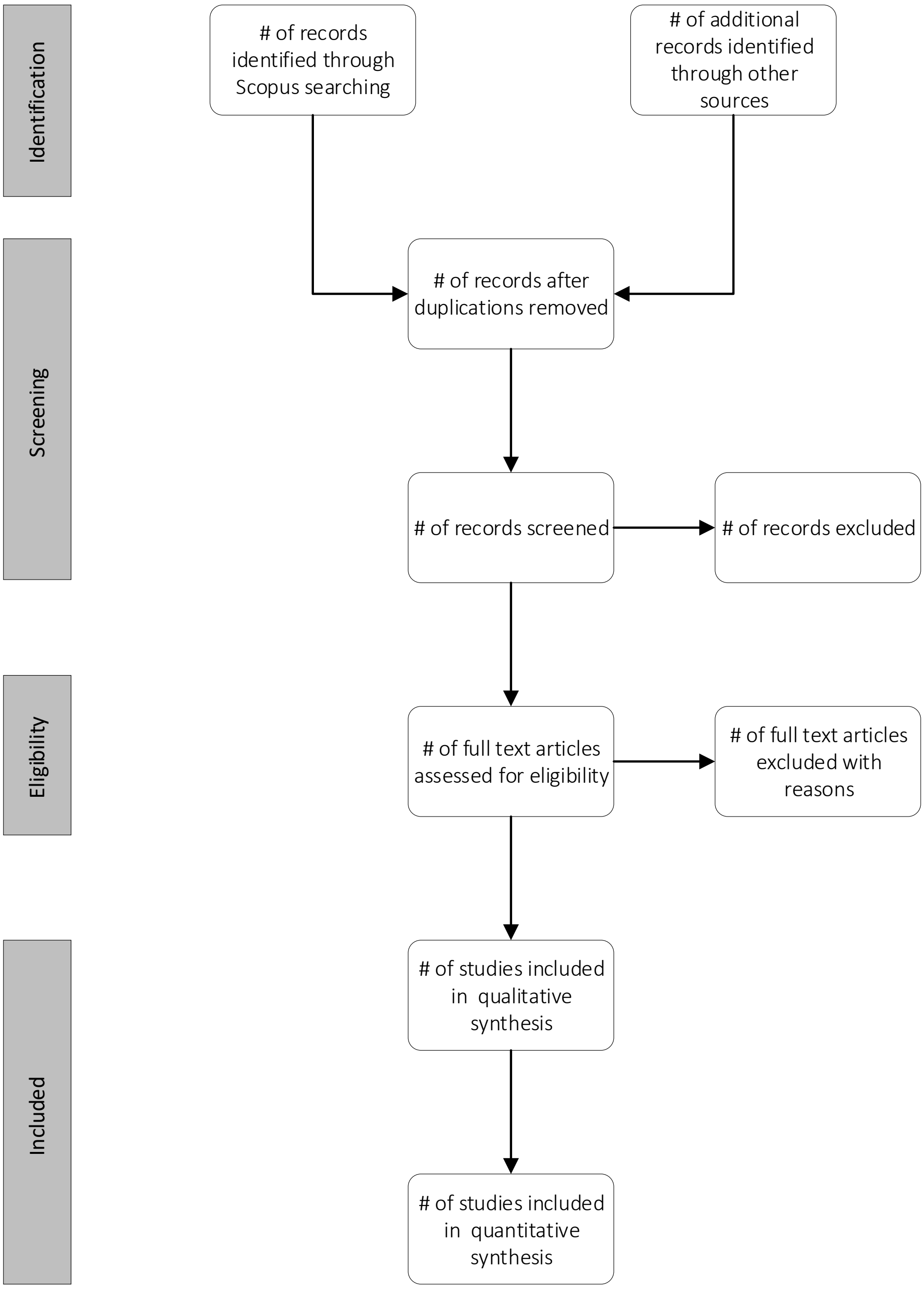


Figure A.2: PRISMA diagram. Source (Moher et al., 2009)

Table A.1: Articles in SLR with assigned ATLAS.ti codes

Title	**Authors**	**Year**	**Document Type**	**ATLAS.ti code**
A cross-strait comparison of innovation policy under industry 4.0 and sustainability development transition (Lin *et al.*, 2017)	Lin K.C., Shyu J.Z., Ding K.	2017	Article	D2
Development of the DGQ role bundle model of the Q occupations (Schlutter & Sommerhoff, 2006)	Schlüter N., Sommerhoff B.	2017	Article	D30
Heidegger, technology and sustainability between intentionality, accountability and empowerment (Nobre *et al.*, 2017)	Nobre A.L., Duarte R., Jacquinet M.	2017	Conference Paper	D31
Learning Factories' Trainings as an Enabler of Proactive Workers' Participation Regarding Industrie 4.0 (Reuter *et al.*, 2017)	Reuter M., Oberc H., Wannöffel M., Kreimeier D., Klippert J., Pawlicki P., Kuhlenkötter B.	2017	Article	D32
Blended learning: State of the nation (Ossiannilsson, 2018)	Ossiannilsson E.	2018	Conference Paper	D33
Exploring gamification to support manufacturing education on industry 4.0 as an enabler for innovation and sustainability (Paravizo *et al.*, 2018)	Paravizo E., Chaim O.C., Braatz D., Muschard B., Rozenfeld H.	2018	Conference Paper	D34
Exploring how usage-focused business models enable circular economy through digital technologies (Bressanelli *et al.*, 2018)	Bressanelli G., Adrodegari F., Perona M., Saccani N.	2018	Article	D35
Industry 4.0 as enabler for a sustainable development: A qualitative assessment of its ecological and social potential (Stock *et al.*, 2018)	Stock T., Obenaus M., Kunz S., Kohl H.	2018	Article	D36
Industry 4.0 technology implementation impact to industrial sustainable energy in Indonesia: A model conceptualization (Hidayatno *et al.*, 2019)	Hidayatno A., Destyanto A.R., Hulu C.A.	2019	Conference Paper	D37
Smart Factory Implementation and Process Innovation: A Preliminary Maturity Model for	Sjödin D.R., Parida V., Leksell M., Petrovic A.	2018	Article	D38

Title	Authors	Year	Document Type	ATLAS.ti code
Leveraging Digitalization in Manufacturing (Sjödin *et al.*, 2018)				
Smart industry and the pathways to HRM 4.0: implications for SCM (Liboni *et al.*, 2019)	Liboni L.B., Cezarino L.O., Jabbour C.J.C., Oliveira B.G., Stefanelli N.O.	2019	Review	D39
SMEs maturity model assessment of IR4.0 digital transformation (Hamidi *et al.*, 2018)	Hamidi S.R., Aziz A.A., Shuhidan S.M., Aziz A.A., Mokhsin M.	2018	Conference Paper	D40
Socio-technical considerations for the use of blockchain technology in healthcare (Wong *et al.*, 2018)	Wong M.C., Yee K.C., Nøhr C.	2018	Conference Paper	D41
Sustainability impact of digitization in logistics (Kayikci, 2018)	Kayikci Y.	2018	Conference Paper	D42
The paradigms of Industry 4.0 and circular economy as enabling drivers for the competitiveness of businesses and territories: The case of an Italian ceramic tiles manufacturing company (Garcia-Muiña *et al.*, 2018)	Garcia-Muiña F.E., González-Sánchez R., Ferrari A.M., Settembre-Blundo D.	2018	Article	D43
Transformative sustainable business models in the light of the digital imperative-a global business economics perspective (Brenner, 2018)	Brenner B.	2018	Review	D44
A holonic framework for managing the sustainable supply chain in emerging economies with smart connected metabolism (Martín-Gómez *et al.*, 2019)	Martín-Gómez A., Aguayo-González F., Luque A.	2019	Article	D45
A review of Internet of Things (IoT) embedded sustainable supply chain for industry 4.0 requirements (Manavalan & Jayakrishna, 2019)	Manavalan E., Jayakrishna K.	2019	Article	D46
Co-determination - An interdisciplinary concept to train PhD students from different disciplines (Conrad *et al.*, 2019)	Conrad A., Oberc H., Wannöffel M., Kuhlenkötter B.	2019	Conference Paper	D47

Title	Authors	Year	Document Type	ATLAS.ti code
Contextual impacts on industrial processes brought by the digital transformation of manufacturing: A systematic review (Savastano *et al.*, 2019)	Savastano M., Amendola C., Bellini B., D'Ascenzo F.	2019	Article	D48
Cooperation in R & D and eco-innovations: The role in companies' socioeconomic performance (Tumelero *et al.*, 2019)	Tumelero C., Sbragia R., Evans S.	2019	Article	D49
Development of a risk framework for Industry 4.0 in the context of sustainability for established manufacturers (Birkel *et al.*, 2019)	Birkel H.S., Veile J.W., Müller J.M., Hartmann E., Voigt K.-I.	2019	Article	D50
Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: A business model proposal (Nascimento *et al.*, 2019)	Nascimento D.L.M., Alencastro V., Quelhas O.L.G., Caiado R.G.G., Garza-Reyes J.A., Lona L.R., Tortorella G.	2019	Review	D51
IoT to enable social sustainability in manufacturing systems (Papetti *et al.*, 2018)	Papetti A., Gregori F., Pandolfi M., Peruzzini M., Germani M.	2018	Conference Paper	D52
Proposal of an ontological approach to design and analyse farm information systems to support Precision Agriculture techniques (Mazzetto *et al.*, 2019)	Mazzetto F., Gallo R., Riedl M., Sacco P.	2019	Conference Paper	D53
Responding to the challenges and opportunities in the 4th industrial revolution in developing countries (Manda & Dhaou, 2019)	Manda M.I., Dhaou S.B.	2019	Conference Paper	D54
Technology usage, expected job sustainability, and perceived job insecurity (Nam, 2019)	Nam T.	2019	Article	D55
Cyber physical systems implementation for asset management improvement: A framework for the transition (Villar-Fidalgo *et al.*, 2018)	Villar-Fidalgo L., Crespo Márquez A., González Prida V., De la Fuente A., Martínez-Galán P., Guillén A.	2018	Conference Paper	D60
From industry 4.0 to nature 4.0 – Sustainable infrastructure evolution by design (Świątek, 2019)	Świątek L.	2019	Conference Paper	D62

Title	Authors	Year	Document Type	ATLAS.ti code
Simulation based optimization frameworks as key enablers for the transformation to industry 4.0 (Alrabhi, 2018)	Alrabghi A.	2018	Conference Paper	D64
Digitalization and leap frogging strategy among the supply chain member: Facing GIG economy and why should logistics players care? (Rahman *et al.*, 2019)	Rahman N.A.A., Muda J., Mohammad M.F., Ahmad M.F., Rahim S.A., Fernando M.-V.	2019	Article	D65
The Role of a Digital Industry 4.0 in a Renewable Energy System (Scharl & Praktiknjo, 2019)	Scharl S., Praktiknjo A.	2019	Article	D66

APPENDIX B: CONTENT ANALYSIS

Table B.1: Literature landscape and final 6 full text documents selection

		ATLAS.ti Assigned Code:	D1	D2	D30	D31	D32	D33	D34	D35	D36	D37	D38	D39	D40	D41	D42	D43	D44	D45	D46	D47	D48	D49	D50	D51	D52	D53	D54	D55	D58	D60	D62	D64	D65	D66
Field Focus	Industrial sectors	Manufacturing	x				x		x		x		x					x				x	x	x	x	x	x				x					
		Energy										x																								x
		Quality Management			x																															
		Social science				x																														
		Human resource												x																				x		
		Supply chain												x			x			x	x														x	
		SMEs													x																					
		Healthcare														x																				
		logistics															x																	x	x	
		Ergonomics																									x									
		Agriculture/farming																										x								
		Asset management																														x				
		Education/Training					x	x	x													x							x							
		Industrial production								x												x									x					
	Organisational focus applications	Innovation		x					x				x					x	x				x	x		x	x		x							x
		Value creation/business processes	x								x																									
		Business models			x					x	x							x	x						x	x									x	
		Jobs/Employment/Work 4.0	x		x		x				x			x	x			x				x							x	x					x	
		Servitization																	x																	
	system/institutional focus	Policy drive		x																									x							x
		Strategy	x	x	x							x			x			x					x						x							x

	ATLAS.ti Assigned Code:	D1	D2	D30	D31	D32	D33	D34	D35	D36	D37	D38	D39	D40	D41	D42	D43	D44	D45	D46	D47	D48	D49	D50	D51	D52	D53	D54	D55	D58	D60	D62	D64	D65	D66
Industry 4.0 concepts	Digitalisation						x					x				x	x					x												x	x
	Digitisation															x	x					x					x								
	Industry 4.0 technology specific focus								x						x										x	x	x								
	Digital transformation			x			x							x		x						x													
	Industry 4.0 Implementation	x	x			x				x			x	x	x			x	x		x			x	x			x	x						x
sustainability or sustainable development concepts	Ecological sustainability	x						x	x	x	x					x	x		x				x	x	x					x		x	x		
	Economic sustainability	x	x	x				x	x	x	x	x		x		x	x	x	x	x		x	x	x	x		x			x				x	
	Social sustainability	x			x	x	x	x		x	x	x	x		x	x	x		x		x			x	x	x		x	x	x					
	Circular economy								x								x		x						x										
	Triple Bottom Line	x																	x			x	x	x						x					
	Sustainable development or SDGs	x						x		x	x																	x				x			
	Job sustainability and insecurity					x				x																		x	x						
Industry 4.0 technologies highlighted	Big Data and analytics	x	x						x	x				x	x	x	x	x			x				x			x					x		x
	Block chain														x																				
	CPS							x		x									x	x				x				x			x				x
	IoT							x	x	x				x			x			x				x		x	x			x					x
	Smart "things"	x										x		x		x	x					x													
	Gamification/simulation							x																						x					
	Digital twins									x																									
	Cloud computing									x						x											x								
	Additive Manufacturing																								x										
Socio-technical systems consideration	Core STS theory concepts				x	x					x		x		x				x					x		x		x				x			x
	T-O-P					x				x				x				x			x	x												x	
	Systems view or thinking		x													x	x			x				x	x						x				
	Knowledge management (especially with Big Data)																				x						x								

		ATLAS.ti Assigned Code:	D1	D2	D30	D31	D32	D33	D34	D35	D36	D37	D38	D39	D40	D41	D42	D43	D44	D45	D46	D47	D48	D49	D50	D51	D52	D53	D54	D55	D58	D60	D62	D64	D65	D66
methodologies employed	*input*	Interviews									x														x	x										x
		Case study								x	x		x					x		x							x		x		x				x	
		Surveys			x										x		x													x						
		Literature review	x						x	x				x					x		x				x				x							
		Qualitative data analysis (general)		x														x						x		x				x						
		Framework		x							x																x						x			
	intermediary	Simulations																													x			x		
		Descriptive analytics		x																																
		Statistical analysis		x																										x						
		Systems modelling										x																								
	output	Qualitative/conceptual																					x	x				x								
		Didactic					x															x														
		Maturity Model											x		x																					
		Framework							x	x									x	x	x				x	x	x	x	x			x		x		
		Mathematical modelling	x																	x			x													
Preferred relevance checks	region of assessment in document	sub-Saharan Africa																											x							
		South America											x											x												
		Europe	x		x		x						x				x	x				x			x		x									x
		Asia		x								x			x																				x	
		North America																												x						
	level of analysis	Macro global/institutional/systemic)		x								x													x				x	x						x
		Micro (firm/industry specific application)	x		x		x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x	x		x	x	x
		Unspecified (academic/school of thought)				x																											x			
Final quality criteria		Socio-technical systems perspective					x				x	x		x	x	x				x					x	x	x		x				x			
		Industry 4.0 leverage	x	x					x	x	x	x	x	x	x		x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x

	ATLAS.ti Assigned Code:	D1	D2	D30	D31	D32	D33	D34	D35	D36	D37	D38	D39	D40	D41	D42	D43	D44	D45	D46	D47	D48	D49	D50	D51	D52	D53	D54	D55	D58	D60	D62	D64	D65	D66
	3D- Sustainability/SD targets or issues addressed	x	x					x	x	x	x	x				x	x		x					x	x			x	x	x					x
	Systems transitions/transformations language/highlight		x	x	x		x	x	x		x				x			x	x								x	x		x	x	x		x	x

APPENDIX C: APPROACH AND METHODOLOGY

Table C.1: Descriptions of various research product methodologies. Adapted from Kleynhans (2020).

Methodology	Description
Theory	According to Nilsen (2015) theory may be defined as "*a set of analytical principles or statements designed to structure our observation, understanding and explanation of the world*". Theories are generalised statements of abstraction or ideas that assert, explain and predict relationships between phenomena through boundaries set by the theory (Kivunja, 2018).
Model	A theoretical model gives an abstract description of a given system (Achinstein, 1965). A model typically involves a deliberate simplification of a phenomenon or a specific aspect of a phenomenon. Models can also be described as theories with a more narrowly defined scope of explanation. Models need not be completely accurate representations of reality to have value. (Nilsen, 2015). A model is not the real world, but merely a human construct to help better understand the real-world systems. (Starting Point, 2019).
Framework	A broad overview, outline, or skeleton of interlinked items (i.e., a system, concept or text) which supports a particular approach to a specific objective (Business Dictionary, 2020) . *A framework denotes a structure, overview, outline, system or plan consisting of various descriptive categories, e.g., concepts, constructs or variables, and the relations between them that are presumed to account for a phenomenon* (Nilsen, 2015). A conceptual framework is a network, or "a plane," of interlinked concepts that together provide a comprehensive understanding of a phenomenon or phenomena. The concepts that constitute a conceptual framework support one another, articulate their respective phenomena, and establish a framework-specific philosophy (Jabareen, 2009).
Roadmap	A plan or strategy intended to achieve a particular goal (Semick, 2016). A roadmap is a strategic plan that defines a goal or desired outcome, and includes the major steps or milestones needed to reach it (Petrick & Echols, 2004). A key characteristic of a roadmap is a high-level plan, defining the overarching strategic objective, and capturing the major steps (Semick, 2016).
Logic Model	A logic model presents a picture of how your effort or initiative is supposed to work. It explains why your strategy is a good solution to the problem at hand. Effective logic models make an explicit, often visual, statement of the activities that will bring about change and the results you expect to see for the community and its people (Taylor-Powell *et al.*, 2008). Other names include roadmap (Taylor-Powell *et al.*, 2008). A logic model includes the following components: Purpose, context, inputs, activities, outputs, effects (Taylor-Powell *et al.*, 2008).
Toolkit	A set of tools designed to be used together or for a particular purpose (Beaven, 2019).

Methodology	Description
	A fixed set of procedures, guidelines and criteria established to ensure a desired or required result or prevent oversights (Beaven, 2019).
Blueprint	The term “blueprint” is derived from the domain of architecture, which means “detailed plan of action” (Adkoli & Deepak, 2012). A Blueprint is a map or specification for a type of program, which ensures that all the aspects of a specific technical domain are covered (Community Toolbox, 2018).
Strategy	A strategy is the process you use to approach a problem. It is a way of describing how you are going to get things done. It is less specific than an action plan (Community Toolbox, 2018).
Typology	A typology is the selection of a certain number of combinations of groups of variables. The selection may be more or less explicit, more or less valid, and more or less based on the data afforded by empirical research (Capecchi, 1968).

APPENDIX D: SME EVALUATION: OVERVIEW DOCUMENT

Towards the development of a model for the integration of Socio-technical Transitions and the Fourth Industrial Revolution

AN OVERVIEW FOR RESEARCH EVALUATION

UNIVERSITEIT
iYUNIVESITHI
STELLENBOSCH
UNIVERSITY
100
1918 · 2018

DRAFT

Author: Martha Mukama Asiimwe

Supervisor: Ms Imke de Kock

This draft is presented for the purposes of evaluating the research study and product. No contents herein may be replicated or published or referenced without the author's consent.

1

1 DOCUMENT OVERVIEW

This study was conducted to analyse and develop an integration between the concepts of Socio-technical Transitions (hereon referred to as STTs) and the Fourth Industrial Revolution (hereon referred to as The 4IR). This document is a compilation of excerpts from the thesis document, providing a summary which has been condensed for the purposes of evaluating the study's research product. The document gives a short introduction to the concepts and thereafter highlights key findings from the literature review undertaken. An overview of the research product development methodology is presented. Thereafter the developed model is presented.

Please note that although this document reads in the same format as the parent thesis document is written, its sections, figures and tables have been numbered and updated to aid its flow. Furthermore, in the process of summarising, some connections and links to the full scope of content found in the parent thesis may have been omitted. However, in case of any ambiguities, the author is happy to provide clarity in the subsequent evaluation interview.

Below is a table of contents for the reader's convenience and to aid navigation to specific points of interest.

2 INTRODUCTION

This section provides an overview of the introduction to the study which is found in Chapter 1 of the thesis document. The purpose of this overview is to familiarise the reader on the concepts of STTs and the 4IR and their relation to the study. Most important, however, is the presentation of the research problem, aim and objectives in Sections 2.3 – 2.4. In the thesis document, STTs and the 4IR are further

2

and fully elaborated on with the context of sustainability and sustainable development. This is omitted in this document in order to summarise this document's content.

2.1 SOCIO-TECHNICAL SYSTEM TRANSITIONS

The concepts of socio-technical systems and socio-technical transitions are strongly related to concepts of sustainability and sustainable development (Baxter & Sommerville, 2011). Socio-technical systems (STS) as described by S. Sorrel (Sorrell, 2018), are the *"dominant technologies, infrastructures, industries, supply chains and organisations responsible for delivering a societal function"*. Socio-technical systems have humanistic, social and technical factors considered in their systemic design (Baxter & Sommerville, 2011). STS operate at a complex systemic level but are, in lay-man perspective, meant to meet wide scale societal needs. This implies incorporating economic, political and social humanistic factors within the system's dynamics. This aspect of STS elevates complexity through adding variability and stochasticity to their dynamics in comparison to a purely technological make-up. Society is an active component of STS as these systems fulfil functions for it and also double as a major resource influencing sustainability through people's interactions with technology (Baxter & Sommerville, 2011).

Social, economic and ecological sustainability needs and issues inherently influence the makeup of socio-technical systems (Tran, 2014). These are included within the external landscape within which these systems exist and in the innovations and technologies in the systems (Sorrell, 2018). Tran (2014) argues that solutions to sustainability issues can't be achieved through mere incremental development of technologies, but have to be aggregately incorporated with the ecological, social and economic aspects of society. These three elements are therefore implied to be cross and interdependent within sustainability and sustainable development targets as well as socio-technical systems (Tran, 2014).

Socio-technical systems (STS) are commonly characterized by facets such as feedback loops, self-organisation of the systems and hierarchies which contribute to their inherent complexity (Geels & Schot, 2007; Tran, 2014). Furthermore, they are described to have three dimensions i.e. landscape, regimes and niches as shown in Figure 1 below (Geels, 2003, 2011). In literature, it is highlighted that these characteristics and dimensions present actors steering transitions within these systems various challenges through factors such as agency, knowledge bases, political framings, social behaviour, industrial structures and environmental and demographic shocks (Elzen *et al.*, 2004). However, the argument is also made that the inherent complexity of STS is what presents their potential to steering towards sustainable development (Savaget *et al.*, 2018). STS present a unique perspective towards sustainability as such systems employ multi-level interactions coupled with the overall systematic view.

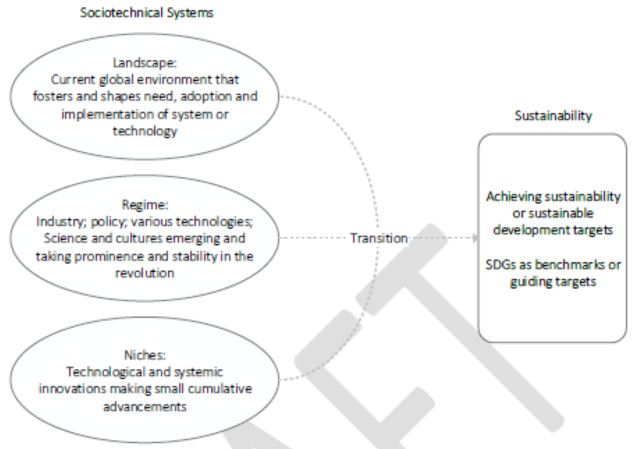


Figure 1: Socio-technical system transitions to sustainable states

2.2 THE FOURTH INDUSTRIAL REVOLUTION (4IR)

The Fourth Industrial Revolution (also known as Industry 4.0 or 4th Industrial Revolution or 4IR for short) is posing major shifts on the global landscape. This revolution seeks to connect resources, services, products and human beings in real time through digitalisation and digitisation (Stock *et al.*, 2018). It is predicted that there will be major impacts on sustainability and the transitions thereof as result of the shift towards application of technologies and concepts in this paradigm (Tran, 2014).

Different literature highlights a variety of perspectives and links between sustainability or sustainable development and the 4IR. These views include the 4IR as a driver for sustainability hence sustainability as an incentive for its expansive implementation (Stock *et al.*, 2018), (Agamuthu, 2017), (Anggusti & Siallagan, 2018), (Habanik *et al.*, 2019), (Kamble *et al.*, 2018); links between 4IR and sustainability in the context of the social, economic and ecological of the sustainability dimensions (de Man & Strandhagen, 2017; Papetti *et al.*, 2018; Stock *et al.*, 2018) and several expounds relating 4IR to sustainability of processes, technologies and whole industries in industrial practice (Kiel & Arnold, 2017), (Carvalho *et al.*, 2018; Dossou, 2018; Kumar *et al.*, 2018; Papetti *et al.*, 2018; Stock & Seliger, 2016) to mention but a few. Although there is a growing database of literature examining the impacts of 4IR on sustainability and sustainable development and vice versa, the question lies in the extent to which systems transitions to sustainable states have been considered and examined in literature in conjunction with the 4IR.

With growing societal awareness of technological effects, increasing ecological and resource depletion as well as an increasing industrial drive towards profitability, there is strong practical and theoretical relevance in the study of the interconnectedness of people, technologies and resources (Bonilla *et al.*, 2018; Habanik *et al.*, 2019; Müller *et al.*, 2018). Despite the growing anticipation for the predicted benefits of the 4IR, there is considerable uncertainty on the implications of a paradigm shift amongst various practitioners and fields (Müller *et al.*, 2018). It is essential for the various domains that apply concepts of the 4IR and the technologies therein to understand the underlying dynamics of interconnectedness. STS studies inherently incorporate, structure and provide a platform to explore and understand these dynamics (Sorrell, 2018). Therefore, an examination of such dynamics and of the shift towards more sustainable states is imperative to groundwork in efforts to meet sustainability and sustainable development goals. As such, research that focuses on analysing the extent to which socio-technical systems and transitions, sustainability and the 4IR are jointly considered plays an important role in contributing to transitions literature by demystifying the links between these concepts with the ultimate aim of identifying challenges, opportunities and laying groundwork for further research.

2.3 RESEARCH PROBLEM

While considering the possibilities that exist within the 4IR concept and in-line with literature (Morrar *et al.*, 2017; Noor, 2019; Stock *et al.*, 2018), the 4IR seems to show opportunities and possibilities in supporting the quest towards sustainability and contributing to sustainability transitions research. However, the integration of 4IR concepts with those of socio-technical transitions seems to be lacking.

A number of frameworks, approaches and theories exist that are geared towards the analysis and evaluation of sustainability transitions and/or socio-technical transitions (European Environment Agency (EEA), 2018; Köhler *et al.*, 2019). However, one of the main areas of critique of such frameworks, approaches and theories are that they lack ways in which to operationalize and institutionalise the principles and driving forces to bring about transitions to sustainability (Geels, 2019) . Furthermore, it is highlighted that there a need for research incorporating multiple technologies or niches as opposed to single technologies and the repercussion these combined technologies/niches have on larger systems (Köhler *et al.*, 2019).

This study is therefore concerned with the integration of the concepts of socio-technical transitions and the 4IR. The study analyses the extent to which literature has jointly considered the concepts and identifies consequent gaps within literature. This is done so as to infer a conceptualisation of both concepts that integrates both concepts and builds a foundation towards the operationalisation of the 4IR within contemporary STTs.

Literature shows that there is a global need to meet sustainability and sustainable development goals (United Nations, 2019; United Nations Department of Economic and Social Affairs, 2014). The analysis of contemporary societal systems as STS towards sustainability/sustainable development goals through STTs has shown value in conceptualising and explaining how these systems may meet societal functions sustainably (European Environment Agency (EEA), 2018; Köhler *et al.*, 2019). STTs analysis has therefore become a distinct and demanding topic amongst global sustainability debates (Köhler *et al.*, 2019). Furthermore, given current global sustainability conundrum, the rise on the 4IR as a technological paradigm has sparked multiple discussions in both academic literature and practice on the paradigm's sustainability implications (Schwab, 2016; World Economic Forum, 2019a, 2020). It is therefore envisaged that an integration of both concepts (STTs and the 4IR) may contribute to and foster contemporary societal systems' analysis in the effort to meet global sustainability and sustainable development targets and goals.

2.4 AIM AND OBJECTIVES

The aim of this research is to contribute towards the fostering of sociotechnical transitions through the

5

analysis, integration and operationalisation of the 4IR within STTs. This aim is to be achieved through the development of a model for the integration of socio-technical transitions and the fourth industrial revolution (I4IR-STT model). The objectives that support the attainment of the stated aim and output are as below:

i. Contextualise the STTs and the 4IR as presented in their core literature and as pertaining to this study;
ii. Conduct an investigation in the extent to which STTs and the 4IR have been jointly considered within academic literature alongside the supporting background context of sustainability or sustainable development and STS. The supporting sub-objectives include:
    a. Conduct a bibliometric analysis examining the literature landscape;
    b. Conduct a content analysis examining how the concepts are jointly addressed and analysed in literature and what key themes and topics emerge; and
    c. Conduct a gap analysis to compare literature analysed to the contextualisation and thus identifying the gaps to be addressed within the body of literature;
iii. Articulate an integration strategy that could potentially form the basis from which the I4IR-STT model could be developed. The sub-objectives that support this objective are:
    a. Present the methodology employed for the development of the model; and
    b. Develop functional specifications for the model;
iv. Develop the I4IR-STT model. Sub-objectives include:
    a. Develop the model;
    b. Develop an operationalisation strategy for the developed model;
    c. Verify the model through the functional requirements for its development and validate the model with Subject Matter Experts (SMEs) and a case study to show case the applicability of the I4IR-STT model through its operationalisation strategy. It is envisaged that the case study should be industry-specific, thus the developed model is customised for a specific industry and then used in an illustrative case study.

3 LITERATURE REVIEW: CONTENT AND GAP ANALYSIS SUMMARY

For this study, literature analysis was conducted in two parts:

i. Firstly, through a conceptual literature review to give context to the concepts of the 4IR and STT theory. The 4IR and STTs concepts were individually analysed and their theory presented as found in academic literature; and
ii. Secondly, through a Systematic Literature Review (SLR) to assess the extent to which these concepts have been jointly addressed in academic literature. The SLR was guided by the following questions:
    a. How does literature present and discuss the concepts of 4IR and STT;
    b. What themes and topics are discussed or emerge within literature in relation to these concepts;
    c. To what extent are these concepts considered together;
    d. What are the gaps within literature in the joint analysis of both concepts; and
    e. What deductions may be made for an integration of the concepts within literature?

6

A literature search conducted through SCOPUS yielded 42 documents/records. Figure 2, presents a PRISMA diagram with a summary of the SLR process and consequent document results.

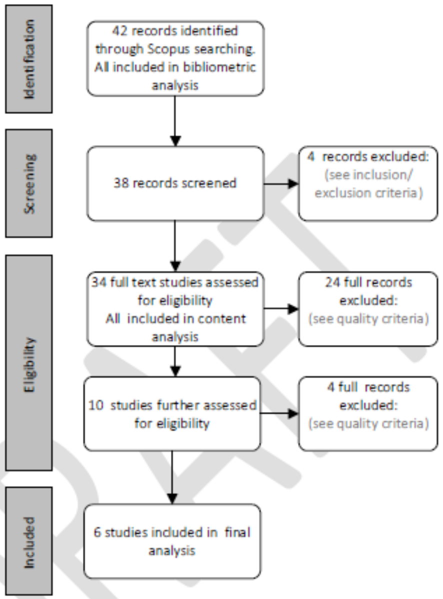


Figure 2: PRISMA diagram with SLR results

The resulting 6 documents included in the final content analysis were Lin et al. (2017), Stock et al. (2018), Martín-Gómez et al. (2019), Nascimento et al. (2019), Manda & Dhaou (2019), and Hidayatno et al. (2019).

Lin et al. (2017) focuses on policy reviews, presenting a generic sectorial comparative study on Industry 4.0 policies between China and Taiwan. Lin et al. (2017) highlights innovation policy and utilises an innovation policy framework for the analysis. This is formed on the basis that Industry 4.0 is a technological innovation and thereby assessing policy frameworks within the Chinese and Taiwanese contexts gives a holistic view of the impact on these countries' national systems. (Lin *et al.*, 2017)

Stock et al. (2018) conducts a qualitative assessment study on the potential of value creation in Industry 4.0 from an industry/sector level perspective and organisation specific perspective. Stock et al. (2018) highlights that although value creation is predominantly an economic sustainability benefit from

Industry 4.0, it has the potential to contribute to other sustainability dimensions. Stock et al. (2018) incorporates a basic socio-technical perspective while setting the article's premise. (Stock *et al.*, 2018)

Martín-Gómez et al. (2019) integrates various frameworks for the three sustainability dimensions within and through supply chain management. Martín-Gómez et al. (2019) provides insights into the relationships between social metabolism, the circular economy and a holonic paradigm while utilising Industry 4.0 as an enabler. Nascimento et al. (2019) also integrates sustainability with supply chain management and the use of technologies that drive Industry 4.0 such as additive manufacturing and cyber physical systems as enablers with circular economy practices (Martín-Gómez *et al.*, 2019; Nascimento *et al.*, 2019).

Manda & Dhaou (2019) discusses the challenges and opportunities for Industry 4.0 in developing countries, using South Africa as a case study. Manda & Dhaou (2019) sets their premise from an applied socio-technical systems perspective. Finally, Hidayatno et al. (2019) presents a casual loop diagram integrating the three sustainability dimensions with a technological factor. With this, the argument is presented that revolutions and global systemic shifts often happen with and due to technology and thus technology presents itself as the most significant social driver (Hidayatno *et al.*, 2019; Manda & Dhaou, 2019).

3.1 CONTENT ANALYSIS OF THE FINAL DOCUMENTS.

Findings are presented through a brief content analysis and were thereafter analysed against contextual 4IR and STT literature to present a gap analysis from which deductions for the study's research product are made. Key findings are summarised below:

3.1.1 OVERALL CONSIDERATION FOR SOCIO-TECHNICAL SYSTEMS TRASITIONS

STT and STS perspectives are mainly inferred in the documents and are presented from the basic argument of human interaction with technology as a key driver for shaping system configuration and transformation. For example, Stock et al. (2018) makes the argument that current human interaction with technology is a key factor to the proper functioning of the system, while linking this to CPS technologies and their functioning (Stock *et al.*, 2018). Martín-Gómez et al. (2019) further elaborates that management for sustainability is embedded in the wholistic system that looks at technology within societal and organisational contexts (Martín-Gómez *et al.*, 2019).

Manda & Dhaou (2019) defines socio-technical systems as an organisation of two independent yet correlating and interacting systems; the technical and social working in synergy (Manda & Dhaou, 2019). The technological system transforms inputs to outputs while the social system comprises of the people, society and the environment that use the technology. Manda & Dhaou (2019) argues that the failure of a technological system can be attributed to the behaviour of social elements within which it operates and the successful transformation towards targets or goals requires an understanding of the social and technical systems and the environments within which they operate. (Manda & Dhaou, 2019).

In comparison to literature presented in the contextualisation, these arguments and sentiments hold a basic understanding of STS. Furthermore, STTs as presented in the contextualisation are not explicitly or clearly defined, discussed and analysed in these documents. However, these are a few noteworthy deductions from these documents on considerations for systems transitions. These are presented as follows:

i. Stock et al., (2018) makes the argument that organisations and systems should transform and adopt technologies that create sustainable value creation and sets the argument that Industry 4.0 encompasses such technologies and hence can be an enabler for transformation within various organisations and systems;
ii. Lin et al. (2017), Stock et al. (2018) and Manda & Dhaou (2019) emphasize that innovation is a critical element for systems in transforming towards sustainable states (Lin *et al.*, 2017; Manda & Dhaou, 2019; Stock *et al.*, 2018);
iii. Stock et al. (2018) also argues that the transformation process should be built on economic development within social equity and ecological boundaries (Stock *et al.*, 2018), thereby highlighting the need for a three-dimension structure for system transitions;
iv. Martín-Gómez et al. (2019) suggests that to analyse societal system transitions towards more sustainable states, indicators at national, regional and industrial sector levels must be assessed and gives credit to the importance of incorporating SDGs towards global systems sustainability (Martín-Gómez *et al.*, 2019); and
v. Martín-Gómez et al. (2019) specifies that creative working processes such as strategic planning and Research and Development (R&D) are important for successful transformation (Martín-Gómez *et al.*, 2019).

Although the sentiment is carried that systems need to transform in order to meet set goals, there is a lack of sufficient elaboration on the process and the definitive nature of these transformations and transitions as discussed in literature such as (Elzen *et al.*, 2004; Farla *et al.*, 2012; Fuenfschilling & Truffer, 2016; Geels, Turnheim, *et al.*, 2019; Hof *et al.*, 2020; Ramos-Mejía *et al.*, 2018; Schot & Kanger, 2018a; Sovacool & Hess, 2017).

3.1.2 FOURTH INDUSTRIAL REVOLUTION CAPABILITIES FOR SUSTAINABILITY AND SYSTEMS TRANSITIONS

It is observed that literature is well versed in the analysis of the 4IR. Lin et al. (2017) defines 4IR as a technological paradigm in which computers and automation are integrated with machine learning and control systems with little input from human beings (Lin *et al.*, 2017). Nascimento et al. (2019) states that the advancement of the 4IR is underpinned by information and communications technologies developing into further technologies such as IoT, cyber physical systems, Big Data and analytics, cloud computing, additive manufacturing to mention but a few (Nascimento *et al.*, 2019). These sentiments are aligned and similar to the core 4IR literature presented in the contextualisation.

However, it is also observed that literature focusses on the 4IR defined as Industry 4.0. This implies a predominant focus on industrial and manufacturing systems. Regardless, literature unanimously agrees that Industry 4.0 holds the potential to positively impact global industrial systems and processes. Industry 4.0 is credited with improved technological efficiency, optimized resources usage, flexibility, increased system capacities and enlarged value creation networks which in turn produce varied quality product and service offerings to the customer or consumer, cleaner technologies, product life cycle management and renewable energy (Lin *et al.*, 2017; Stock *et al.*, 2018). All these are presented as positive contributions within the three dimensions of sustainability. Furthermore, it is argued that society can maximize on these benefits by transitioning towards the achievement of sustainability targets (Stock *et al.*, 2018). However, literature also specifies key concerns for the adoption and

implementation of Industry 4.0 technologies that may negate efforts toward achieving these targets. These are summarised in Table 1 below.

Table 1: Concerns for implementation (Lin *et al.*, 2017; Manda & Dhaou, 2019)

Social	Ecological	Economic
Automation of Jobs which leads to simplification of jobs by tech systems resulting in extortion and exploitation and/or replacement of human labour Increased cyber dependence which increases risk for cyber-attacks leading to concerns for transparency and privacy issues Anticipated rising inequalities and social gaps between emerging and developed countries or communities	Initial increased material and energy usage in the implementation of new technologies	Intense capital implications for the adoption resulting in hesitancy Need for upskilling workers and a need for future skills some of which are not existent at the moment. ICT infrastructure still poor in most developing countries which may render technologies inefficient or further increase equality disparities.

Lin et al. (2017) and Manda & Dhaou (2019) specify drivers for successful implementation of Industry 4.0 technologies within current systems. These include strategic planning, innovation, education and training, information and communications technology and policy, regulations and legislation.

Strategic planning is suggested for the successful implementation of companies and for achieving set targets (Lin *et al.*, 2017; Stock *et al.*, 2018). Lin et al. (2017) and Stock et al. (2018) specify strategies for achieving systemic sustainable development targets within the contexts they address.

In the economic sustainability dimensions; innovation drive is highlighted as a key driver for the adaptation to technological shifts. Martín-Gómez et al. (2019) further highlights managerial strategy as important towards organisational structure and process optimisation towards organisational sustainability (Martín-Gómez *et al.*, 2019). Stock et al. (2018) highlights product life cycles, business model innovations, quality improvements as key. Connectivity through information systems, leveraging data and integrating various fields and sectors is also highlighted as a key strategy towards achieving economic sustainability (Stock *et al.*, 2018). Within the ecological dimension, establishment of green development is presented as a key strategy to achieve targets such as reductions in waste, reduction in material and resource usage, reduced energy consumption and scaled renewable energy initiatives (Stock *et al.*, 2018). Nascimento et al. (2019) and Martín-Gómez et al. (2019) propose the incorporation of circular economy which is described as a system that is restorative and regenerative as a strategy for the achieving combined ecological and economic targets (Martín-Gómez *et al.*, 2019; Nascimento *et al.*, 2019). Within the social dimension education and training through upskilling and reskilling of workers is viewed as key components for combating the social concerns with new technological paradigms. Furthermore, Martín-Gómez et al. (2019) states the need for both vertical (systemic) and horizontal (organisational processes) integration of technologies within the drive towards sustainability while Lin et al. (2017) presents these integrations as key within the policy and regulation and legislative driver for 4IR implementation (Lin *et al.*, 2017; Martín-Gómez *et al.*, 2019).

As mentioned, and as can be observed above, the analysis of 4IR in this literature focusses on specific industrial fields such as manufacturing or industrial production processes, computer sciences, information systems and infrastructure development. Stock et al. (2018) and Nascimento et al. (2019)

hold a dominant manufacturing view, Martín-Gómez et al. (2019) looks at sustainable supply chain management whereas Hidayatno et al. (2019) looks at energy within a manufacturing context.

3.2 GAP ANALYSIS

From the contextualisation of the main concepts presented in Chapter 2 and the SLR findings presented through the content analysis, it is observed that there exists gaps and disconnects between the conceptual and SLR literature. Gaps identified highlight important content absent in the joint consideration of the concepts of the 4IR and STTs. Disconnects highlight differences between the conceptual and systematic literature in how they analyse both concepts. The gap analysis thereby presents both gaps in and disconnects between the conceptual literature and the SLR literature content in the analysis of the 4IR and STTs in the following sub-sections. The gaps and disconnects are later translated into deductions for the integration strategy for the envisaged model.

3.2.1 OVERALL GAPS IN LITERATURE

Gaps identified in literature are deduced from the conceptual literature as well as the literature analysed from the SLR. These are presented below:

3.2.1.1 OVERALL LACK OF A CONSOLIDATED INTEGRATED ANALYSIS OF SOCIO-TECHNICAL TRANSITIONS AND THE FOURTH INDUSTRIAL REVOLUTION IN LITERATURE

In terms of a joint consideration for both concepts, inferences are drawn from content analysis within the contextual background of sustainability and sustainable development. These include:

i. Sustainability targets such as SDGs are relevant and important considerations or drivers for the adoption, implementation and utilisation of technologies and innovations, and are important targets or performance indicators for societal systems (Lin *et al.*, 2017; Manda & Dhaou, 2019; Nobre *et al.*, 2017; Paravizo *et al.*, 2018; Stock *et al.*, 2018);
ii. Current systems need to consider transitioning to attain above-mentioned sustainability targets or SDGs. Furthermore, strategies towards these targets and utilisation of technologies that drive the 4IR need to be wholistic, in that they consider various fields and sectoral inputs, at different levels (from micro to macro and/or organisational to global) within all dimensions of sustainability (i.e. economic, social and ecological) (Brenner, 2018; Manda & Dhaou, 2019; Stock *et al.*, 2018); and
iii. Industry 4.0 and therefore the 4IR encompasses multiple technologies that possess a multitude of functionalities that affect and influence various facets of contemporary global socio-economic and systemic structures. Understanding this paradigm is thus imperative as it poses a multitude of opportunities and challenges to address some of the grand societal challenges faced today.(Lin *et al.*, 2017; Manda & Dhaou, 2019; Müller *et al.*, 2018; Savastano *et al.*, 2019)

11

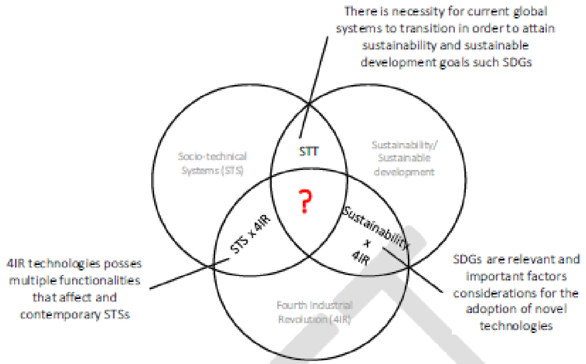


Figure 3: Literature's joint consideration of the main concepts

However, a definitive integrated analysis of the 4IR and STTs as they are presented in Chapter 2 of this study, is largely at miss. There is an overall lack of a descriptive or conceptual relationship between the 4IR and STTs. The 4IR not only poses a multitude of opportunities to solve some of the contemporary societal challenges, but also continues to affect and influence various societal structures on a global spectrum (Li *et al.*, 2017). Incorporating the 4IR within STT provides a contemporary and applicable context to how STTs occur. Furthermore, an orientation of the 4IR with STT would enable a further understanding of contributions, challenges, hinderances and enablers that are brought into effect by novel technologies within STT.

3.2.1.2 OPPORTUNITIES FOR FUTURE RESEARCH IN SOCIO-TECHNICAL TRANSITIONS LITERATURE

Core STTs literature highlights a few gaps in the theoretical analysis of the STT. These gaps present opportunities for exploitation within novel studies as a contribute to the body of knowledge. These include:

i. Previous studies on transitions have typically been conducted after transitions have occurred i.e. application and case studies in literature are retrospective (Elzen *et al.*, 2004). Although advantageous for analysis, this presents the gap in synthesis as studies conducted are limited in application to current systems due to constant and consistently shifting contexts;
ii. Emerging technologies with new sustainability capabilities are often under-utilised in analysis, hence new functionalities are not taken into consideration (Elzen *et al.*, 2004); and
iii. The need to analyse not just single technologies but combinations of multiple emerging and exiting technologies or niches which bring about new dynamics for systems and their transitions (Köhler *et al.*, 2019)

Given the contemporality of the 4IR to current systems, it is envisaged that an integrated study on both concepts would benefit STTs literature in addressing the above opportunities for further research.

12

3.2.2 DISCONNECTS IDENTIFIED BETWEEN THE CONCEPTUAL AND SYSTEMATIC REVIEW LITERATURE

Additionally, following a contrast between the SLR content and the conceptual literature on STTs and the 4IR, disconnects between the literature are identified and presented in the following subsections:

3.2.2.1 LACK OF SUFFICIENT ELABORATION ON SOCIO-TECHNICAL TRANSITIONS

Although transitions/transformation language is inferred, utilised and highlighted in some of the SLR literature (refer to Bressanelli *et al.*, 2018; Hidayatno *et al.*, 2019; Lin *et al.*, 2017; Manda & Dhaou, 2019; Martín-Gómez *et al.*, 2019; Paravizo *et al.*, 2018; Scharl & Praktiknjo, 2019) there is little to no overall employment of STT theory. This limits the critical understanding of what transitions are, their designs, dynamics and implications for current systems. Consequently, there is little to no explorative analysis of the 4IR's orientation in STT design and its impacts within this regard. A lack of understanding and proper systemic integration and alignment of societal needs with technological shifts is detrimental to the global systemic success (European Environment Agency (EEA), 2018)

3.2.2.2 LACK OF SUFFICIENT CONSIDERATION OF SYSTEMS ORIENTED TOWARDS SOCIETAL FUNCTIONS

Literature highlights that STS are to be designed to meet societal needs. Given the undeniable orientation of current systems as socio-technical, STS studies prove useful in understanding the current system dynamics as well mitigating arising challenges. Baxter and Sommerville (2011) argue that given the repercussions of human interactions with technology within systems, it is important to not merely analyse systems from socio-technical perspectives but to develop, evolve and transition these systems in order to meet system requirements, goals and targets (Baxter & Sommerville, 2011) which in this case, encapsulate sustainability and sustainable development goals .

The main distinction between STS and other systems where human beings generally interact with various forms of technology is that STS are designed and oriented to fulfil societal functions such as food, water, health, transportation, energy, communications etc. (European Environment Agency (EEA), 2018). Literature thereby highlights this fact as a key factor in defining STS and their transitions.

However, given the societal function imperative in STTs design, literature analysed in the SLR appears to overall lack in this wholistic perspective. This is mostly due to the dominant economic sustainability targets fuelled by analysing the 4IR as Industry 4.0 within the industrial or manufacturing setting limits efforts towards wholistic sustainability and sustainable developments targets for societal functions.

3.2.2.3 OVERALL DOMINANT SINGLE VIEW OF THE FOURTH INDUSTRIAL REVOLUTION AS INDUSTRY 4.0

Most literature analysed is applied to the manufacturing and industrial setting which mainly considers the Industry 4.0 component of the 4IR. Although valid, it is understood that the scope of the 4IR goes beyond Industry 4.0, which is one facet of the larger context. Technologies that drive the 4IR display potential for positive impact and contributions in other sectors, that need to be analysed, explored and incorporated in STT.

Additionally, this view of the 4IR limits the academic analysis of 4IR down in the SLR literature to production values chains, the manufacturing and industrial production context which mostly narrows sustainability targets towards the economic dimensions. This limits the sustainability contribution to a

dominant economic perspective. This, however, is a limited premise for transitions towards sustainability as the economic benefits of technology within an industrial setting do not generally imply the achievement of sustainability or sustainable development targets for a society (European Environment Agency (EEA), 2018).

Furthermore, the Industry 4.0 view limits studies in the SLR to a firm/organisation/industry level which in the wider spectrum maybe considered as a micro perspective. Analysis of STS and the transitions thereof should include macro and meso dimensions and perspectives (Geels & Schot, 2010).

4 RESEARCH PRODUCT DEVELOPMENT METHODOLOGY OVERVIEW

It is envisaged that the model fills the gaps and addressed the disconnects identified in literature and presented in Section 3.2 above. Therefore, the gaps and disconnects presented are utilised in the development of a strategy for the integration of both concepts by translating them to deductions for the strategy. It is envisaged that the inferred integration strategy incorporate the following deductions from literature presented in Table 2 below.

Table 2: Deductions for the model

Deduction ID	Deduction	Section from Chapter 4 being addressed
D1	Sufficiently integrate and orient elements of the 4IR and STTs.	Section 3.2.1.1
D2	Comprehensively draw on the analysis of transitions from a socio-technical systems perspective.	Sections 3.2.2.1 and 3.2.2.2
D3	Analyse the 4IR within its wider context i.e. not just a single driving technology or only pertaining to the manufacturing and industrial production fields as Industry 4.0 as observed in literature.	Sections 3.2.2.3 and 3.2.1.2
D4	Account for a transition to a more sustainable state with the 4IR elements being employed	Section 3.2.2.2
D5	Ensure contemporality i.e. applicability of the research product should be to contemporary systems and transitions	Section 3.2.1.2
D6	Adequately standardize the product to allow modification for various STS applications taking into account varying contexts such as the system's societal function being fulfilled, sustainability and sustainable development targets to be met and scale of analysis.	Sections 3.2.2.1, 3.2.2.2 and 3.2.2.3. This is also a design consideration.

4.1 DEVELOPMENT METHODOLOGY

This study employs Van Aken's general model for design processes (Van Aken *et al.*, 2007) displayed in Figure 4 below, as the methodology for the development process of the model. Van Aken's model for design process management is a process-step model where the process of developing an intended object (in this case, a model) is broken down into vital process steps while work in each step is controlled by the process management. Process steps in the model do not follow a fixed sequence but are further governed by iterative and explorative processes where exploration allows the designer to explore steps without the necessity of completing the current step while iteration allows the designer to re-visit and modify completed steps. This ensures flexibility and agility within the development process. (Van Aken *et al.*, 2007)

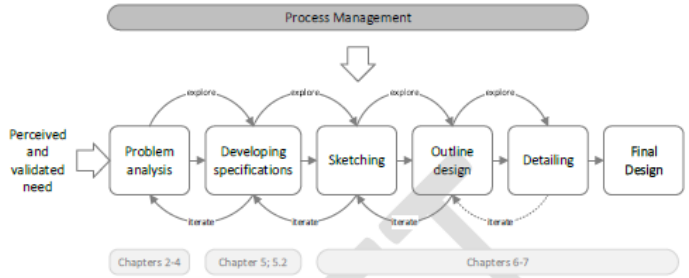


Figure 4: General model for a design process (Van Aken *et al.*, 2007)

Furthermore, given that the model is aimed at a systemic integration of the 4IR and STTs that pertain to contemporary societal systems; the model development employs a Systems Thinking approach in the integration of both concepts. Arnold & Wade (2015) describe Systems Thinking as a wholistic perspective that recognises the relationship between system components to be an important factor to how the system operates. Similarly to STS theory, Systems thinking highlights feedback loops, emergent properties, complexity, hierarchies, self-organisation, dynamics and un-intended consequences within systems.

(Arnold & Wade, 2015) present a Systems Thinking Systemigram which is a synthesis of definitions from literature on Systems Thinking. The Systemigram highlights connections that are important for consideration in the applying systems thinking. The Systemigram is adapted for development of the model and is presented in Figure 5 below. Elements of the Systemigram are translated into 4 guiding principles in the development of the model.

15

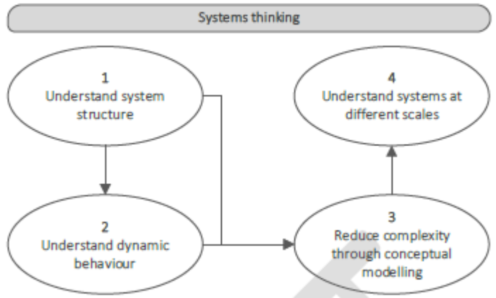


Figure 5: Systems Thinking guiding principles for the I4IR-STT model development. Adapted from Arnold & Wade (2015)

4.2 FUNCTIONAL SPECIFICATIONS FOR THE MODEL'S DEVELOPMENT

Functional specifications for the envisaged model are presented in Table 3 below:

Table 3: Functional specifications for the model

Requirement ID	Requirement	Motivation
Functional requirements		
F1	The model should sufficiently articulate an integration and orientation of elements of the 4IR and STTs together.	The need for the model mainly stems from the lack of a sufficient integration of the concepts 4IR and STTs in literature despite evident connections between the two concepts. The model is developed to make a contribution to literature by integrating elements of the two concepts The model should therefore fill this gap by conceptualising an orientation of the two concepts together and their dynamics.
F2	The model should take into account a transition to a more sustainable state with the 4IR elements employed.	This study emphasizes a joint analysis of the 4IR and STT within the contextual background of sustainability and sustainable development. The 4IR by itself is technological revolution with multiple technologies affecting various societal systems. However, it is observed in literature that STTs pertain to societal functions and have a three-dimensional sustainability implication to them. It is therefore imperative to investigate the impact of the 4IR's technologies with societal systems towards STTs beyond economic sustainability of said systems. This is so as to avoid advocating for mere technological transitions which do not necessarily imply a transition to sustainability equally focussed on all three sustainability dimensions, or that addresses the grand societal challenges.

16

F3	The model should sufficiently employ STTs theory from an STS background context in the integration.	This study bases sustainability transitions analysis on an STS perspective as presented in the literature analysis. The model should therefore employ and utilise STTs theory as such drawn from literature. This is done to address the disconnect from literature on a lack of sufficient elaboration of STTs from an STS perspective
F4	The model should analyse the development and understanding of the 4IR within its wholistic context.	Furthermore the model should incorporate the 4IR and its concepts holistically and not just through the lens of Industry 4.0 and the manufacturing context. This is due to the dominant view of the 4IR in literature as Industry 4.0 It is envisaged that the 4IR affects society beyond the scope of Industry 4.0. The model should therefore elaborate on the sustainability impacts of the 4IR on other societal systems
F5	The model should be applicable to contemporary contexts.	The model should exemplify an integration of both concepts of the 4IR and STTs as they pertain to contemporary societal contexts
Design restrictions		
R1	The model is developed from a systems or industrial engineering perspective as it is the study's research domain. Expounds from other fields may be continually added by SMEs in those fields.	It is also acknowledged that other disciplines such as social sciences form part and contribute towards the holistic understanding of STTs and that conversely, the 4IR affects multiple sectors around the globe outside of the technical realm. However, the background of this research stems from a systems or industrial engineering which is inherently more technically inclined. The model, therefore, is developed using systems engineering and industrial engineering principles for systems thinking. However, it should also not be constrained to the industrial engineering field and should be developed to allow input from other fields for transdisciplinary and trans-sectoral input as applied to STTs
R2	The model does not provide new meaning or theory around STTs and the 4IR. However, it integrates both concepts using theory and examples provided in literature.	The intent of developing the model is not to create new theory and meaning around STTs studies or the 4IR. The model should however incorporate existent literature to integrate the concepts of STTs and the 4IR.
R3	The model is not developed as a practical tool but offers a descriptive approach towards conceptualizing the integration of the 4IR and STT.	Concepts of the 4IR and STTs are by nature abstract. The aim of developing the model is to provide a conceptual yet basic integration of both concepts. Therefore, by itself, the model is not operationalizable i.e. it may not be applied directly to a solve practical STT or 4IR problems. However, it may contribute to the understanding how the two concepts are linked and have integrated dynamics. From this understanding, however, one may develop insights that may have practical implications for contemporary STTs contexts in light of the 4IR.

17

Boundary conditions		
B1	The model must not be utilised without contextual additions by users.	It is understood from literature that the STT and the 4IR are not homogenous in application. Different STT contexts and scales of analysis may have varying implications to be considered. Context may be related to specific societal systems and how they are influenced by factors such as geographical location, socio-economic context, political context, and other technological development and adoption to mention but a few. Furthermore, these contexts have various scales and levels of analysis from organisational to global scales. Therefore, the model should account for varying STTs contexts and scales of analysis. Where a specific context/unit of analysis is applied, the model does not use such context-specific input prescriptively but only as a demonstration of the integration of the 4IR and STTs. Therefore, where needed, it is beneficial for users to have some contextual knowledge for a more applicable utilisation of the model
B2	The model is not to be used prescriptively in the analysis of STTs or the 4IR.	The model should not be applied as-is to solve any context-specific contemporary STT and 4IR issues. However, it may be used to draw insights from which meanings and implications may be developed that may aid in solving context-specific problems
User requirements		
U1	The model should be understandable and unambiguous	The model should be easy to follow and understand especially for users that are not familiar with STTs.
U2	The model should be clear and concise	Details and explanations should be comprehensive yet brief.
U3	The model should be open ended to allow exploratory discourse from various disciplines and contexts.	The model should be usable by people from various fields and disciplines as the applicability of the concepts at hand pertains multiple fields
U4	The model should be accompanied by some practical utility.	The model is developed from an engineering perspective which requisites practical utility to academic products. The model itself is not developed to directly address this, however, a tool should be presented alongside it to guide users on navigating implications for practical insights drawn from the model for their respective fields/sectors.

18

5 THE I4IR-STT MODEL

A consolidated diagrammatic conceptualisation of the I4IR-STT model is presented in Figure 6 below.

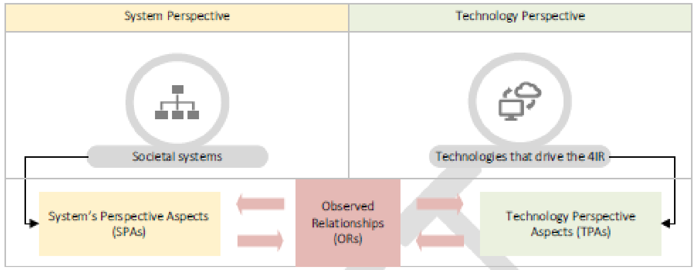


Figure 6: Consolidated I4IR-STT model

As can be seen in Figure 6, the I4IR-STT model is overarchingly dual-modal[1] in its integration of the concepts of STTs and the 4IR. The I4IR-STT model utilises two elements of concepts of STTs and the 4IR for their integration i.e. societal systems and technologies that drive the 4IR as elements respectively. The rationale behind this is explained in Section 5.1. From the elements, the model takes two perspectives to the integration i.e. a system perspective and technology perspective from the elements. Perspectives are presented in Section 5.2. Aspects for the system's perspectives referred to as SPAs are drawn from the societal system's outlook. Conversely the technology perspective draws aspects (referred to as TPAs) for the integration from a technological angle. SPAs and TPAs are presented in Sections 5.2.1 and 5.2.2. The dynamics of how these aspects relate are represented through Observed Relationships (ORs) which detail the flows of relationships. ORs are presented in Sections 5.3.1 – 5.3.6. The model as presented in Figure 6, conceptually structures and summarises the arrangement of STTs and 4IR elements, the perspectives and aspects for the integration and the observed relationships discussed in Sections 5.1 - 5.3 below. Furthermore, the colours utilised in Figure 6 are maintained consistently in the rest of the chapter to diagrammatically highlight, reference and/or differentiate perspectives and the respective aspects (i.e. system perspective and aspects in yellow and technology perspectives and aspects in green) as well as observed relationships (in red).

5.1 CONCEPTUAL ELEMENTS OF SOCIOTECHNICAL TRANSITIONS AND THE FOURTH INDUSTRIAL REVOLUTION

The developed model is a conceptualisation of an integration of the 4IR within STT. From the functional requirement F1, it is envisaged that the model should sufficiently integrate and orient elements of the 4IR and STTs together. Elements of the concepts of STTs and the 4IR are drawn from the study's conceptual literature and are presented in the sub-sections below:

[1] The term 'dual-modal' is utilised to mean the approach to which the integration is expressed (modal) and in reference to the sets of twos i.e. two perspectives drawn from two elements (dual) from which several aspects and relationships emerge. (Oxford Dictionary, 2020)

19

5.1.1 ELEMENTS OF THE FOURTH INDUSTRIAL REVOLUTION FOR THE I4IR-STT MODEL

Literature defines the scope of the 4IR as a fusion of technologies that cut across the physical, biological and digital domains and having various fields, sectors and facets of society (Li *et al.*, 2017; Schwab, 2016). This implies that a key aspect of the 4IR is the combination of the technologies that drive it and hence these technologies are employed as elements of the 4IR within the model. A key disconnect observed from the gap analysis is the dominant view of the 4IR as Industry 4.0 (refer to Section 3.2.2.3). This has led to an analysis that is dominated by manufacturing and industrial production fields, and hence technologies that drive the 4IR that are applied there such as CPS, 3D printing, digital twins to mention but a few. While such technologies may have applications in other sectors such as health, transportation, energy; it is envisaged that the proposed model employs the technologies that drive the 4IR with the motive of demonstrating a wholistic view of the technologies as they are applied to meet sustainability and sustainable development targets across all sectors, especially those that pertain to systems that fulfil societal functions. This is also as requisite by requirements specification F4 in the functional specifications of the model.

5.1.2 ELEMENTS OF SOCIOTECHNICAL TRANSITIONS FOR THE INTEGRATION

From literature, STTs are largely analytically described using the Multi-Level Perspective (MLP) as presented in literature. The MLP specifies the analysis of STTs through three dimensions i.e. niches, regime and landscape. Köhler *et al.* (2019) states that the analytical focus on STTs is primarily centred on the regime dimension. Sorrell (2018) states further states that STTs are often defined as large scale transformations of regimes. Furthermore, regimes are also described as the socio-technical system regime i.e. the system that fulfils societal function (Geels, 2011; Geels & Schot, 2007; Sorrell, 2018). It is envisaged that integration of the concepts of the 4IR and STTs is fostered through the analysis of technologies that drive the 4IR as they are integrated within systems that fulfil societal functions such as transport, communication, energy, food and agriculture, urban planning to mention but a few (Geels, 2005) hereon referred to as societal systems. Thus, it is proposed that the model utilises societal systems as the integration element from STTs.

5.2 PERSPECTIVES AND ASPECTS

The integration of the concepts of STTs and the 4IR for the model is drawn from the functional specifications of the model. Furthermore, the integration borrows guidance System's Thinking principle - *understanding the system structure* – in grounding the relationships between societal systems and technologies that drive the 4IR (Arnold & Wade, 2015). Du Preez *et al.* (2009) highlight that the fundementals of Systems Thinking is observing a system in its entirety while simultaneously trying to understand the parts and processes within it. The model expresses the integration of both concepts from two perspectives i.e. a system perspective and a technology perspective[2].

[2] The author recognises the integrated taxonomies of system and technology. Literature shows that system and technology often demonstrate that technology can be a system (Carroll, 2017; Sandén & Hillman, 2011; Val Dusek, 2006) and a system encompasses technology (Berkhout *et al.*, 2004; Elzen *et al.*, 2004; Geels & Kemp, 2012) However, for the purposes of the study, the latter relationship between the terms 'system' and 'technology' is retained, and therefore the terms as pertaining to the model's perspectives are differentiated in this respect for the sole of purpose of demonstrating the integration of societal systems and technologies that drive the 4IR. In relation to the perspectives, a system is viewed as a whole such as societal system which encompasses knowledge structures, user practices and domains, symbolic meanings, policy,

20

A system perspective is employed to aid in viewing societal systems and technologies that drive the 4IR as part of one organism within a broader nature and is therefore more concerned with the wider macro system and emphasizes overall goals and systemic features (Bond, 1999). As Kim (1999) argues, it is redesigning concepts at this systemic levels that offers more leverage to shape and influence STTs towards more sustainable states. Geels (2011) highlights that a characteristic of STTs is that they are often goal oriented and purposive i.e. they are enacted in efforts to address grand societal sustainability and sustainable development challenges. In the Multi-Level Perspective of transitions (Geels, 2011; Geels & Kemp, 2012), the transitions process is often initiated from the socio-technical landscape (the external environment within which the socio-technical regime exists) which exerts pressure on the regime, opening it up and creating windows of opportunity for niche innovations. Pressure from the landscape may result from issues such as long-standing grand sustainability challenges existent in the system (Elzen *et al.*, 2004; Geels, 2011; Geels, Sovacool, *et al.*, 2019). These challenges create the expectation for technological niche innovations targeted at offering solutions to the challenges. As the MLP describes, the landscape then influences niche innovations through expectations such as development of technologies that contribute to solutions for the system's grand sustainability challenges. Therefore, for the I4IR-STT model, the system perspective highlights integration through the links between societal systems' sustainability or sustainable development needs and targets and the benefits and challenges of utilising the technologies that drive the 4IR towards achieving or fulfilling the system's needs. The systems' perspective descriptively draws aspects for the integration between societal systems and technologies that drive the 4IR from the societal systems' point of view.

In contrast, the technology perspective highlights technological factors that cumulatively become responsible for steering and enacting a process - which in this case is the processes that relate to a transitions (Bond, 1999). Technological advancements within niches are described to occur incrementally with small adjustments accumulating into stable trajectories which later have the potential to replace an existing regime (Geels, 2011). Dynamics such as technology development and adoption, the utilisation of the technologies as well as the technologies' relationship with the incumbent regime are proposed the as aspects of the technology aspect of the model. Through focusing on these aspects, the I4IR-STT model is envisaged to demonstrate the level of integration of the technologies that drive the 4IR in contemporary societal systems and hence highlighting their potential for enacting transitions in said systems.

The system and technology perspectives' aspects are further expounded on in subsequent sections 5.2.1 and 5.2.2. Furthermore each aspect presented for a perspective is associated with a functional specification of the model. The functional specifications are thereby presented with the aspects.

5.2.1 SYSTEM PERSPECTIVE ASPECTS

The system's perspective draws the integration of STTs and the 4IR from the societal system's point of view. From literature, it is observed that a key connection between the 4IR and STTs is the quest

technology, infrastructure, institutions, industry structure (Elzen *et al.*, 2004) and 'technology' a part of it which for the purposes of this study is considered be internal to it such as incumbent technology or external to it such as a niche or technological innovation that is in the process of being diffused or is yet to be diffused into the system such as technologies that drive the 4IR. (Geels, 2005; Li *et al.*, 2017)

towards sustainability (Köhler *et al.*, 2019; Li *et al.*, 2017; World Economic Forum, 2020). Societal systems are faced with grand sustainability and sustainable development challenges for which various solutions and targets such as the SDGs are set forth. Societal systems are envisaged to adopt and utilise technologies that drive the 4IR due to their potential to contribute to solutions to grand societal sustainability challenges that these systems experience (Morrar *et al.*, 2017; Müller *et al.*, 2018; Pantuliano, 2020). However, it is also observed from literature that technologies that drive the 4IR also pose challenges societal systems (World Economic Forum, 2020)These challenges are may create negative feedback in the quest towards sustainability and sustainable development. These aspects give a macro systemic view in the rationale of the integration between the technologies and societal systems i.e. societal system is posed with challenges, for which solutions are developed and technologies may contribute to said solutions. However, the converse is also true, technology may pose challenges to the system when utilised or adopted.

Therefore, from a societal system's perspective the societal system's grand sustainability challenges and the technologies' contributions to the system's solutions and challenges posed to the societal system in adopting the technology are proposed as aspects of the system perspective of the model. The proposed system perspective aspects are further elaborated on in the sub-sections below:

5.2.1.1 SOCIETAL SYSTEM GRAND SUSTAINABILITY CHALLENGES

Literature highlights that issues such as climate change, global warming, long standing illnesses amongst people, food shortages, drought to mention but a few are some of the grand challenges triggering a need for a global sustainability shift within contemporary societal systems (Geels, 2011; Geels, Turnheim, *et al.*, 2019; Kanger & Schot, 2018). It is therefore envisaged challenges therefore prompt and requisite the utilisation of technologies with the aiming of contributing to solutions for the above challenges. This aspect is associated with functional requirement F2 (refer to Table 3).

5.2.1.2 SUSTAINABILITY SOLUTIONS CONTRIBUTED TO BY UTILISING TECHNOLOGIES DRIVING THE FOURTH INDUSTRIAL

It is also observed from literature that for STTs to be enacted, there has to be a definitive positive move from unsustainability to sustainability within the societal system or its components where the technology is applied or utilised (European Environment Agency (EEA), 2018; Geels, Sovacool, *et al.*, 2019). Given the potential of the technologies that drive 4IR to make sustainability or sustainable development contributions to societal systems where they are utilised, it is the envisaged that identification of these contributions in reference to the applicable societal system demonstrates a point of integration for both technologies and the societal systems. This aspect is associated with functional requirements F2 and F4 (refer to Table 3).

5.2.1.3 CHALLENGES TO THE SOCIETAL SYSTEM FOR THE ADOPTION AND UTILISATION OF TECHNOLOGIES DRIVING THE FOURTH INDUSTRIAL REVOLUTION

Literature highlights multiple concerns for the adoption and utilisation of technologies that drive the 4IR within societal systems (Schwab, 2016; World Economic Forum, 2020). Majority of these challenges are highlighted as strategic and policy-related as contemporary regimes are in the process of further adjusting to the emerging technologies (Lin *et al.*, 2017; Manda & Dhaou, 2019; Müller *et al.*, 2018; World Economic Forum, 2020). Others pertain to societal implications such as work and employment and ethics and identity (World Economic Forum, 2020).

These challenges may present bottlenecks for the adoption and utilisation of the technologies within societal systems. However, they also signify social interest in the 4IR's impact on sustainability and sustainable development as actors and institutions engage in various forms of discourse to find a way forward (Manda & Dhaou, 2019; World Economic Forum, 2020). Furthermore, challenges highlight opportunities for improvement in the development of the technologies to incorporate societal actors' needs (Geels & Schot, 2010). This aspect is associated with functional requirement F4 (refer to Table 3).

5.2.2 TECHNOLOGY PERSPECTIVE ASPECTS

The technology perspective draws aspects for the integration of STTs and the 4IR from a technological angle. The following aspects are proposed for this perspective of the model:

i. Technology development stages;
ii. Technology adoption stages;
iii. Level of cross-utilisation and interconnectedness of technologies that drive the 4IR; and
iv. Nature of relationship between technologies that drive the 4IR and the incumbent system technology.

The above aspects are elaborated on in the following subsections:

5.2.2.1 TECHNOLOGY DEVELOPMENT AND ADOPTION

Given the contemporality of the 4IR and an overarching theme of innovation within literature, it is envisaged that technology development and adoption life cycles may offer useful insight as aspects in analysing the technologies that drive the 4IR and how they are being utilised within contemporary societal systems.

In the I4IR-STT model, technology development and adoption indicate the extent to which technologies that drive the 4IR are being diffused into contemporary societal systems (Du Preez *et al.*, 2009). The cycles give insight in market saturation of technologies i.e. their interpretation in the model may be utilised to understand how a technology's maturity and consumer behaviour within a societal system influences market saturation of the technology (Tran, 2014). This further ripples into the technologies' potential for enabling a transition process within the societal system as literature highlights that there is evidence of a correlation between market saturation of niche technologies and development of the phases in transitions (Geels & Kemp, 2007; Geels, Sovacool, *et al.*, 2019; Kemp & Rotmans, 2004; Tran, 2014).

Furthermore, the above life cycle stages are tools used in systems and industrial engineering (Du Preez *et al.*, 2009) and therefore contribute to the fulfilment of design restriction R1. Additionally, the technology development and adoption aspects are associated with functional requirement F4. (refer to Table 3).

5.2.2.2 INTERCONNECTEDNESS OF TECHNOLOGIES THAT DRIVE THE FOURTH INDUSTRIAL REVOLUTION

The broader utilisation of technologies that drive the 4IR within societal systems for various purposes is envisaged to be component in understanding the underlying dynamics in the relationship between the technologies that drive the 4IR and societal systems. From literature, the technologies that drive the 4IR are described to be interconnected, integrated and interoperable in their utilisation across

23

multiple sectors and systems (Schwab, 2016). This is envisaged to add dynamism to how these technologies are utilised within societal systems towards sustainability targets (Köhler *et al.*, 2019; World Economic Forum, 2020) This aspect is associated with functional requirement F4 (refer to Table 3).

5.2.2.3 NATURE OF RELATIONSHIP BETWEEN TECHNOLOGIES THAT DRIVE THE FOURTH INDUSTRIAL REVOLUTION AND THE SOCIETAL SYSTEM'S INCUMBENT TECHNOLOGY

Literature argues that technologically centred STTs are often initiated in the regime through technological changes within the societal system (Köhler *et al.*, 2019). Therefore from a technology perspective, it is envisaged that the dynamic interaction between the technologies that drive the 4IR with incumbent[3] technologies (Sandén & Hillman, 2011) in a societal system highlight an integrative dynamic between the 4IR and STTs.

Due to limitations to the scope of this study, the author limits the description of the nature of relationships between technologies that drive the 4IR and the societal system's incumbent technology to either competitive or complementary. Furthermore, in addition to the afore mentioned relationships, it is contemplated that the relationship between technologies that drive the 4IR and the society system's incumbent is also dependent on the existence of the incumbent technology (Du Preez *et al.*, 2009). If an incumbent technology exists within the regime, then the new technology forms a relationship with the incumbent which is described either as complementary or competitive. However, if an incumbent technology does not exist within a societal system, then the new technology is considered radical i.e. it performs a function that has not been previously done by any technology within the societal system. (Geels, 2011; Geels & Kemp, 2007; Geels *et al.*, 2016; Sovacool & Hess, 2017). This aspect is associated with functional requirement F3 and design restriction R2 (refer to Table 3).

The above system and technology perspectives and their aspects as presented in Sections 5.2.1 and 5.2.2 culminate into the I4IR-STT model's outline design. Table 4 below summaries the perspectives and aspects alongside the functional specification associated with them.

Table 4: Perspective aspects with functional specifications

Perspective	Aspect	Assigned Code	Functional Specification associated
System perspective	Societal system grand sustainability challenges	SPA 1	F2
	Sustainability solutions contributed to by technology	SPA 2	F2
	Societal system challenges for the adoption and utilisation of technologies that drive the 4IR	SPA 3	F4
Technology perspective	Technology development stages	TPA 1	F4; R1
	Technology adoption stages	TPA 2	F4; R1

[3] For this study an incumbent technology is defined as the technology within a societal system that either fulfils the same function as a technology that is introduced to the societal system within the scope of technologies driving the 4IR .

24

	Interconnectedness of technologies that drive the 4IR	TPA 3	F4
	Nature of relationship between a technology that drives the 4IR the incumbent technology	TPA 4	F3; R2

Furthermore, aspects of the system and technology perspective of model have been assigned codes for their reference within the model. These codes are preliminarily utilised in Figure 8 to demonstrate the logical flow of Table 5 and later (and more importantly) utilised in the presentation of the final design of the model. The outline design is presented in Figure 7 below:

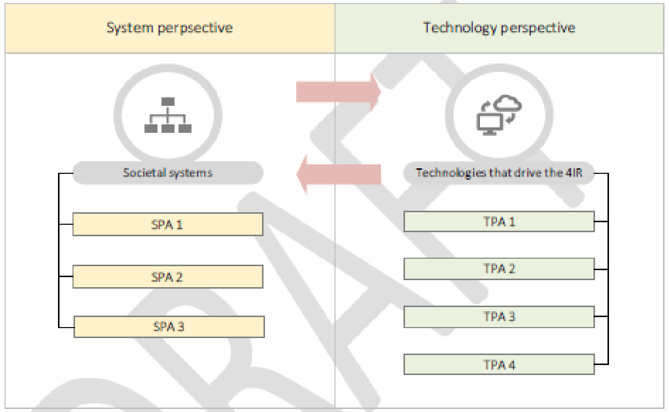


Figure 7: I4IR-STT Model outline design

As may be observed in Figure 7 the model perspectives are highlighted, as well as their subsequent aspects. In the next section the I4IR-STT model's perspectives are exemplified from literature in order to further elaborate and deduce the integration.

5.3 OBSERVED RELATIONSHIPS

In the previous Section, perspectives of the I4IR-STT model and their aspects have been presented as deduced from literature. To further develop the integration within model, the model proposes the development of relationships between SPAs and TPAs presented. These relationships are later referred to as Observed Relationships (ORs) as they are induced and exemplified from literature. Examples identified demonstrate how technologies that drive the 4IR are integrated in various societal systems, through identified aspects in Section 4.2 from both a system and technology perspective and are presented in Table 5 below. Additionally, this exemplification and induction of ORs draws from a principle of Systems Thinking i.e. '*understanding dynamic behaviour*' (Arnold & Wade, 2015) which implies identifying and understanding relationships between the technologies that drive the 4IR and contemporary societal systems which demonstrate their integration. (Arnold & Wade, 2015).

25

Furthermore, the exemplification and induction of ORs is also in fulfilment of design restriction R2 (refer to Table 3).

A semi-structured literature search is employed in identifying the examples from literature. Furthermore, for contemporality, grey literature is utilised which includes working papers, reports, insights, articles, and documents from non-academic statutory and corporate bodies analysing the 4IR, its progression and it's impacts on the global community. Figure 8 below demonstrates the logical of the flow of Table 5. The table is structured according to technologies that drive the 4IR as most grey literature obtained is centred around these technologies. This is not reflective of the focus of the exemplification but is a logical decision for the purposes of the flow of Table 5. For each technology, examples of societal systems within which they are utilised are presented. Thereafter, aspects for the integration categorised under their respective perspective are elaborated on for each technology and societal system case.

Due to the extensive scope of the technologies that drive the 4IR and the scope of this study, a few key technologies are identified that are envisaged to offer a comprehensive demonstration of the system integration. These technologies include Artificial Intelligence (AI) and Machine Learning (ML), Internet of Things (IoT), Big Data and Analytics, 3D Printing, and Digital Platforms. These key technologies are observed to have multiple applications across all domains in the 4IR and are contemplated to offer some of the most significant foundational building blocks or fuel that drives the 4IR in the contemporary world (Schwab, 2016; World Economic Forum, 2019b). Additionally due to the wide scope of societal systems, the exemplification is also limited to a few societal systems such as energy, health care, agriculture, education and transport for the purposes of the demonstration. The examples obtained across all aspects are verified and validated to ensure contemporary relevance with a Subject Matter Expert (SME). For the purposes of the demonstration, the term technology refers to [a] technology that drives the 4IR unless specifically defined otherwise for example 'incumbent technology'. Furthermore, the term system refers to societal system (s) such as transport, energy, etc

26

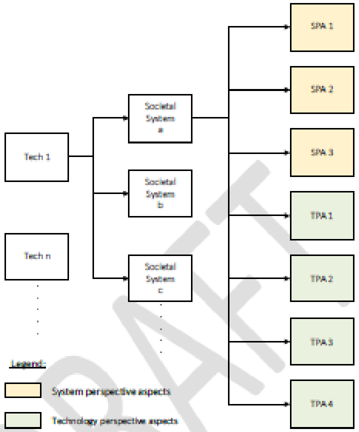


Figure 8: Logical flow of Table 5

27

Table 5: Exemplification of the integration of societal systems and technologies that drive the 4IR through aspects of the I4IR-STT model's perspectives.

		System perspective aspects			Technology perspective aspects			
Technology	Societal System	Societal system's grand sustainability challenges	Sustainability solutions contributed to	Societal system's challenges for the utilisation of technology	Examples of specific technology[4] utilised	Relationship with incumbent regime's technologies[5]	Technology development	Technology adoption
Artificial Intelligence (AI) (Niestadt et al., 2019; OECD, 2019a)	Transportation[6]: Specific applications in road transport.	Increased number of vehicles which still widely depend on fossil fuels leading to increased carbon emissions contributing to global warming. Efforts to improve or reduce mental, physical and emotional strain on road users. Reduction in the number of traffic-related accidents.	Traffic management leading to less traffic congestion and hence reductions in vehicle emissions. Enabling of ride sharing platforms contributes to the minimization of the number of cars on roads, contributing to reductions in traffic pollution. Improvement of road and rail safety through autonomous vehicles and trains which contributes to less crashes, and more human lives saved from accidents.	Legal, safety and ethical concerns from user data collection and its safety. Ethical concerns for AI having full autonomy in decision making and observation of safety regulations such as traffic rules. Workforce disruption for drivers in the transportation business. Lack of policy on the disposal or replacement of existing assets and infrastructure[7].	Autonomous vehicles (AVs) Digital ride sharing platforms such as Uber that use AI algorithms.	Complementary from the production/supply side, AI applications such as AVs improvements to incumbent vehicles with human drivers in full charge of vehicle's mobility. Complementary and competitive on the demand or consumer side: completely autonomous vehicles aiming to do away with human-driver cars in a few decades but currently operating in a complementary manner.	Development stage: Although there are efforts to market development and stabilisation process underway, companies ranging from large multinationals to start-ups are developing AVs and some AVs already on market sold by companies such as Tesla; there is still significantly low market share on a global scale. Most existing AVs are partially autonomous giving driver assistance or partial driving autonomy. Fully autonomous vehicles are yet to still be rolled out. Furthermore, the existence of media hype that inflates the perceived level of development of AI technologies within this system.	Late adopters on the supply side of the road transport industry (e.g. vehicle manufacturers) Innovators to early adopters on the demand side (vehicle users).
	Health systems	Long standing illnesses without cures for example non communicable diseases such as heart blood pressure, cancer, etc; Emergent global health issues such as pandemics; Lack of access to health care services in some areas of the world;	Enabling precision medicine; Fostering mobile health care; early detection of patient medical conditions; optimising clinical decision making; accelerated discovery of new treatments and medications; Optimised management of health systems; Surveillance and alerts of disease breakouts	Concerns for data usage, it's security and patient privacy. Large amounts of un-synthesized health data for decision support due to health systems operating in silos.	Big data and analytics for tracking and disease detection Machine Learning (ML) and deep learning algorithms	Complementary: AI applications used to support specimen testing, drug development and improve diagnostics. This contributes improvements to existing health systems and health care service delivery	Experimentation during development stage: some of the applications have been tested for research but nothing has been disseminated to the markets yet. Where some of the technology is adopted in some contexts, it is used in silos.	Innovators and some marginal early adopters.
	Agriculture/Food production	On the supply side: drought, plants and animal diseases and crop pests. The need for food production efficiency On the demand side: food supply shortages due to drought and low agricultural yields.	Improving cognitive computing technologies on farms which identify crop readiness and diseases, thereby improving agricultural yields; Monitor crop and soil health and the impacts of environmental factors on existent yields for further yield optimisation.	Lack of adopted standards and interoperability of health systems.	ML algorithms Predictive Analytics Agricultural robotics	Complementary: AI applications used to support contemporary agricultural monitoring equipment and improve data analysis.	Development - growth stage: existence of start-ups building and offering the applications in the agricultural sector. Some parts, however, still under experimentation which is pre-development.	Innovators and early adopters.

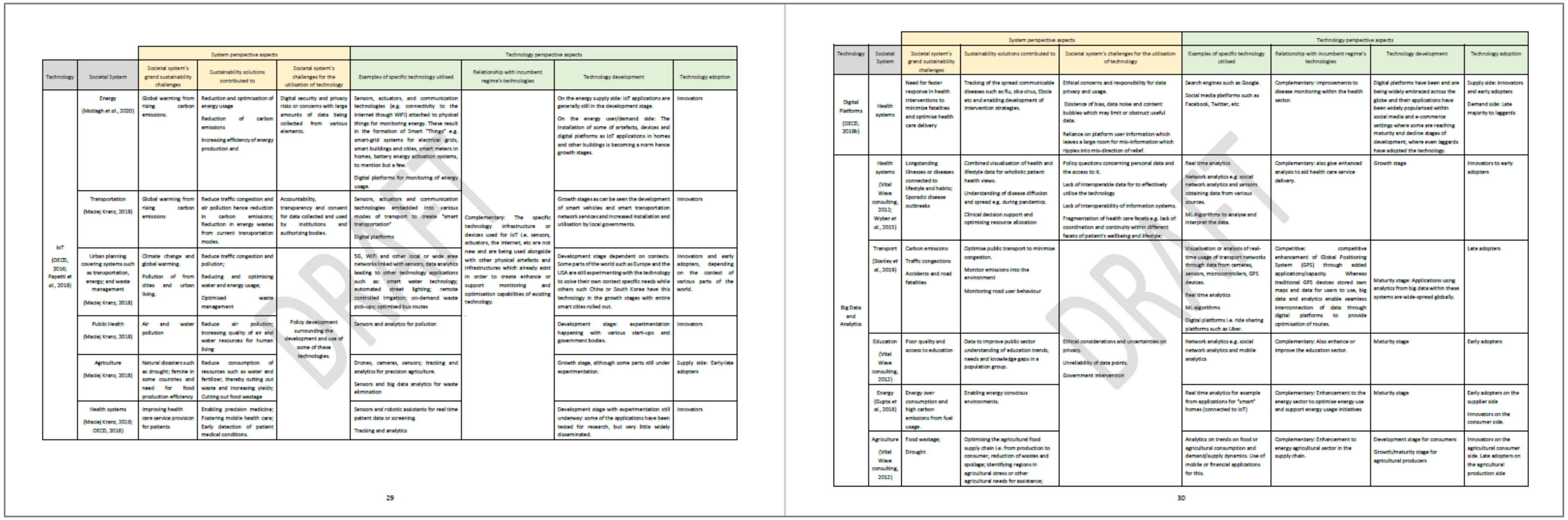
[4] Technologies presented here also fall under the scope of technologies driving the 4IR but are broken down to the specifics of the technologies which may include processes, products or artefacts or systems (Sandén & Hillman, 2011).

[5] The nature of relationship between the technologies is described in relation to their function (Sandén & Hillman, 2011).

[6] It is noted that the transport system has a wide scope of modes including rail, water and air transportation. However, literature shows that the use of AI is significantly more developed in road transport compared to other modes of transport such as air, rail and water and AI applications in these modes of transport is still being researched. (Niestadt *et al.*, 2019)

[7] This is exemplary of resistance to change within the system due to lock-in due to stability from economies of use. Artefacts and material networks (in this case non-autonomous vehicles and their current transportation networks) already in use are locked in and may not easily be abandoned which creates stabilisation within the system and difficulty for the system to adopt new technologies (Geels, 2012; Geels & Kemp, 2007).

28



Technology	Societal System	System perspective aspects: Societal system's grand sustainability challenges	System perspective aspects: Sustainability solutions contributed to	System perspective aspects: Societal system's challenges for the utilisation of technology	Technology perspective aspects: Examples of specific technology utilised	Technology perspective aspects: Relationship with incumbent regime's technologies	Technology perspective aspects: Technology development	Technology perspective aspects: Technology adoption
IoT (OECD, 2016; Papetti et al., 2018)	Energy (Motlagh et al., 2020)	Global warming from rising carbon emissions.	Reduction and optimisation of energy usage Reduction of carbon emissions Increasing efficiency of energy production and	Digital security and privacy risks or concerns with large amounts of data being collected from various elements.	Sensors, actuators, and communication technologies (e.g. connectivity to the internet though WiFi) attached to physical things for monitoring energy. These result in the formation of Smart "Things" e.g. smart-grid systems for electrical grids, smart buildings and cities, smart meters in homes, battery energy activation systems, to mention but a few. Digital platforms for monitoring of energy usage.	Complementary: The specific technology infrastructure or devices used for IoT i.e. sensors, actuators, the internet, etc are not new and are being used alongside with other physical artefacts and infrastructures which already exist in order to create enhance or support monitoring and optimisation capabilities of existing technology.	On the energy supply side: IoT applications are generally still in the development stage. On the energy user/demand side: The installation of some of artefacts, devices and digital platforms as IoT applications in homes and other buildings is becoming a norm hence growth stages.	Innovators
	Transportation (Maciej Kranz, 2018)	Global warming from rising carbon emissions	Reduce traffic congestion and air pollution hence reduction in carbon emissions; Reduction in energy wastes from current transportation modes.	Accountability, transparency and consent for data collected and used by institutions and authorizing bodies.	Sensors, actuators and communication technologies embedded into various modes of transport to create "smart transportation" Digital platforms		Growth stages as can be seen the development of smart vehicles and smart transportation network services and increased installation and utilisation by local governments.	Innovators
	Urban planning covering systems such as transportation, energy; and waste management (Maciej Kranz, 2018)	Climate change and global warming. Pollution of from cities and urban living.	Reduce traffic congestion and pollution; Reducing and optimising water and energy usage; Optimised waste management	Policy development surrounding the development and use of some of these technologies.	5G, WiFi and other local or wide area networks linked with sensors, data analytics leading to other technology applications such as: smart water technology; automated street lighting; remote controlled irrigation; on-demand waste pick-ups; optimised bus routes		Development stage dependent on contexts. Some parts of the world such as Europe and the USA are still experimenting with the technology to solve their own context specific needs while others such China or South Korea have this technology in the growth stages with entire smart cities rolled out.	Innovators and early adopters, depending on the context of various parts of the world.
	Public Health (Maciej Kranz, 2018)	Air and water pollution	Reduce air pollution; Increasing quality of air and water resources for human living		Sensors and analytics for pollution		Development stage: experimentation happening with various start-ups and government bodies.	Innovators
	Agriculture (Maciej Kranz, 2018)	Natural disasters such as drought; famine in some countries and need for food production efficiency	Reduce consumption of resources such as water and fertilizer, thereby cutting out waste and increasing yields; Cutting out food wastage		Drones, cameras, sensors; tracking and analytics for precision agriculture. Sensors and big data analytics for waste elimination		Growth stage, although some parts still under experimentation.	Supply side: Early-late adopters
	Health systems (Maciej Kranz, 2018; OECD, 2018)	Improving health care service provision for patients	Enabling precision medicine; Fostering mobile health care; Early detection of patient medical conditions.		Sensors and robotic assistants for real time patient data or screening. Tracking and analytics		Development stage with experimentation still underway: some of the applications have been tested for research, but very little widely disseminated.	Innovators

29

Technology	Societal System	System perspective aspects: Societal system's grand sustainability challenges	System perspective aspects: Sustainability solutions contributed to	System perspective aspects: Societal system's challenges for the utilisation of technology	Technology perspective aspects: Examples of specific technology utilised	Technology perspective aspects: Relationship with incumbent regime's technologies	Technology perspective aspects: Technology development	Technology perspective aspects: Technology adoption
Digital Platforms (OECD, 2019b)	Health systems	Need for faster response in health interventions to minimize fatalities and optimise health care delivery	Tracking of the spread communicable diseases such as flu, zika virus, Ebola etc and enabling development of intervention strategies.	Ethical concerns and responsibility for data privacy and usage. Existence of bias, data noise and content bubbles which may limit or obstruct useful data. Reliance on platform user information which leaves a large room for mis-information which ripples into mis-direction of relief.	Search engines such as Google. Social media platforms such as Facebook, Twitter, etc	Complementary: improvements to disease monitoring within the health sector.	Digital platforms have been and are being widely embraced across the globe and their applications have been widely popularised within social media and e-commerce settings where some are reaching maturity and decline stages of development, where even laggards have adopted the technology.	Supply side: Innovators and early adopters Demand side: Late majority to laggards
Big Data and Analytics	Health systems (Vital Wave consulting, 2012; Wyber et al., 2015)	Longstanding illnesses or diseases connected to lifestyle and habits; Sporadic disease outbreaks	Combined visualisation of health and lifestyle data for wholistic patient health views. Understanding of disease diffusion and spread e.g. during pandemics. Clinical decision support and optimising resource allocation	Policy questions concerning personal data and the access to it. Lack of interoperable data for to effectively utilise the technology Lack of interoperability of information systems. Fragmentation of health care facets e.g. lack of coordination and continuity within different facets of patient's wellbeing and lifestyle;	Real time analytics Network analytics e.g. social network analytics and sensors obtaining data from various sources. ML Algorithms to analyse and interpret the data.	Complementary: also give enhanced analysis to aid health care service delivery.	Growth stage	Innovators to early adopters
	Transport (Stanley et al., 2019)	Carbon emissions Traffic congestions Accidents and road fatalities	Optimise public transport to minimise congestion. Monitor emissions into the environment Monitoring road user behaviour		Visualisation or analysis of real-time usage of transport networks through data from cameras, sensors, microcontrollers, GPS devices. Real time analytics ML algorithms Digital platforms i.e. ride sharing platforms such as Uber.	Competitive: competitive enhancement of Global Positioning System (GPS) through added applications/capacity. Whereas traditional GPS devices stored own maps and data for users to use, big data and analytics enable seamless interconnection of data through digital platforms to provide optimisation of routes.	Maturity stage: Applications using analytics from big data within these systems are wide-spread globally.	Late adopters
	Education (Vital Wave consulting, 2012)	Poor quality and access to education	Data to improve public sector understanding of education trends, needs and knowledge gaps in a population group.	Ethical considerations and uncertainties on privacy. Unreliability of data points. Government intervention	Network analytics e.g. social network analytics and mobile analytics	Complementary: Also enhance or improve the education sector.	Maturity stage	Early adopters
	Energy (Gupta et al., 2018)	Energy over consumption and high carbon emissions from fuel usage.	Enabling energy conscious environments.		Real time analytics for example from applications for "smart" homes (connected to IoT)	Complementary: Enhancement to the energy sector to optimise energy use and support energy usage initiatives	Maturity stage	Early adopters on the supplier side Innovators on the consumer side.
	Agriculture (Vital Wave consulting, 2012)	Food wastage; Drought	Optimising the agricultural food supply chain i.e. from production to consumer, reduction of wastes and spoilage; identifying regions in agricultural stress or other agricultural needs for assistance;		Analytics on trends on food or agricultural consumption and demand/supply dynamics. Use of mobile or financial applications for this.	Complementary: Enhancement to energy agricultural sector in the supply chain.	Development stage for consumers Growth/maturity stage for agricultural producers	Innovators on the agricultural consumer side. Late adopters on the agricultural production side

30

From the examples obtained from literature and presented in Table 5 above, observations are made that elaborate on relationships between the proposed model's aspects for integration. It is important to note that these observations are not theoretically binding or encompassing. However, they are helpful in further widening an understanding of the integration of the technologies that drive the 4IR within societal systems through the system and technology perspectives. These observed relationships (ORs) between aspects of the model are discussed in the subsections below:

5.3.1 OBSERVED RELATIONSHIP 1: PURPOSE AND GUIDING VISIONS

From literature analysed and literature presented in Table 5, technologies that drive the 4IR are envisaged to contribute to solutions to grand sustainability and sustainable development challenges within the societal systems they are being utilised. Table 5 exemplifies that technologies' contributions are geared towards solutions to grand sustainability challenges such as climate change, global warming, global health issues such as pandemics and treatments for longstanding non-communicable diseases, pollution to mention but a few. Solutions to these challenges are largely embedded in global directives and targets such as the SDGs (United Nations, 2019). Within STTs, sustainability and sustainable development targets and goals set in addressing these challenges such as the UN SDGs are encompassed as guiding visions for transitions within contemporary societal systems (Geels, Sovacool, *et al.*, 2019; OECD, 2016, 2019a). Furthermore, grand sustainability challenges also exert pressure on existing societal systems regimes to transition to more sustainable states. This is synonymous to landscape pressures as described in the MLP. Therefore, such pressures are consequently opening windows of opportunities for technological niches and innovations within the 4IR to infiltrate current societal systems.

Furthermore, it is envisaged that guiding visions are being fostered by or driven by society i.e. through civil societal groups and actor networks.[8] This, in part, is also aided by technologies such digital platforms, big data and analytics which are enabling the visualisation and analysis of data on various global social, economic, and environmental sustainability metrics. Social groups and actors are thereby able to drive and advocate for agency and change where sustainability and sustainable development issues arise (Johansson & Scaramuzzino, 2019; World Economic Forum, 2019a). Such action may further catalyse the development of technologies that drive the 4IR and increase the innovative drive to address such global sustainability issues (Müller *et al.*, 2018); which contributes to the establishment of protective spaces for 4IR technological and market niche and thus reinforcing the pressures, stress, and tensions on existing systems to transition (Geels, 2004, 2005). Figure 9 below further demonstrates the possible cyclical triggers with actor groups for the adoption and development of technologies that drive the 4IR within societal systems.

[8] Civil society engagement is observed at different scales in the contemporary world. For example, on a macro scale, the United Nations Environment Programme (UNEP) lists over 600 civil society groups in various categories such non-governmental organisations, women groups, children and youth groups from over 60 countries across the globe (UNEP, 2020a). These groups are given observer status over the organisation's sustainability endeavours and are included in dialogue towards decisions making and policy formulation (UNEP, 2020b). On micro scale, other examples show communities taking matters into their hands and are reportedly initiating and building projects to meet sustainability needs such as renewable energy and enact transition processes in their local contexts (Ison & Langham, 2015) and/or using technologies that drive the 4IR to drive initiatives e.g. Omdena, a platform for global collaborative AI solutions development for grand sustainability challenges (https://omdena.com/projects/#running_challenges);

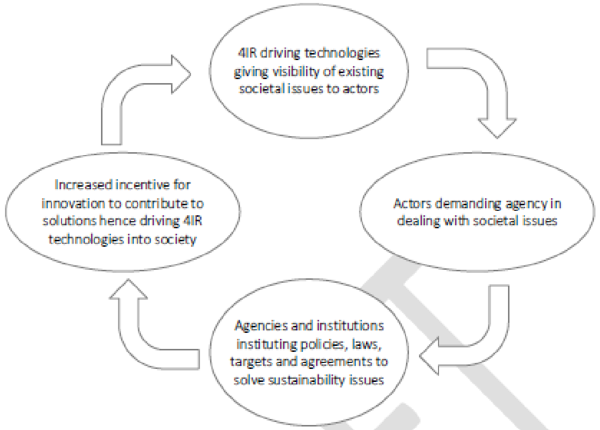


Figure 9: Actor trigger cycle for the adoption of technologies that drive the 4IR towards sustainability

This translates into a relationship between societal systems and technologies that drive the 4IR as demonstrated in Figure 10 below:

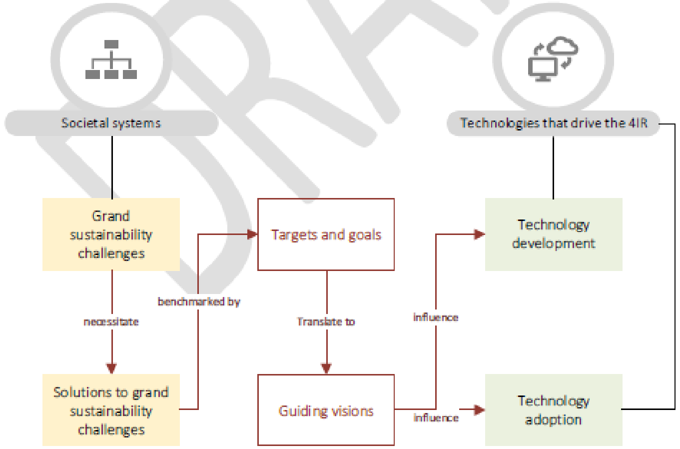


Figure 10: Observed Relationship 1 (OR 1)

As maybe observed in Figure 10, contemporary societal systems possess grand sustainability challenges which necessitate solutions. Proposed solutions are developed with targets such as SDGs which ultimately become guiding visions for societal systems in the transitions process. Guiding visions embraced for the collective good may then influence the development of technologies and their adoption within society depending on their alignment with said visions.

5.3.2 OBSERVED RELATIONSHIP 2: EMERGENCE OF TECHNOLOGIES

Guiding visions may imply the utilisation of purposive technology i.e. technology is developed and adopted in a societal system in order to address challenges the system faces. However, some of the technologies that drive the 4IR may emerge contingently into societal systems. When emerged, these technologies still pose challenges for the systems in which they are utilised and may also contribute to solutions to grand sustainability challenges. These effects may further affect and influence the development and adoption of these technologies.

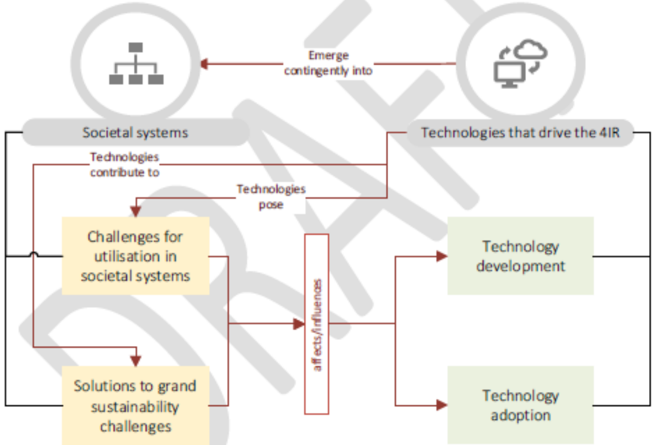


Figure 11: Observed Relationship 2 (OR 2)

It is therefore important to note that targets and goals such as SDGs may not necessarily be initiators for the development and adoption of the 4IR's technologies but have added momentum to the technologies' development and adoption given their potential to contribute solutions to society's grand sustainability challenges (Berkhout *et al.*, 2004; Schwab, 2016). As Berkhout *et al.* (2004) argues, guiding visions are not an absolute necessity for transitions to occur. However, in some of the cases with the 4IR, they are existent play a vital role in driving the adoption and utilisation of the technologies. Furthermore, the presence of a guiding vision such as SDGs does not imply success for the transitions process in a societal system (Berkhout *et al.*, 2004). But as Berkhout *et al.* (2004) further argues, such visions are effective in seeding a transition through their engagement at the macro landscape level

33

where legislation and general opinion are defined, and are later channelled into market and regulatory signals which then in turn influence the adoption of technologies which originate at the niche micro-level.

5.3.3 OBSERVED RELATIONSHIP 3: HINDERANCES TO THE UTILISATION OF TECHNOLOGIES THAT DRIVE FOURTH INDUSTRIAL REVOLUTION WITHIN SOCIETAL FUNCTION SYSTEMS

From Table 5, it is noted from the examples that technologies that drive the 4IR poses challenges for their utilisation within the societal systems they are utilised. These challenges encompass both technological and social concerns. Some of the challenges for utilising technologies that drive the 4IR highlighted in literature include:

i. Ethical risks and concerns for the adoption of some of the technologies such as AI where the advancement of robots;
ii. Lack of developed infrastructure for some of the technology for example 5G and AI in societal systems such as health and urban planning;
iii. Safety and security concerns due to the involvement of people's personal data across multiple platforms;
iv. Poor quality of data received from under-developed areas where technology infrastructure is still under-developed;
v. Lack of devised legislative standards and policy for the utilisation of the technologies, for example the use of big data and analytics in health care; and
vi. Minimal realised interoperability i.e. synchronizing findings within sectors and cross-sector for sustainability benefit still infant)

These challenges stem from the depth of interoperability and integration in the utilisation of the technologies with existing systems and the social implications this has on various actors within the societal system (World Economic Forum, 2019a). These challenges consequently translate to hinderances for the adoption of the technologies within societal systems. Furthermore these challenges or hinderances may also signify the channels through which possible lock-ins with the incumbent technology or resistances from the regime may arise.

34

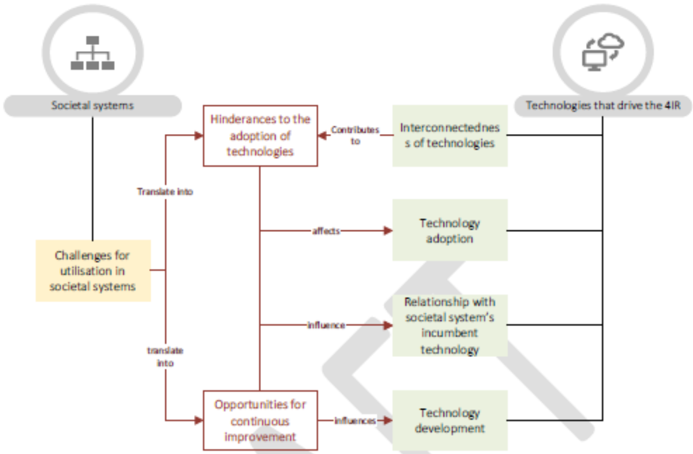


Figure 12: Observed Relationship 3 (OR 3)

Although challenges or hinderances to the utilisation or adoption of technologies may be interpreted as bottlenecks in the grand scheme of a systemic transition, from a technological perspective, they may possess a positive connotation. As demonstrated in Figure 12 above, challenges and hence hinderances also signify a degree of consideration for the wider adoption of technologies that drive the 4IR by society and therefore present the innovators and niche actors with opportunities for continuous improvement of the technology. This foster further development and adoption and enhance reinforce the technology's ability to enable a transition with the societal system it is utilised.

5.3.4 OBSERVED RELATIONSHIP 4: THE INTERCONNECTEDNESS OF TECHNOLOGIES THAT DRIVE THE FOURTH INDUSTRIAL REVOLUTION

It is observed from Table 5 that firstly; grand sustainability challenges cut across multiple societal systems for example global warming and rising carbon emissions is challenge across transportation and energy systems. This is also as a result of these systems being functionally interconnected through other mutual technologies such as the use of fossil fuels (Sandén & Hillman, 2011). Secondly, a single technology is not the sole contributor to a solution to a grand sustainability challenge within a societal system e.g. AI and IoT are both being utilised to make contributions to the reduction of carbon missions within the transport system and digital platforms and Big Data and analytics make a contribution to monitoring of disease outbreaks within health systems for better health intervention (refer to Table 5).

Technologies that drive the 4IR's are also functionally interconnected. Technologies may have either a supportive relationship where the one technology gives assistance to another's functioning or an enabling relationship where a technology is vital or makes it possible for another technology to function (Sandén & Hillman, 2011). To further illustrate the interconnectedness of technologies that drive the

4IR, relationships between the technologies are demonstrated in Table 6 incorporating the wider scope of the technologies than exemplified in Table 5.

In Table 6, all technologies are labelled with codes (Tx) and their interrelation descriptors i.e. the crosses "X" and noughts "O" are given. "X" denotes a supportive relationship whereas "O" denotes an enabling relationship. The table is read in a horizontal to vertical (x-y) order to describe the relationships for example technology T1 has a supportive relationship with T4, which means that T1 gives assistance to the function of T4. To demonstrate a relationship in Table 6 below: Big Data and analytics (coded T3) has an enabling relationship with IoT (coded T4). This means that Big Data and analytics as a technology is vital or necessary for the functioning of IoT. Data collected from the various infrastructure for purposes such as optimisation gives purpose and usefulness to the sensors embedded in the infrastructure which creates IoT applications (OECD, 2018). Furthermore, this is also demonstrated and supported by the information presented in Table 5 above as Big Data is key in the utilisation of IoT within societal systems such as in agriculture, urban planning etc. (OECD, 2018).

Table 6: Functional interconnections of the 4IR driving technologies

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	Code	Technologies
T1		o	o	o	o	x	o	ox	x	x	x	x	ox	x	T1	AI
T2	x		o	o	o	x	o	ox	x	x	x	x	ox	x	T2	ML
T3	x	x		o	ox	x	o	ox	x	x	x	x	ox	x	T3	BD and Analytics
T4	x	x	ox		ox	x	ox	x	x	ox	x		ox	x	T4	IoT
T5	x	x	o	ox		x	o	ox	ox	ox	x	x	ox		T5	Digital Platforms
T6	o	o	o	o	ox		o	o	x	x	x		x		T6	Advanced Robotics
T7	x	x	x	ox	x	x		x	x	x	x		o		T7	Cloud Computing
T8	ox	o	x	o	o		o		ox	x		x	o		T8	Block Chain and cryptography
T9	o	o	o	o	o	o	o	o		o	o		o	o	T9	AVs
T10	x	o	o	o	o	ox	o	o	o		o	o	o		T10	VR/AR
T11	o	x	x	o	o	x	o			x		x	o	o	T11	3D Printing
T12	x	o	o	o	o		o	o			o			x	T12	Biotechnology
T13	x	x	x	x	x	x	o	x	x	x	x				T13	5G
T14	o	o	o	ox		x			x		x	o			T14	New materials

On a macro[9] scale, technologies that drive the 4IR are making small micro[10]-scale contributions to sustainability and sustainable development solutions across multiple societal systems that can be aggregated. Given the interconnectedness of the technologies it can be expected that a single technology within this scope of technologies may not necessarily be accountable for a transition within the societal system it utilised. The adoption and utilisation of multiple technologies within the same system towards similar function and/or sustainability or sustainable development targets may better support or reinforce the transition process within the societal system. Furthermore, due to the interconnected of societal systems, grand sustainability challenges such as global warming require combined effort within societal systems at a macro-level in order to realise sustainability and sustainable development targets. Therefore as shown in Figure 13 below, the interconnectedness of technologies adopted and utilised across multiple societal systems better supports the transition process to achieve substantial sustainability or sustainable development targets.

[9] The term 'macro-scale' is utilised to refer to or describe a global or national scale.

[10] The term 'micro-scale' is utilised to refer to smaller civil society communities or specific industry or firm or organisation scale.

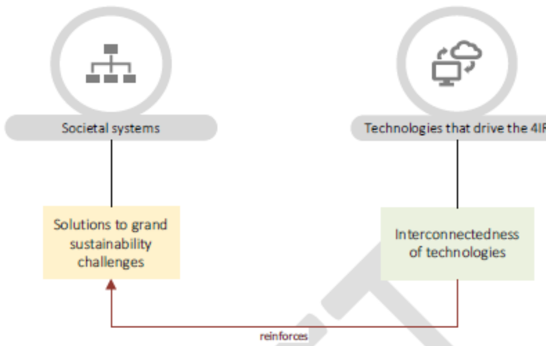


Figure 13: Observed Relationship 4 (OR 4)

5.3.5 OBSERVED RELATIONSHIP 5: LEVEL OF DEVELOPMENT AND ADOPTION OF THE TECHNOLOGIES WITHIN SOCIETAL FUNCTION SYSTEMS

It is observed majority of the technologies within societal systems as exemplified in Table 5 are within the development stage and mainly adopted as far as early adopters phase. This, is in line with observations from the literature study, demonstrates the novelty and contemporariness of the concepts at hand. An emerging distinction in the development and adoption of technologies driving the 4IR is contemporary nature of these cycles on the demand and supply side of the societal system. It is observed that in some cases, the development and/or adoption of technologies that drive the 4IR differs between the demand and supply side. An example of this is the adoption of AI driven transportation in the transport system is envisaged to be embraced by late adopters on the supply (manufacturing) side yet only adopted by innovators on the demand (user) side. This in-part may be attributed to varying actor perspectives with the system on the technologies. Niche actors continuously innovate and develop technologies that take advantage of opportunities to breakthrough from landscape pressures such as societal grand sustainability challenges. However, in this case, regime actors may be slower at adopting the technologies due to vested interests such as investments and consumption patterns with the incumbent technology, as well as concerns for the utilisation of the technologies. Another example that presents a reverse case, is the utilisation of digital platforms in health care systems. Whereas users on the demand side may be familiar with digital platforms in their day to day living e.g. social media platforms, specific applications of digital platforms within the health care industry are embraced by mostly innovators and early adopters. This is may be largely as a result of concerns for the adoption of digital platforms in health care systems on the supply side as presented in Table 5.

Furthermore, due to the interconnected and interoperable nature of the technologies, there is a seeming push-pull effect i.e. technologies may be dependent on usability and adoption for further development yet society may conversely be reliant on their further development to widely apply and utilise them. This gives weight to the importance of the social aspects in the adoption and development

advancement of technologies towards transitions. Technologies that drive the 4IR are contemplated to influence a large part of social norms and require significant value shifts amongst users (Schwab, 2016). Therefore the 4IR driving technologies may not only change societal systems functioning towards sustainability, but also require and enable social actors to behave and function differently within those systems towards the same goals. Although this may possibly cause lock-ins and resistance from incumbent regimes where societal change is rejected, it may also in the reverse case accelerate the drive towards system's transitions if actors buy in. This supports the idea that transitions are not solely enacted on the technical system but require social configurations and people to change for their effectiveness.

Lastly, as mentioned in Section 5.3.4, it is envisaged that the long-time sustainability gains may only effectively be realised when there is collective growth in development and adoption of technologies across multiple societal systems aggregated to a global scale. The initial development and adoption of technologies necessitates an evaluation of the overall sustainability potential of the technology. However, this is undetermined at the contemporary level of development and adoption of the technologies.

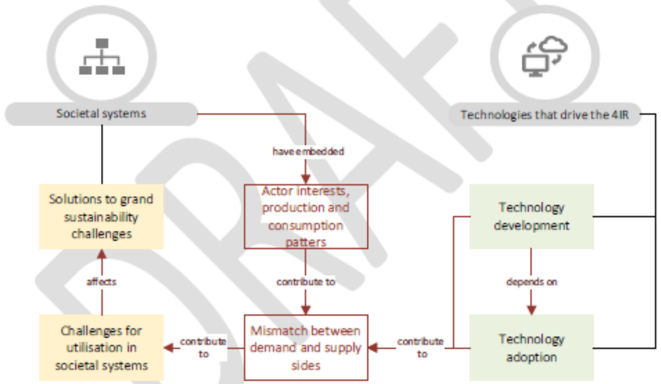


Figure 14: Observed Relationship 5 (OR 5)

5.3.6 OBSERVED RELATIONSHIP 6: RELATIONSHIP WITH THE INCUMBENT TECHNOLOGY

Literature argues that the transitions process towards sustainability or sustainable development targets in societal systems experiences various resistances to change due to locked-in systems built around the existing technology (Elzen *et al.*, 2004; Geels & Kemp, 2012; Köhler *et al.*, 2019; Schot & Kanger, 2018b). For example, the use of fossil fuels such as coal, oil and natural gas forms a large part of lock-in mechanisms in the incumbent transport and energy systems. Sustainability targets in these systems therefore, although for the common good, are not necessarily always the popular choice due to vested interests by actors within institutions and locked in production and consumption patterns (Köhler *et al.*, 2019).

Hence, the relationship with the incumbent technology plays a vital role in the adoption and utilisation of technologies driving the 4IR within the systems. It is observed from the exemplification in Table 5 that within contemporary societal systems, a majority of technologies driving the 4IR have a complementary relationship with system's incumbent technology during the transitions process. Exemplified technologies are observed there is a case for technologies that arise symbiotically i.e. are in support of the incumbent technologies to meet certain goals e.g. through applications such measuring, monitoring and optimisation of the incumbent technology towards sustainability and sustainable development targets. This may offer support or an enhancement of the ability of technologies driving the 4IR in enabling or aiding a transition process within the societal systems they are utilised as regime actors are given opportunity to "buy-in" to the technologies.

However, it is also noted that given the scope of the technologies exemplified, the above observation is not all encompassing. Furthermore, given the level of development of most of technologies on either the supply or demand side; the nature of the relationship between technologies that drive the 4IR and the incumbent technology may dynamically change over the course of the technologies' development and adoption. This may be due to various social and institutional dynamics that are harder to determine at this stage. However, the overarching notion as displayed in Figure 15 below is that the relationship between technologies that drive the 4IR and the societal system's incumbent has an overall effect on the adoption of the former technologies' by regime actors which can translate into a hinderance or enable to the technologies' ability to aid the transition process with the societal system.

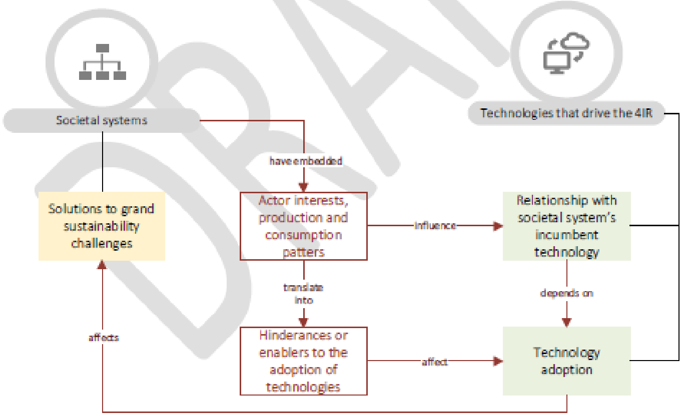


Figure 15: Observed Relationship 6 (OR 6)

The Observed Relationships (ORs) in above sub-sections thereby highlight relationships between aspects of the I4IR-STT model's perspectives and give detail to the integration of the societal systems and technologies that drive the 4IR. As can be seen in Figure 16, societal systems and technologies that drive the 4IR integrate through relationships that flow between the aspects of each perspective. ORs 1-7 have been diagrammatically and theoretically expounded on in Figures Figure 10 - Figure 15

39

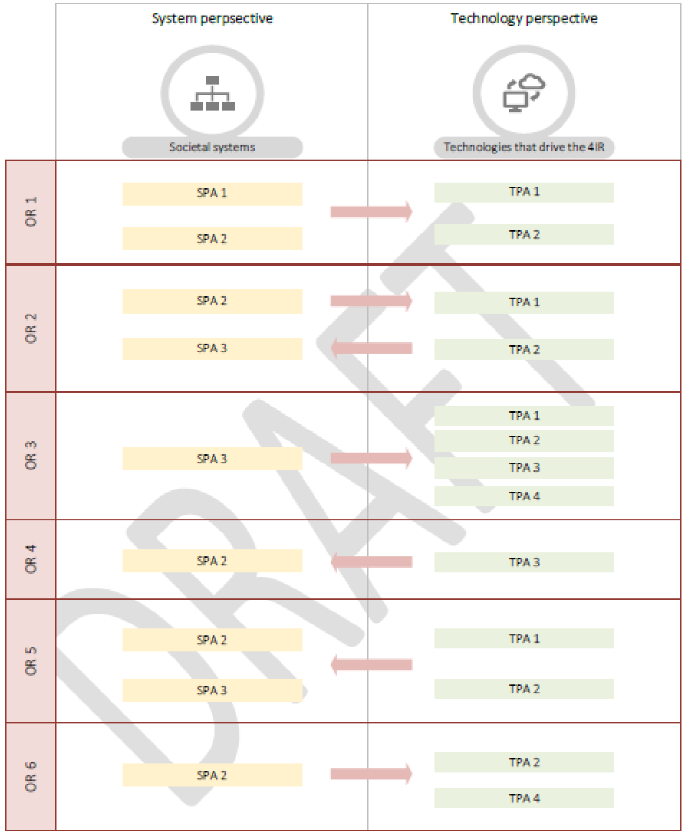


Figure 16: Synthesized perspectives, aspects and observed relationships

5.4 STRATEGY FOR THE OPERATIONALISATION OF THE I4IR-STT MODEL

In this section, an operationalisation strategy for the I4IR-STT model is presented. By itself, the model only demonstrates an integration of the 4IR and STTs. However, it does not enable the user to action any insight they may obtain from the model. It is for this reason the operationalisation strategy is developed i.e. to give practical utility to the model. Furthermore, the strategy for the operationalisation of the model borrows rationale from Principle 4 of the Applied Systems Thinking which is to understand

40

systems at different scales of analysis (Allen & Shonnard, 2012)

The primary aim of understanding the integration of technologies that drive the 4IR within societal systems in STTs within the global contemporary context is so as to influence elements of the transitions process with the aim of achieving sustainability and sustainable development targets. This is because STTs literature argues that the transitions process may not be planned but it may be influenced (Elzen *et al.*, 2004; Köhler *et al.*, 2019; Markard *et al.*, 2020; Schot & Kanger, 2018a). Though the model draws distinctions between societal systems and technologies that drive the 4IR for the purposes of demonstrating a conceptual integration, it noted from literature that societal systems encompass these technologies and that these technologies are embedded within societal systems (Elzen *et al.*, 2004; Sandén & Hillman, 2011). Technologies play a key role in transition process as transitions occur when new sociotechnical system configurations are formed around technologies, replacing the old ones to meet a societal system's needs (Köhler *et al.*, 2019) and hence developing intervention efforts to influence the transition process is of valuable contribution towards sustainability and sustainable development targets and goals. To develop the strategy, the following considerations are taken into account to enhance its practicableness. These are discussed in the following sub-sections:

5.4.1 SCALE AND UNIT OF ANALYSIS

Literature on previous transitions demonstrates that the transitions process is enacted from the smallest unit of societal system, and then aggregated over time to entire system on global scale (Belz, 2004; Geels, 2012, 2005). Similarly, transitions in contemporary societal systems with technologies that drive the 4IR may be viewed in the same manner. The transitions process is embedded within societal systems and is enacted at several sub-system levels in which various 4IR driving technologies are utilised.

It is observed that technologies that drive the 4IR have the potential to contribute towards sustainability/sustainable development at various levels of societal systems towards transitions. Multiple technologies that drive the 4IR may have sustainability implications to different parts of the same societal system and yet contribute towards similar sustainability solutions hence addressing the same societal system's challenges. This is demonstrated in the examples presented in Table 5 where technologies such as AI are presenting alternatives and improvements to vehicle types in the transportation systems or technologies such as Big Data and analytics is presenting sustainability impacts and contributions to transport networks and routes within the same system. Additionally, both Big Data and IoT are being utilised to make contributions to optimising energy usage with the energy system. Due to their interconnectedness, technologies that drive the 4IR demonstrate a bottom-up linking characteristic in the transitions process when viewed aggregately across the entire societal system.

Furthermore, societal systems are embedded within the global landscape which also has various contexts that inform the nature and conditions for a transition. Therefore, the same transition in societal system may inherently look different within different geographical and societal contexts. However, the underlying or starting unit of analysis may be initiated from a specific societal system's subsystem which may be adopting and utilising a specific 4IR driving technology.

Therefore, the first step of the operationalisation strategy in the practical application of the I4IR-STT model is to demarcate the system. The model has been developed in a generic manner and therefore

does not draw practical system boundaries for the user. It is recommended that the user identifies the societal system and of interest and demarcates the scope of the system to the point where a specific technology is envisaged to be utilised. Furthermore, the user should specify geographical and societal contextual boundaries for the system being analysed. This enhances the practicalities of utilising the model.

5.4.2 UTILISING THE I4IR-STT MODEL IN ITS OPERATIONALISATION

The main aim of the operationalisation strategy is to enable the I4IR-STT model's user to identify opportunities for exploiting technologies that drive the 4IR within a societal system of interest towards or within a transitions process. The model demonstrates the integration of technologies and societal systems from system and technology perspectives and their consequent aspects. Subsequently, relationships are drawn between the aspects to demonstrate the integration. Therefore, a key consideration for users in practically applying the model is the identification of the aspects and analysis of subsequent relationships between aspects. From the model, aspects are identified from both a technological and societal system's perspective for a comprehensive understanding of the dynamics between the societal system and the technology.

Insights obtained from the model's aspects and ORs are envisaged to enlighten the user on the basics of the dynamics in utilising the 4IR's technologies within the specific societal system. Insights may thereafter guide the user towards a recommended appropriate intervention framework with STTs analysis that further guides them in the analysis of their societal system or component of interest.

It is acknowledged that given the generic nature of the model, varying academic domains and contexts may produce further aspects and relationships than those utilised to deduce the I4IR-STT model. However, the provided aspects give a starting point to guide the user their analysis.

5.4.3 SOCIO-TECHNICAL TRANSITIONS FRAMEWORK ADDITIONS FOR THE OPERATIONALISATION STRATEGY

From the model, it is demonstrated that the technologies that drive the 4IR have a strong orientation to the niches dimension in STT analysis (refer to Section 5.4.1) and may therefore, be analysed as such within contemporary societal systems transitions. STTs theory articulates analytical orientations and frameworks that are helpful in the shaping an approach towards identifying, understanding and strategizing efforts to influence transitions. Literature presents the MLP, Technology Innovation System (TIS), Strategic Niche Management (SNM), and Technology Management (TM) frameworks for the analysis of STTs. the MLP is primarily utilised to understand the overall STTs process where as the TIS, SNM and TM frameworks have a strong emphasis towards management and practical interventions for technological innovations and niches in the transitions process (Roberts & Geels, 2019). It is therefore proposed that the TIS, SNM and TM frameworks are incorporated into the operationalisation strategy.

Table 7: Comparison of STT frameworks for intervention approaches. Source (Roberts & Geels, 2019)

	Technology Innovation Systems (TIS)	Strategic Niche Management (SNM)	Technology Management (TM)
Focus point	Formative phase of technologies which includes innovation and emphasis of instruments to enhance innovation activities.	Nurturing of innovative technologies and networks so they are competitive with incumbents.	Goal-orientated modulation towards long term visions
Indication for adoption	Lack of technologies that contribute to solutions for specific sustainability targets and goals.	Existence of inhibition towards niche technologies within societal systems which disempowers their potential for contribution to sustainability. This is derived from the relationship with the incumbent technology.	Need to define sustainability/sustainable development goals and visions within system as well as to steer technologies within system towards the goals and visions.

The above considerations culminate into an operationalisation strategy for the shown in Figure 17 below:

Figure 17: I4IR-STT model operationalisation

The first step is to demarcate the system through geographical and societal contexts as inputs. This involves the identification and scoping of a societal system of interest as well as technologies that drive the 4IR utilised therein. The output of this step (i.e. a societal system/sub-system and identified technology) are then fed into the second step as inputs. The second step is to develop aspects for an integrated analysis from both the system's and technology's perspective. These aspects are then utilised into the third step in which the user may analyse relationships between the societal system and technologies that drive the 4IR from aspects drawn. From the relationships, the user develops insights that are utilised into the fourth step of strategy. Lastly, the user adopts or selects a framework as an intervention approach based on insights obtained from the relationship analysis. Table 8 below summarises this procedure.

43

Table 8: Operationalisation strategy elaborated

	Description	Inputs	Outputs
STEP 1	Demarcation of societal system of interest and narrowing the scope of the system to the point where a specific technology is envisaged to be utilised. Furthermore, the user specify and utilise geographical and societal contextual boundaries for the system being analysed. (as per Section 5.4.1)	Information on societal system Information on [potential] technologies that drive the 4IR within the system Geographical and societal contexts	Demarcated societal sub-system and technology for analysis.
STEP 2	Identification of the aspects. Aspects are as presented in I4IR-STT model From the model, and are identified from both a technological and societal system's perspective for a comprehensive understanding of the dynamics between the societal system and the technology (as per Section 5.4.2)	Demarcated societal sub-system and technology for analysis. I4IR-STT model	Aspects for the integration from both systems and technology perspective
STEP 3	Identification and analysis of subsequent relationships between aspects. Insights are thereafter drawn from the relationships (as per Section 5.4.2)	Aspects for the integration from both systems and technology perspective I4IR-STT model for exemplification.	Relationships between the aspects
STEP 4	Identify an intervention framework within the scope of SNM, TIS and TM. (as per Section 5.4.3)	Insights from relationships between the aspects	A framework to be utilised as an intervention approach for the societal system

44

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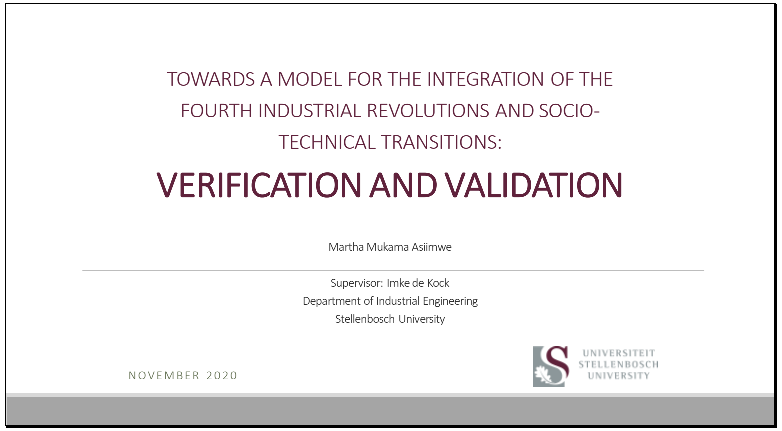
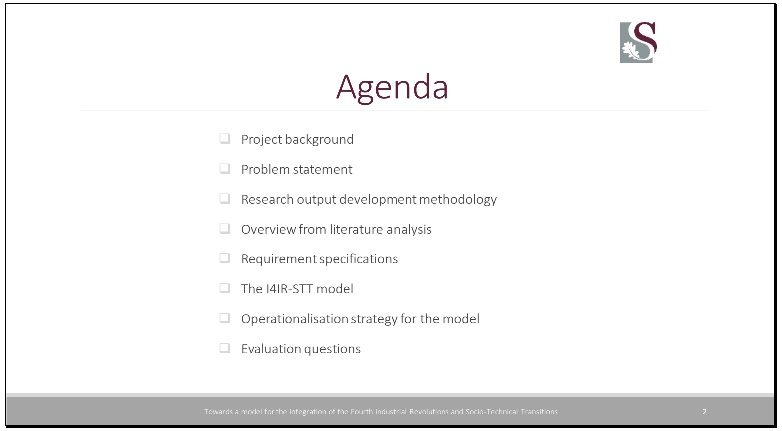
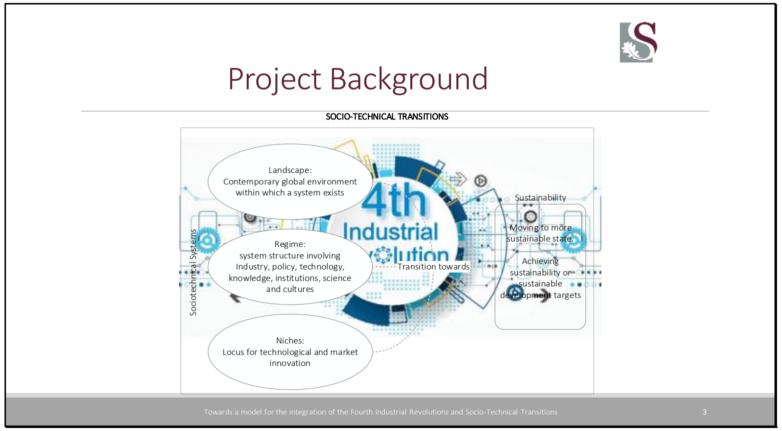
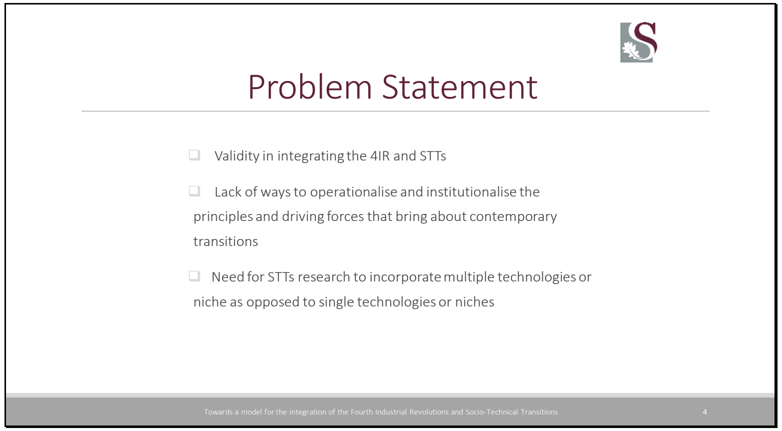
APPENDIX E: SME EVALUATION: PRESENTATION









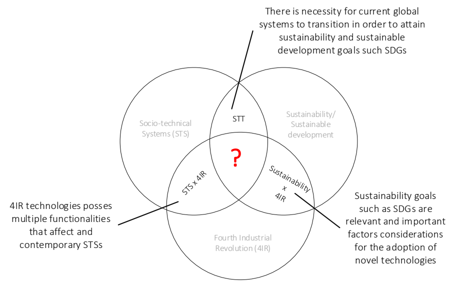
Literature Analysis

Conducted in two phases:

- A conceptual analysis giving context to the topics and concepts of STTs and the 4IR; and
- A Systematic Literature Review to analyse the extent to which these concepts have jointly considered within academic literature. Findings:
  - 42 articles – June 2019
  - Main themes on innovation, policy and strategy, business models, value creation
  - Large manufacturing and industrial production focus
  - Majority from Europe

Towards a model for the integration of the Fourth Industrial Revolutions and Socio-Technical Transitions 5

Literature Analysis



Towards a model for the integration of the Fourth Industrial Revolutions and Socio-Technical Transitions 6

Gap Analysis

Identifying gaps and disconnects from contrasting the conceptual literature and literature analysed in the systematic review

Gaps

- Lack of consolidated integrated conceptual analysis of STTs and the 4IR
- Need for contemporality in the analysis of STTs
- Under-utilisation of emerging technologies in STTs analysis
- Need to analyse multiple technologies together

Disconnects

- Lack of sufficient elaboration of STTs
- Lack of sufficient consideration of systems oriented towards societal functions
- Overall dominant single view of the 4IR as Industry 4.0

Towards a model for the integration of the Fourth Industrial Revolutions and Socio-Technical Transitions 7

Requirement Specifications

Functional specifications for the model's development as specified by Van Aken (2009)

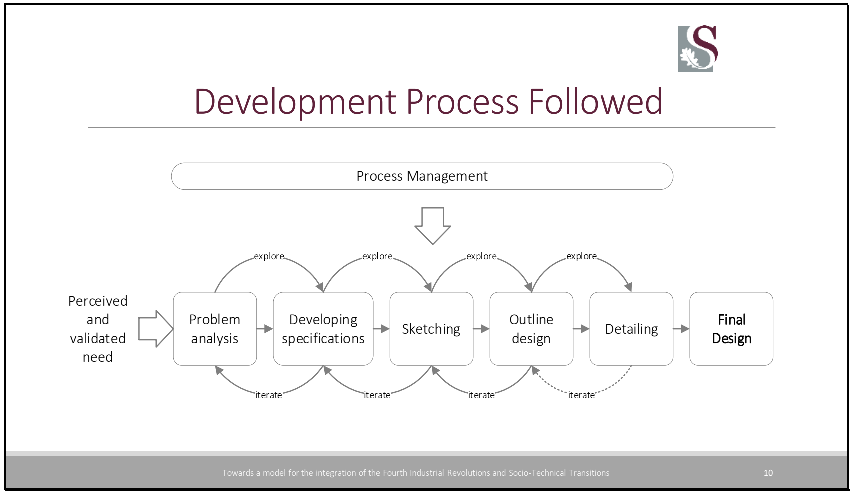
Functional requirements:

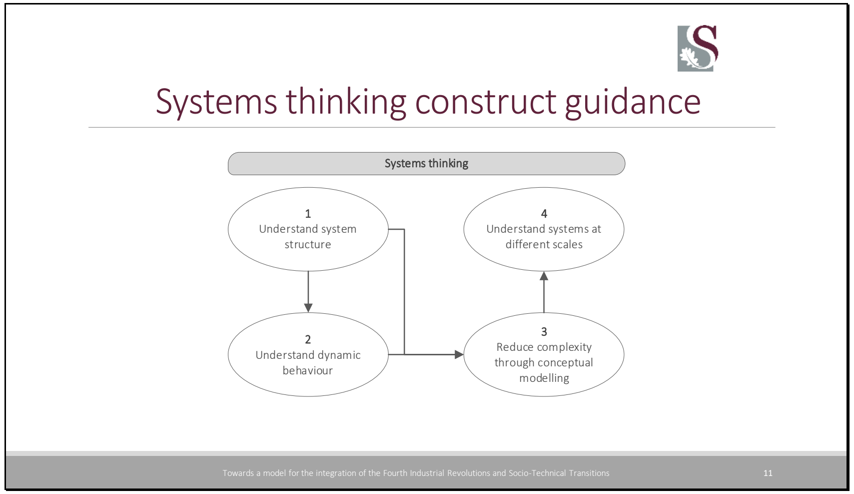
- Sufficiently articulate an integration and orientation of elements of the 4IR and STTs
- Take into account transition to a more sustainable state for the system
- Employ STTs theory from STS background
- Analyse the 4IR from its wholistic context
- Should be applicable to contemporary contexts

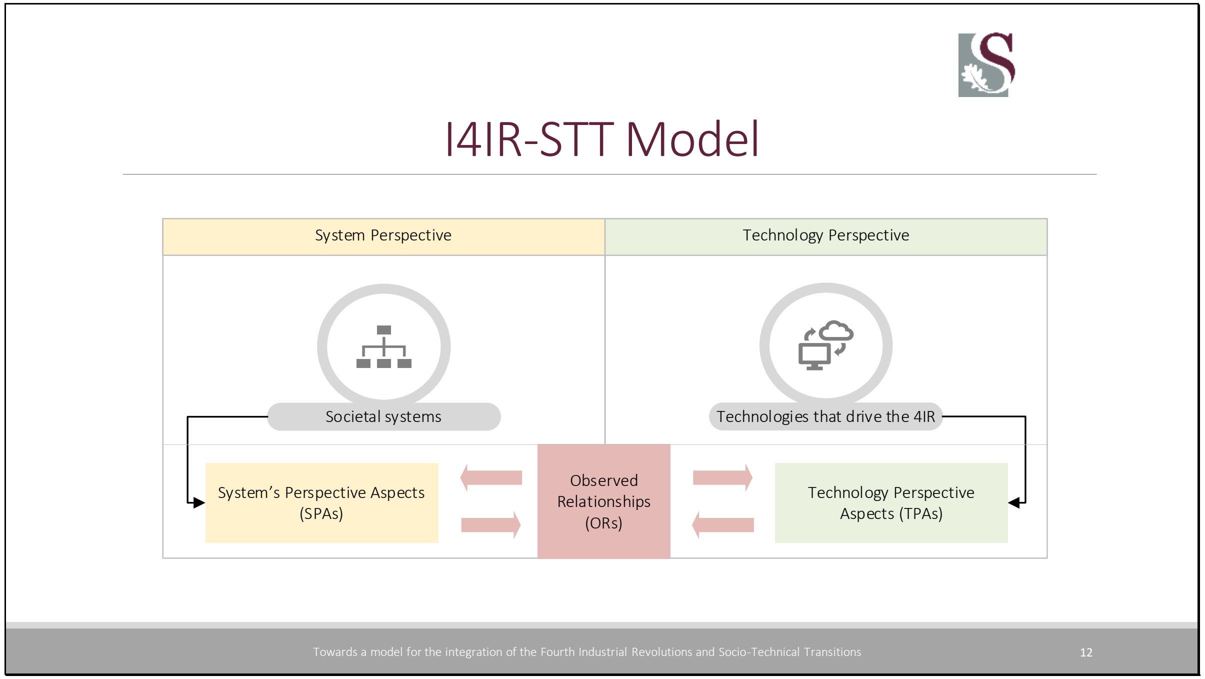
Design restrictions:

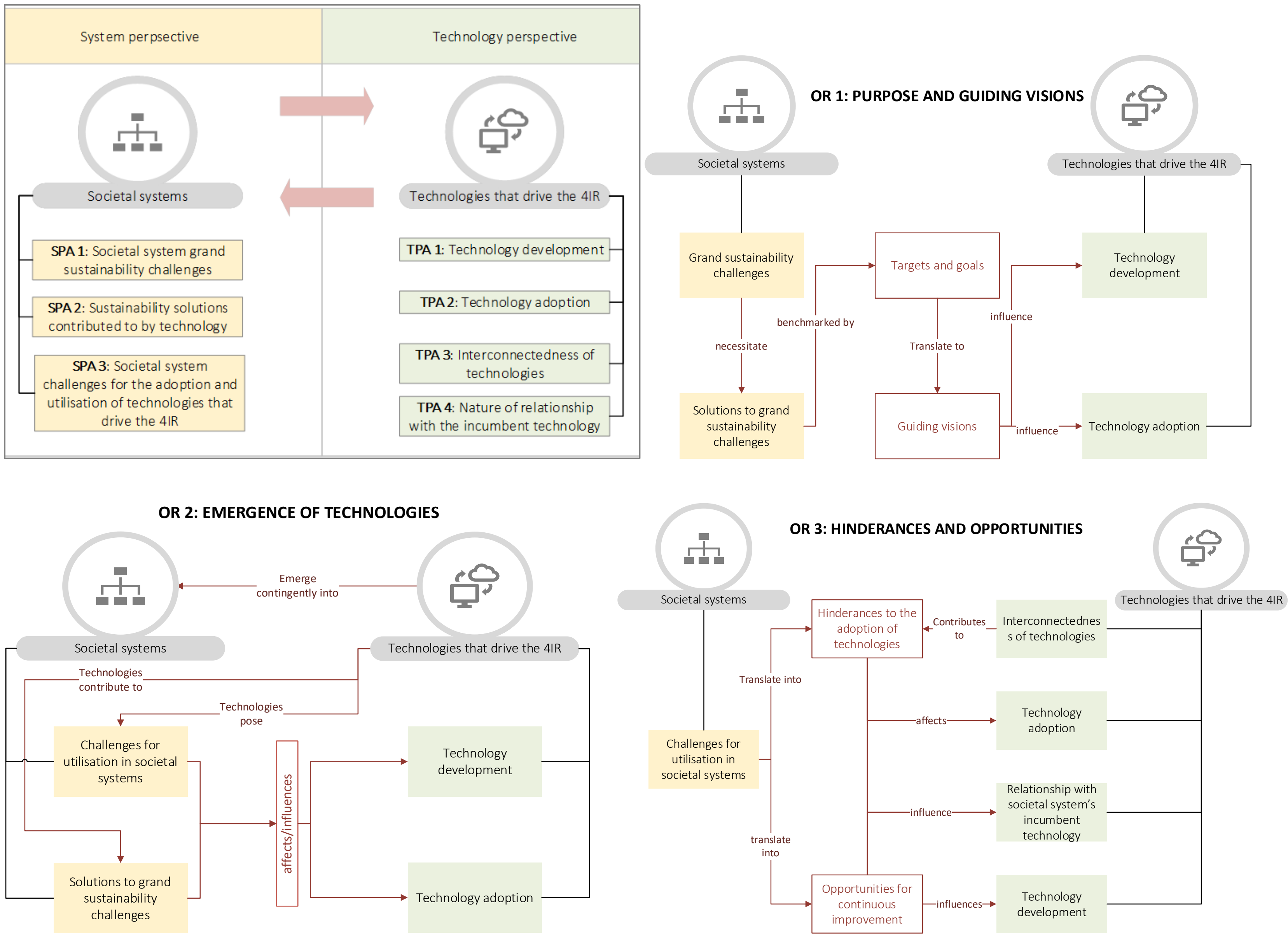
- Model is developed from an industrial or systems engineering perspective.
- Model does not provide new meaning around the 4IR and STTs
- Model is not a practical tool, but offers a descriptive approach

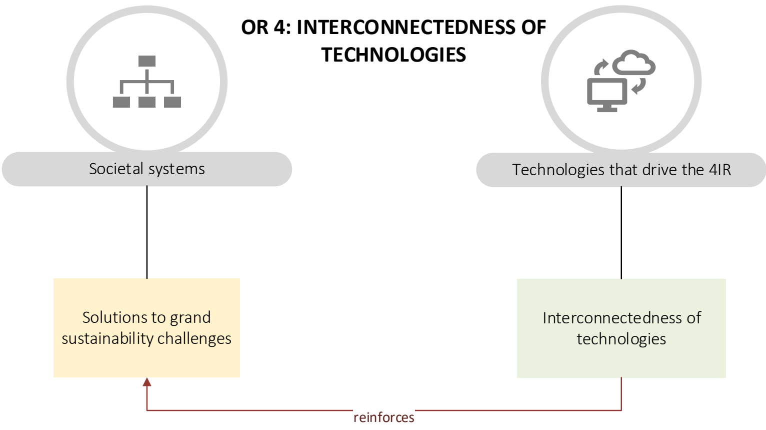
Towards a model for the integration of the Fourth Industrial Revolutions and Socio-Technical Transitions 8

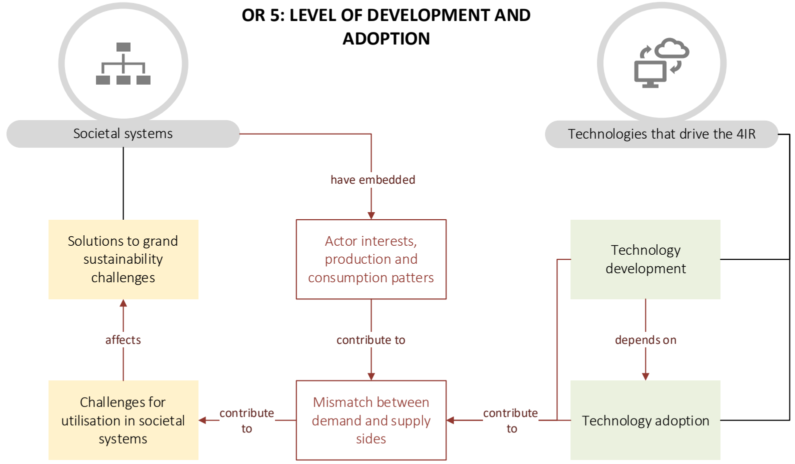

Development Process Followed
Process Management
Perceived and validated need
Problem analysis
Developing specifications
Sketching
Outline design
Detailing
Final Design
explore
iterate

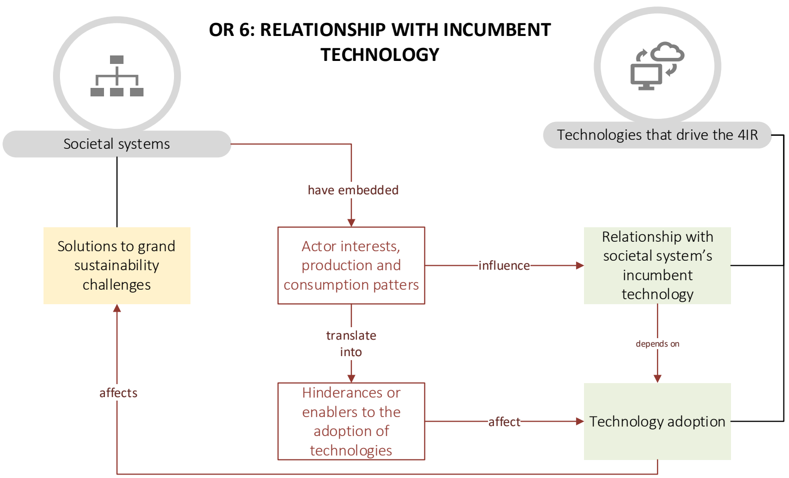

Systems thinking construct guidance
Systems thinking
1 Understand system structure
2 Understand dynamic behaviour
3 Reduce complexity through conceptual modelling
4 Understand systems at different scales

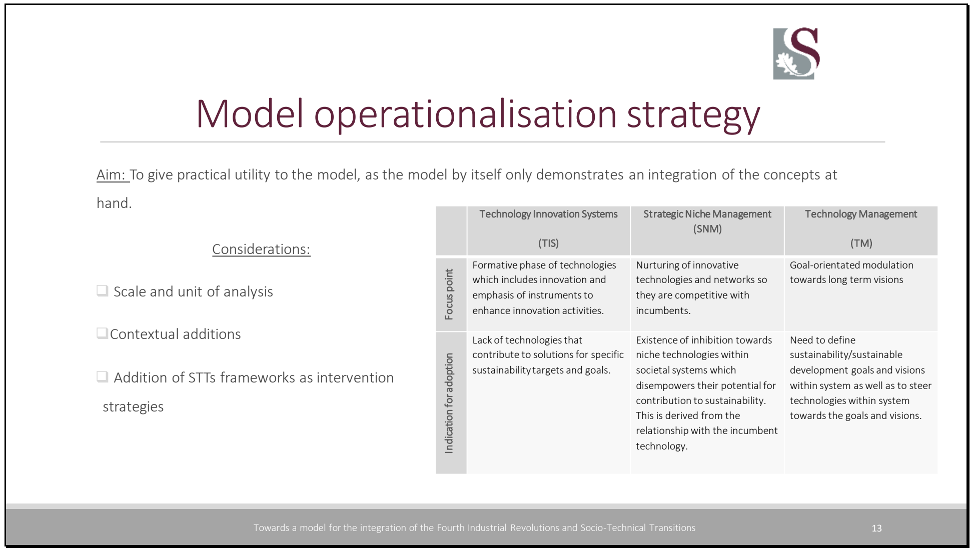

I4IR-STT Model
System Perspective
Technology Perspective
Societal systems
Technologies that drive the 4IR
System's Perspective Aspects (SPAs)
Observed Relationships (ORs)
Technology Perspective Aspects (TPAs)
Towards a model for the integration of the Fourth Industrial Revolutions and Socio-Technical Transitions
12

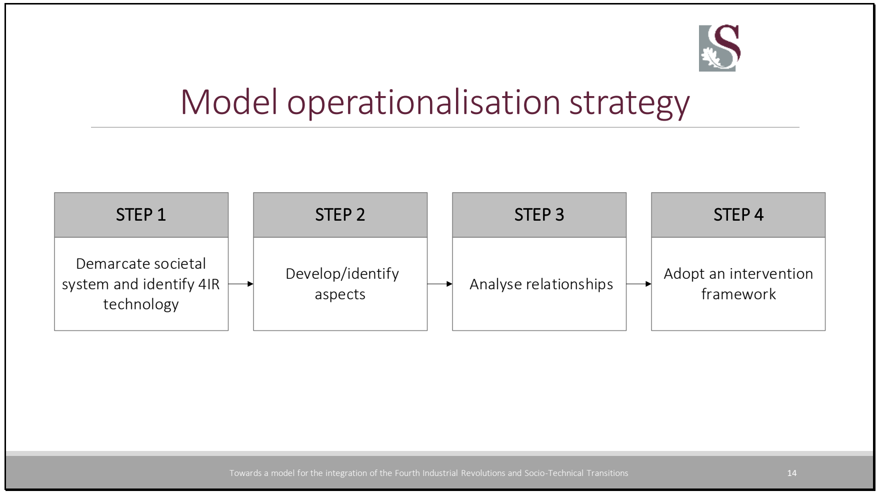

System perpsective
Technology perspective
Societal systems
Technologies that drive the 4IR
SPA 1: Societal system grand sustainability challenges
SPA 2: Sustainability solutions contributed to by technology
SPA 3: Societal system challenges for the adoption and utilisation of technologies that drive the 4IR
TPA 1: Technology development
TPA 2: Technology adoption
TPA 3: Interconnectedness of technologies
TPA 4: Nature of relationship with the incumbent technology
OR 1: PURPOSE AND GUIDING VISIONS
Societal systems
Technologies that drive the 4IR
Grand sustainability challenges
necessitate
Solutions to grand sustainability challenges
benchmarked by
Targets and goals
Translate to
Guiding visions
influence
influence
Technology development
Technology adoption
OR 2: EMERGENCE OF TECHNOLOGIES
Emerge contingently into
Societal systems
Technologies that drive the 4IR
Technologies contribute to
Technologies pose
Challenges for utilisation in societal systems
Solutions to grand sustainability challenges
affects/influences
Technology development
Technology adoption
OR 3: HINDERANCES AND OPPORTUNITIES
Societal systems
Technologies that drive the 4IR
Hinderances to the adoption of technologies
Contributes to
Interconnectedness of technologies
Translate into
Challenges for utilisation in societal systems
affects
Technology adoption
influence
Relationship with societal system's incumbent technology
translate into
Opportunities for continuous improvement
influences
Technology development


OR 4: INTERCONNECTEDNESS OF TECHNOLOGIES
Societal systems
Technologies that drive the 4IR
Solutions to grand sustainability challenges
Interconnectedness of technologies
reinforces


OR 5: LEVEL OF DEVELOPMENT AND ADOPTION
Societal systems
Technologies that drive the 4IR
have embedded
Solutions to grand sustainability challenges
Actor interests, production and consumption patters
Technology development
affects
contribute to
depends on
Challenges for utilisation in societal systems
contribute to
Mismatch between demand and supply sides
contribute to
Technology adoption


OR 6: RELATIONSHIP WITH INCUMBENT TECHNOLOGY
Societal systems
Technologies that drive the 4IR
have embedded
Solutions to grand sustainability challenges
Actor interests, production and consumption patters
influence
Relationship with societal system's incumbent technology
translate into
depends on
affects
Hinderances or enablers to the adoption of technologies
affect
Technology adoption


Model operationalisation strategy
Aim: To give practical utility to the model, as the model by itself only demonstrates an integration of the concepts at hand.
Considerations:
Scale and unit of analysis
Contextual additions
Addition of STTs frameworks as intervention strategies
Technology Innovation Systems (TIS)
Strategic Niche Management (SNM)
Technology Management (TM)
Focus point
Formative phase of technologies which includes innovation and emphasis of instruments to enhance innovation activities.
Nurturing of innovative technologies and networks so they are competitive with incumbents.
Goal-orientated modulation towards long term visions
Indication for adoption
Lack of technologies that contribute to solutions for specific sustainability targets and goals.
Existence of inhibition towards niche technologies within societal systems which disempowers their potential for contribution to sustainability. This is derived from the relationship with the incumbent technology.
Need to define sustainability/sustainable development goals and visions within system as well as to steer technologies within system towards the goals and visions.
Towards a model for the integration of the Fourth Industrial Revolutions and Socio-Technical Transitions
13



	Description	Inputs	Outputs
STEP 1	Demarcation of societal system of interest and narrowing the scope of the system to the point where a specific technology is envisaged to be utilised. Furthermore, the user specify and utilise geographical and societal contextual boundaries for the system being analysed.	Information on societal system Information on [potential] technologies that drive the 4IR within the system Geographical and societal contexts	Demarcated societal system technology analysis.
STEP 2	Identification of the aspects. Aspects are as presented in I4IR-STT model From the model, and are identified from both a technological and societal system's perspective for a comprehensive understanding of the dynamics between the societal system and the technology	Demarcated societal sub-system and technology for analysis. I4IR-STT model	Aspects for integration both systems technology perspective
STEP 3	Identification and analysis of subsequent relationships between aspects. Insights are thereafter drawn from the relationships	Aspects for the integration from both systems and technology perspective I4IR-STT model for exemplification.	Relationships between aspects
STEP 4	Identify an intervention framework within the scope of SNM, TIS and TM.	Insights from relationships between the aspects	A framework utilised as intervention approach for societal syste

APPENDIX F: SME EVALUATION: INTERVIEW QUESTIONS AND SUMMARISED RESPONSES

i. Do you have any knowledge on the STTs/4IR and what is the extent of your engagement with it?
ii. Do the stated requirement specifications and methodology adequately contribute to the research product?
iii. Does the research product should sufficiently articulate an integration and orientation of the elements of the 4IR and STTs together? –
   a. What is your opinion on the elements, perspectives, aspects of the integration and observed relationships?
   b. Are the above, sufficient? What would you add or remove?
iv. Will the research product achieve its stated purpose? i.e., demonstrating an integration of the concepts and enabling ones understanding towards this integration.
v. What do you consider to be the key strengths of the proposed research product and methodology?
vi. What would you recommend as improvements for the research product?
vii. In your opinion, what are the limitations of the research product?
viii. What do you consider to be the key weaknesses of the proposed research product and methodology?
ix. Where do you think the research product would fail, if operationalised?
x. Are there any bodies of literature that you feel have been excluded that should be considered for? (Systematic, grey etc)

Table F.1: Responses and comments from SMEs

Comments	SME 1: Dr. AS	SME 2: Dr. FDL	SME 3: Dr. AB	SME 4: Dr. APB
Academical expertise/focus	**Agriculture x 4IR**	**Wider transitions or transformations towards sustainability**	**Socio-technical Transitions**	**Engineering Management and conceptual modelling for industry.**
Commentary on the research methodology and requirement specifications	*Thinks they are sufficient.*	*The research approach is well articulated, methodology is well followed. The methodology is sufficiently and well-structured to produce the model. That is sufficient. Well conducted piece of research at the master's level.*	*requirement specifications and methodology are sufficient.*	*Research is relevant and new enough.* *Research is done sufficiently from an academical point of view. Research methodology is sound.*
Limitations of the methodology and requirement specifications?	No specific comment made	*Other literature present that is still up and coming or being published.*	No specific comment made	*Be clear on which literature research where and why it was done the way it (contextual vs SLR)*
Recommendations for literature revisions.	No specific comment made	No specific comment made	No specific comment made	*Give more procedural context for the reader.* *Explain what was done and why it was done.* *There is more statements on the restrictions on how the model functions than what it actually does. Be clear on what the model is used for and how it is going work practically. The model is not as restricted as I think it is, so clarify this.*
Improvements on the methodology or requirement specifications	*Take a more human centred approach in the functional requirements and which goes over to the boundaries.* *Improve overall thesis narrative in declaring what is not observed.*	*What I found in literature has to do with decarbonisation.* *- Nothing on the assessment on of the negative effects of technologies* *- The assumption is that all technologies are sustainable and as long as the sustainability imperative is achieved then the technology should be ok. But how sustainable are the technologies especially in assessing the various parts of the value chain and how this affects the overall sustainability quest? Future research can dive into sustainability footprint of various 4IR technologies.* *Also change this in the narrative: Acknowledge that there is negative effects of technology. <- limitations of the research* *His main critique is taking STTs approach without accounting for other approaches for transitions to sustainability.* *Make clear and improve the narrative.*	*Narrative, improve the narrative to make it easy for the reader to follow the story, and account for views such as the environmental view on STTs not included in the research.*	*Table 17: explain how you did reference the table. Clarification in the narrative.* *<u>requirement specifications commentary:</u>* *Revise narrative to be explicit on what the model is going to be used for and how it will work practically.* *Add what is purpose of the model?* *Inductive reasoning: I am using qualitative information to understand the world or this phenomenon.* *Deductive reasoning/approach: I have done the model, let me see how it works in certain environments, through a case study.* *The model should be testable in different environments.* *Clarify the restrictions. R2 and R3* *- I claim that the model does not generate theory yet go back and generate theory. State the intent and be very clear that this is an understanding model, in the sense that it is not meant to build new theory around the concepts, but it is an understanding model that helps one to understand the integration of both concepts and therefore understand their links better. However, in testing the model, it shows that it has practical implications that are outlined later on in the thesis.* *Prescriptively (boundary condition)– it can be used as an aid. I am not prescribing that people must use it or even claim that this is the ultimate model. It is something people can use.*
Commentary on the model, its components and its sufficiency in achieving stated aim	*Likes the systemic view of the model, it is a great view of the mechanics, of seeing the interaction between society and technology. Has not seen anything like it. He thinks it is quite solid.*	*Model aspects, aspects and ORs are fine and valid.*	*The model is great, but one must demonstrate how it will be used.*	*Model is constructed soundly.* *It seems, though that only the societal systems perspective is subject to a systems perspective. Suggestion is to change that to societal*

Comments	SME 1: Dr. AS	SME 2: Dr. FDL	SME 3: Dr. AB	SME 4: Dr. APB
	He believes it achieves the stated purpose because it does demonstrate the integration, covering both a societal and technological perspective. The relationships between technology and societal system, that is the main focus.			*perspective because technologies are also subject to a system orientation.* *There is sufficient justification for the components of the model, so it sound.*
Key strengths of model	*Confident that the model would be able to operationalizable and applicable in the real-world setting.* *It is simple and step-wise*	*Model is sufficiently robust to prepare to answer the how questions in the research process.* *Likes the Perspectives and the ORs, it is a very useful tool to build on to more detailed analysis. Can be used a steppingstone for more comprehensive analysis in the real-life case and further research.*	*Model is a useful approach on how to analyse both concepts. The dual perspective*	*Being able to connect two areas which have historically been difficult to connect i.e., the social environment and technology environment.* *Model could be quite powerful as it could also be used in different contexts outside of just the 4IR, could be for valuing up other ideas against STTs*
Weaknesses/limitations of the model	*One needs to test the model within a real-world context for applicability. It is not stand alone*	*Nothing on the assessment on of the negative effects of technologies* *The assumption is that all technologies are sustainable and as long as the sustainability imperative is achieved then the technology should be ok. But how sustainable are the technologies especially in assessing the various parts of the value chain and how this affects the overall sustainability quest? Future research can dive into sustainability footprint of various 4IR technologies.*	*Environment perspective is not explicit in the model.* *It is important to demonstrate its applicability, facilitation with a case would be important.* *The only limitation that is that user perceptions are often retrospective, we are unable to predict how that is going to look like especially since most technologies are still emerging.*	*Model might look different in different socio-economic and cultural contexts, or even political contexts.*
Where model's potential for failure lies	*Complications in accounting for different value chains while applying for the mode*	*Context missing which makes the operationalisation farfetched from the model.*	*In the operationalisation: at what level one would operationalise the model.*	*The model would fail:* *Figure 1 in the evaluation:* *- Practiced by the wrong person or a wrong user. If the user does not have a good understanding of systems thinking, or societal and technological aspects or a good understanding of cross relationships. Then the model would fail. A precondition for using the model should be a certain level of Technology Management expertise.* *- The model would be as exact if there is not a good balance between the landscape, regime and niche view of STTs.* *- the model would fail if sustainability were not understood at the right level or write context as is stated.* *- Model could fail if there is drastic changes in the regime or landscape dimensions that changes the reason for existence or changes the overall motivation or target held by society.*
Recommendations for improvements of the model	***Include user perception of technology:*** *How people interact with technology (e.g., in how it is marketed) would be different from the development of such a*	*Relationships to add:* *Business case: as a factor for technologies to be adopted: either opposed or in tandem in the public good*	*Facilitate it with a case study.* *Society's behaviour towards the technology has to be explicitly stated. Society*	*Change societal systems perspective to societal perspective because even technology has a systemic perspective.*

Comments	SME 1: Dr. AS	SME 2: Dr. FDL	SME 3: Dr. AB	SME 4: Dr. APB
	technology. Customer perception of technology. *Technology could be a great concept – but user perception may hinder how that technology is absorbed.*	*rationale. There has to be a business case rationale.* *Sustainability imperative – SDGs is too broad.* *Technology is driven by a business rationale.* *Market is not paying green products.* *What other things that need to be add/other commentary* *Position the model in terms of geography/sectors/etc:* *- Sectoral/regional systems of innovation – need to account for it* *- recognise that there are different frameworks that do not emerge in isolation.* *Sector specification, value chain specification, geographical specification.* *Scope narrowing, observing relationships at value chains, sectors.* *Interconnectedness of tech, complementarities of technologies* *Technology also defined as know-hows, value knowledge, artefacts.* *"Say that you are aware of what you don't include, but it is beyond your scope to address them"*	*influences the technology, technology influences society. How society behaves towards a technology or perceives the technology is important.* *The only limitation with that is that user perceptions are often retrospective, we are unable to predict how that is going to look like especially since most technologies are still emerging.* *Proposed: nature interaction or perspective of the technology. Environmental perspective.* *Individual vs organisational behaviour towards the same technology – so account for or clarify the nesting and acknowledge that they can be different.*	*Could bring on the systems aspect to the technology perspective.* *In Table 17: add references to ensure that it is not opinion or fact.* *Suggests to call it or describe it as an understanding model.* *Explicitly state that the analysis of sustainability in this context is within the context of the greater good.* *Position sustainability at the enterprise of organisational level* *Add as a boundary: the model is applicable at a higher level. So macro level even if it can be used by people across different levels.* *Be very clear about the extent or scope engagement.* *Change to full words rather than acronyms in explaining the model, for ease of reading in cross referencing. So write out in full what is ORs TPA SPA, allows for a generic templatises.* *The arrows must be explained, is there causality between SPAs and TPAs? The arrows, where they are going and why.* *OR diagrams, state where it begins and where it is headed.* *Add title of OR to the captions of the figures.* *Clarify the supportive vs enabling relationships. Just brief explanations of that. Or clarity in writing.* *Account for different value chains and context.*
Key strengths of the operationalisation strategy	*It is simple and step-wise*	No specific comment made	No specific comment made	No specific comment made
Key weaknesses of the operationalisation strategy	No specific comment made	*It is stepwise, which is rigid. Recommends a more modular approach which gives room for building onto the model.*	No specific comment made	No specific comment made
Recommendations for the Improvements of the operationalisation strategy	*Account for sectoral value chains/sectoral dynamics. Different sub-sectors would be different.* *Account for who, what, where and when? – who has agency and who plays a role, in the use of the model and operationalising it, in identifying opportunities for technologies within the 4IR towards sustainability visions.* *How does the operationalisation fit into the corporate/economic situation? – who is involved.* *Competitiveness may be the problem.*	*Operationalisation steps can be made into building blocks or modules, not stepwise.* *Need to openness to allow for modification based on relevance. Narrative must include this:* *Add to scale and unit of analysis: the geographical, context, sectoral, knowledge and capabilities, nurturing of ecosystem.* *SNM – embryonic technologies* *TM – here solutions*	*Addition for feedback, as one analyses there is other aspects that come up where it would be useful to look at.* *Who uses the model?* *Define a user.* *If the user is not defined and the system not demarcated, it can be overwhelming for a user to have to work through the info.* *How to guide and narrow down the information.*	No specific comment made

Comments	SME 1: Dr. AS	SME 2: Dr. FDL	SME 3: Dr. AB	SME 4: Dr. APB
	Recommendations: Apply a different sector, apply a different user to test usability of the model			