Digitalisation and Business Model Innovation: Exploring the Microfoundations of Dynamic Consistency

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Declaration

This thesis is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the Preface and specified in the text.

It is not substantially the same as any work that I have submitted, or is being concurrently submitted, for a degree or diploma or other qualification at the University of Cambridge or any other university or similar institution except as declared in the Preface and specified in the text. I further state that no substantial part of my thesis has already been submitted, or is being concurrently submitted, for any such degree, diploma or other qualification at the University of Cambridge or any other university or similar institution except as declared in the Preface and specified in the text.

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Abstract

The Industry 4.0 paradigm (I4.0) as the digitalisation of manufacturing firms denotes the exploitation of real-time data originating from a ubiquitous interconnection of objects, machines and humans (via the internet) across the entire value network. I4.0 not only serves as a catalyst to improve value-adding activities or to design new product and service solutions but also, more fundamentally, enables manufacturing firms to innovate their established business models (BMs). Against this rapid socio-technological shift, manufacturers face the challenge of holistically innovating their BMs. This requires the individualisation of the value proposition alongside the flexibilisation of their value creating and capturing activities, as well as a continuous adaptation and alignment of these activities with the firm's organisational systems and the resource and competence base. Adopting the view of a BMI (business model innovation) as a system of interdependent activities, the continuous alignment of activities across the BMI is called dynamic consistency. However, it is not clear what mechanisms denote the notion of dynamic consistency. This thesis operationalises the microfoundations of dynamic consistency in an I4.0-driven BMI by empirically investigating six European manufacturing firms. Following the design themes of BMI, it argues that the notion of dynamic consistency comprises three main aspects: (1) a value focus on data and software; (2) a flexi-directional interlinkage to facilitate the exchange of information and materials; (3) agile working ensembles governing changes to the activity system. Moreover, it proposes open-mindedness and integrity of behaviour as a cognitive foundation that facilitates changes to the activity system. Taken together, these microfoundations provide reasoning for manufacturing firms to transform their traditional make-and-sell BM into a sense-and-act BM, yielding higher profits and profitability. The results demonstrate that the notion of BMI as an activity system must be complemented by the cognitive perspective of BMI to sufficiently operationalise the concept of dynamic consistency. This thesis is anticipated to be a starting point for further studies to achieve consistency during I4.0-driven BMI to generate superior and sustained value appropriation for manufacturing firms.

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Publications

Journal Publications

Köbnick, P., Velu, C., McFarlane, D. (2020) 'Preparing for Industry 4.0: digital business model innovation in the food and beverage industry', *International Journal of Mechatronics and Manufacturing Systems,* 13(1), pp. 59-89.

Conference Publications

Köbnick, P., Velu, C., McFarlane, D. (2018): 'Navigating through Industry 4.0 holistically: taking a business model innovation lens to drive the implementation of digitalisation – case study evidence from European automotive suppliers', *EDSI 2019 – the 10th European Decision Science Conference*

Köbnick, P., Velu, C., McFarlane, D. (2018): 'Preparing for Industry 4.0: understanding digital awareness in the food and beverage industry', *Industry 4.0 Academia Summit, Manchester*

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Abbreviations and Definitions

Abbreviation	Definition
AI	Artificial intelligence
BM	Business model
BMI	Business model innovation
CAD	Computer aided design
CEO	Chief executive officer
CFO	Chief financial officer
CNC	Computerised numerical control
COO	Chief operations officer
CPSs	Cyber-physical systems
CRM	Customer relationship management
CTO	Chief technology officer
ERP	Enterprise resource planning
I4.0	Industry 4.0
I4.0-driven BMI	Industry 4.0-driven business model innovation
ICT	Information and communication technologies
IoT	Internet of Things
KPI	Key performance indicator
MES-MOM	Manufacturing execution system – manufacturing operations management
OEM	Original equipment manufacturer
PLM	Product lifecycle management
SSOT	Single source of truth
USP	Unique selling point

1. Introduction

1.1 Research Motivation

A shared notion among industrial and academic leaders is that digitalisation applied to manufacturing “will transform every link in the manufacturing value chain, from research and development, supply chain, and factory operations to marketing, sales, and service” (Hartmann, King and Narayanan, 2015, p. 1). The revolution in manufacturing is largely the result of the ubiquitous interconnection of objects, devices and humans via the internet, making accessible large amounts of real-time data; many call it the Fourth Industrial Revolution, or Industry 4.0 (I4.0) for short (Kagermann *et al.*, 2012). McFarlane (2017) defines the application of digitalisation to manufacturing as “the application of digital information from multiple sources, formats, owners for the enhancement of manufacturing products, processes, supply chains and services”. Despite the properties of digital data[1] being the underlying driver of digitalisation, it is not a technical process but “a sociotechnical process of applying digitized technology to broader social and institutional contexts that render digital technologies infrastructural” (Tilson, Lyytinen and Sørensen, 2010, p. 749). It can be operationalised as the transformation of processes, content or objects that used to be primarily physical or analogue into something that is primarily digital (Fichman, Dos Santos and Zheng, 2014).

A wide exhaustion of traditional productivity levers has led manufacturing firms to invest significant resources in the development of digital advances. To seek new ways to change customer relationships, enhance internal processes and develop new business models (BMs) (Fitzgerald, 2012; Statista, 2017; Schneider, 2018). Firms thereby attempt to resolve the common tension between economies of scale and scope (Brettel *et al.*, 2014). This thinking was leveraged by the speed in which digitalisation disrupted the media and retail industries within just one decade. A BM can be understood as the architecture for a business to create value for customers and appropriate a share of this value in terms of profit by orchestrating the four main components of a BM, which can be summarised as

[1] Properties of digital data: replication with the same quality at nearly zero marginal costs and near real-time transmissibility across the globe (Iansiti and Lakhani, 2014; Brynjolfsson and McAfee, 2016)

the 4Vs: (V1) the *value proposition* (Richardson, 2008; Demil and Lecocq, 2010); (V2) the *value creation and delivery* system (Richardson, 2008; Teece, 2010; Zott *et al.*, 2011); (V3) the *value capture* mechanism (Richardson, 2008; Teece, 2010; Zott *et al.*, 2011); and (V4) the *value network* of partners (Teece, 2010; Zott and Amit, 2010; Velu, 2017). These 4V's are further interdependent and thereby characterise the BM as a system of interdependent activities (Zott and Amit, 2010; Velu, 2017).

However, despite signs of progression, manufacturing firms seem to have substantial problems understanding the idea of I4.0 and how to relate it to their specific domain (Burmeister *et al.*, 2016; Müller, Buliga, *et al.*, 2018). Leaders in manufacturing firms exhibit strong ambiguity about their perception of I4.0; they view it either as a vision that should be accomplished, or as a mission, meaning a way to achieve a certain business goal (ends versus means) (Erol, Schumacher and Sihn, 2016). As a consequence, firms are struggling to identify opportunities for strategic fields of action and to derive holistic initiatives that enable them to move towards an I4.0 firm and sustainably appropriate a share of the projected added value for them (Müller, Buliga and Voigt, 2018). Incumbent manufacturing firms especially, whose BMs have been centred predominantly on the make-and-sell BM style of "simply" producing a product and then selling it, find it difficult to take holistic and comprehensive advantage of I4.0 (Bauernhansl *et al.*, 2015); holistic here refers to advancing the firm's BM as a whole by means of I4.0, including products and services, alongside value capture and creation activities. Increasing evidence suggests that BM innovation (BMI) is a crucial and valuable concept for informing a firm's holistic management of I4.0 for creating and capturing sustained value from I4.0 (Thoben, Wiesner and Wuest, 2017; OECD, 2017; Burmeister, Lüttgens and Piller, 2015).

1.2 Research Objectives

Due to the exponential pace of digital developments[2] (Brynjolfsson and McAfee, 2016) and the integrative nature of I4.0, changes to a given component of a BM are likely to have a significant impact on other components (Demil and Lecocq, 2010; Kiel *et al.*, 2017; Müller, Buliga, *et al.*, 2018), as the activities in a BM are interdependent (Amit and Zott, 2001;

[2] The power of micro-processors doubles every 18 months, known as "Moore's Law", a technology development speed that has not been observed in other domains before (Brynjolfsson and McAfee, 2016).

Zott and Amit, 2010). Understanding the notion of interdependency among BM components and their underlying activities is crucial for understanding how manufacturing firms may create and capture sustained value from I4.0, especially as every change in one activity has an impact, either positive or negative, on another activity in the system (Velu, 2017).

A literature stream that may inform the underlying mechanisms of interdependency is the field of dynamic BMI. Scholars in this field examine changes to the BM as an organisational change process (Saebi *et al.*, 2017), which seems promising for the notion of I4.0 as a sociotechnical change process. Demil and Lecocq (2010) advocate continuous work on the alignment of activities to achieve a superior competitive advantage; they term this process "dynamic consistency".

While several aspects have been discussed that deserve consideration during the process of innovating a BM, scholarship lacks a clear understanding of the mechanisms that underpin the process of dynamic consistency, in particular against the backdrop of the fast progression of digitalisation in manufacturing firms. Therefore, the following research question can be formulated (Figure 1):

What are the microfoundations of dynamic consistency in I4.0-driven BMI?

Gaining a deeper understanding of the microfoundations of dynamic consistency will provide valuable insights for scholars and practitioners into the mechanisms involved in aligning the activities during I4.0-driven BMI in order to create and capture superior value from I4.0 in manufacturing firms. Moreover, it is hoped that the results clarify how I4.0 provides a strategic vision and guidance for what aspects and mechanisms manufacturers need to consider to use I4.0 to its fullest potential. This would deepen the understanding of how manufacturing firms manage BMI holistically on an ongoing basis.

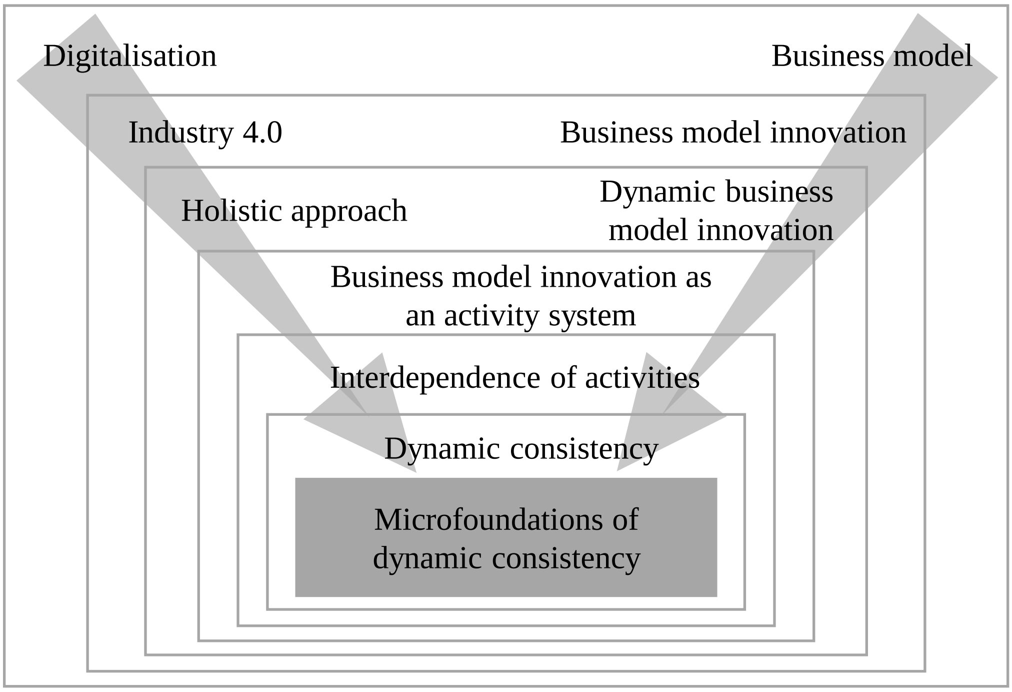

Figure 1. Bodies of research and positioning of research gap

1.3 Research Approach

An empirical research design seeks to obtain a better understanding of the microfoundations underlying the continuous alignment of activities in I4.0-driven BMI. This thesis presents the results of three exploratory and six in-depth case studies with about 70 semi-structured expert interviews in two manufacturing industries. It examines the holistic introduction of I4.0 in the European automotive supply and mechanical and plant engineering industries, and its impact on BMI. To the author's knowledge, it is one of the first studies in which the I4.0-driven BMI process of several manufacturing companies is examined over time from different perspectives within the management teams of each firm. This research proposes that a holistic management of I4.0 implementation enables manufacturing firms to transform their traditional "make-and-sell" BM into a "sense-and-act" BM (Köbnick *et al.*, 2020). In a sense–act BM, manufacturing firms use I4.0 to granularly sense real customer needs, then proactively act on individual information about the customer to fulfil these needs. This BM archetype accounts for the increasing ubiquity of available real-time data and the shift towards individualised solutions that enable enhanced customer experiences and thus yield higher productivity and profits for manufacturers. Moreover, this study suggests critical mechanisms that manufacturing firms need to consider for this I4.0-driven BMI transformation to achieve alignment among the activities, denoting the microfoundations of dynamic consistency.

These microfoundations of dynamic consistency are explicated in this study along the ordering scheme of the BMI as an activity system and related design themes – content, structure and governance (Amit and Zott, 2001; Zott and Amit, 2010). Content denotes the organisation and selection of key activities, while structure describes the mechanisms deployed to interlink activities with each other to achieve alignment across the activity system. Governance implies the organisational regime regulating decision-making authorities alongside the incentive structure. The findings of this thesis contend the following (design) mechanisms to enable a continuously appropriate exchange of information and material between activities, denoting the microfoundations of dynamic consistency:

Content. The findings show that manufacturing firms should select their core activities with a *value focus on data and software as a catalyst*. This implies that manufacturing firms can improve customer experience by leveraging their existing domain expertise by using data and software to: (1) individualise their value proposition with *digitalised product and service offerings*; (2) thereby obtain detailed information about customers' needs to *granularly segment customer demands*; and (3) make value-adding activities more flexible and responsive to fulfil these granularly segmented customer demands, especially by *cloning the physical activities coherently into digital*. By focusing on the digitalisation of product and service offerings, and the cloning of physical activities into digital, manufacturing firms use data and software to improve the flow and exchange of information, laying the foundation to improve the flow of materials as well. Granular and improved insights about customers eventually enhance customer experience through targeted product-service offerings and the rapid fulfilment of changing customer demands on quality and on time.

Structure. While this value focus on data and software is the groundwork for improved, more granular and timely exchanges of information and eventually materials, an *active flexi-directional interlinkage* of activities provides the structure that eventually activates the potential, laid by the groundwork, to enhance customer experience. To effectively improve the flow of information, data obtained through digitalised product and service offerings, or data of digitally cloned physical activities, must be available and exchangeable in real time. Findings suggest this to be realised through *holistic real-time interoperability* of software suites. Across manufacturing firms, a holistic interoperability of different software suites, including enterprise resource planning (ERP), manufacturing execution systems (MES), product lifecycle management (PLM) or customer relationship management (CRM) systems, is technically realised through a single source of truth (SSOT), where all software suites access and write into the same pool of data to ensure that data used are correct and up to date, mostly realised through multiple, interconnected databases. While a holistic interoperability is key for enabling efficient flows of information, manufacturing firms also need to *adapt their processes actively* to ensure the effective flow of both digital and, especially, physical processes. An active process adaptation refers to the ability to flexibly disassemble processes and reassemble them as required to improve flows of information or materials with a view to enhancing customer experience.

Governance. Placing a value focus on data and software, and establishing an active flexi-directional interlinkage, are subject to swift decision-making and the contribution of various functions within and beyond a firm. In contrast to the prevalent decision-making of superiors in manufacturing firms, this thesis argues that *agile working ensembles* constitute an appropriate authority for taking decisions about changes needed to improve the flow of information and materials. Agile working ensembles can be compared to an orchestra ensemble, where a cross-functional expert team of musicians is responsible for collectively delivering a harmonic concert. Similarly, agile working ensembles in manufacturing firms are composed of cross-functional experts that are empowered to *approach challenges entrepreneurially*, meaning to take decisions as they occur and as appropriate to swiftly enhance customer experience. Moreover, like an orchestra ensemble, all the members of which receive a shared ovation, the reward for an outstanding performance of a manufacturing firm must be shared across the cross-functional teams that contribute to and are responsible for the outcome. Paying tribute to the increasing collaboration across the value network of firms, *value* must even be *thought of across the fences* of the focal firm's boundaries.

While these mechanisms provide valuable insights on how manufacturing firms manage the alignment of activities, this study surprisingly found that the view of BMI as an activity system does not sufficiently explain the notion of dynamic consistency. In addition to the activity system view, the view of BMI as a cognitive schema essentially contributes to the understanding and achievement of dynamic consistency. Thereby, this study reveals the importance of specific cognitive foundations, i.e. individual mindsets and beliefs, as well as collective behaviours, that enable the content, structure and governance mechanisms discussed above to take shape in the first place: The findings propose an *open-minded integrity of behaviour*, where leaders take championship for an I4.0 vision. Leadership teams must develop a shared understanding of how I4.0 applied holistically may benefit their firm. In addition, the integrative notion and the fast-paced technological developments of I4.0 demand swift action of manufacturers in many respects. Therefore, the findings indicate that a *sense of family* should be created, referring to acting with integrity and an open, collaborative behaviour based on trust and transparency for the journey of transformation.

Considered together, the cognitive foundations and the content, structure and governance mechanisms enable a firm to transform their make–sell BM into a sense–act BM. “Sense” indicates the necessity and capability to closely understand either existing or potential customers with their individual needs based on granular information about their applications, current and expected usage patterns and the like, mostly obtained through digitalised products and services. Based on this information, customer needs can be granularly segmented into fulfillable demands. “Act” refers to the manufacturer’s ability to take advantage of these individual customer demands proactively. Flexibility plays a vital role in several respects. First, it indicates the capability to understand the required changes to the manufacturer’s product and service mix in order to enable customers of existing and new products and services to better fulfil their customers’ wishes. Second, it denotes the ability to develop and produce these individualised products and services rapidly, and deliver them on time and on quality. However, flexibility is subject to effective access to data and transparent information flows, enabled by strategically using I4.0 to obtain valuable information and take the required actions in the respective value-adding activities. Only then the flow of information and materials can be reorganised appropriately.

Based on these findings, the thesis makes three major contributions. First, it enriches the BMI literature by explicating the microfoundations of dynamic consistency; in particular, how manufacturing firms manage the alignment of the activities underlying the process of I4.0-driven BMI: what activities are critical to deploy (content mechanisms), what structures ensure an appropriate interlinkage between activities (structure mechanisms), and what are suitable decision-making rights and incentive structures within the firm and across the network of firms (governance mechanism). This process of managing the alignment dynamically requires leadership and the development of an appropriate collective culture and behaviour strategy that matches the roadmap of the I4.0-driven BMI in order to fully realise the benefits of I4.0 while managing the costs and risks.

Second, this study contributes to the definitional discourse among BMI scholars. To date, BMI has been mostly either viewed from an activity system perspective or a cognitive schema perspective; only a small number of studies discuss the value of integrating both perspectives (Berends *et al.*, 2016, and Velu, 2017). This study is among the first that explicitly demonstrates, on the basis of empirical evidence, how both perspectives converge to provide a more comprehensive and holistic understanding of a firm's BMI process. Specifically, in the realm of I4.0, where real-time information gained from a ubiquity of data becomes central for manufacturing firms, an integrated view of the activity system perspective and the cognitive schema perspective is shown as crucial. The cognitive schema perspective emphasises the significance of humans who, as decision-makers, create cognitive maps based on swiftly flowing and changing information, operationalised by aligning activities across the BM through an appropriate selection of activities and the establishment of appropriate flows of materials and information between activities.

Third, the study contributes to the state-of-the-art knowledge on I4.0 by presenting a BMI framework that enables manufacturing firms to transform their BM from make–sell into sense–act, allowing them to make step-change improvements to their productivity and profit margins through the targeted fulfilment of customer needs. Given the opportunities and challenges manufacturing firms are facing with I4.0, these contributions offer a novel understanding of how manufacturing firms should seek to create and capture value with I4.0, and thereby expand existing knowledge from both theoretical and managerial perspectives.

1.4 Structure of the Thesis

Figure 2 shows the structure of the thesis. Chapter 2 reviews the current state-of-the-art literature in I4.0 and BMI, with a specific focus on I4.0-driven BMI, and a stream of literature discussing the dynamics of BMI. Chapter 3 describes and derives the methodological approach taken to answer the research question posed, while Chapter 4 gives an overview of the case study firms examined, including information about their BM, their I4.0-driven BMI and the challenges they faced along the way. The findings obtained from analysing the case study data are presented in Chapter 5. Finally, Chapter 6 briefly summarises and discusses the findings, emphasising the contribution of this study to state-of-the-art knowledge on BMI and I4.0, alongside practical implications, followed by an examination of the study's limitations and prospective pathways for future research. A brief summary concludes this thesis.

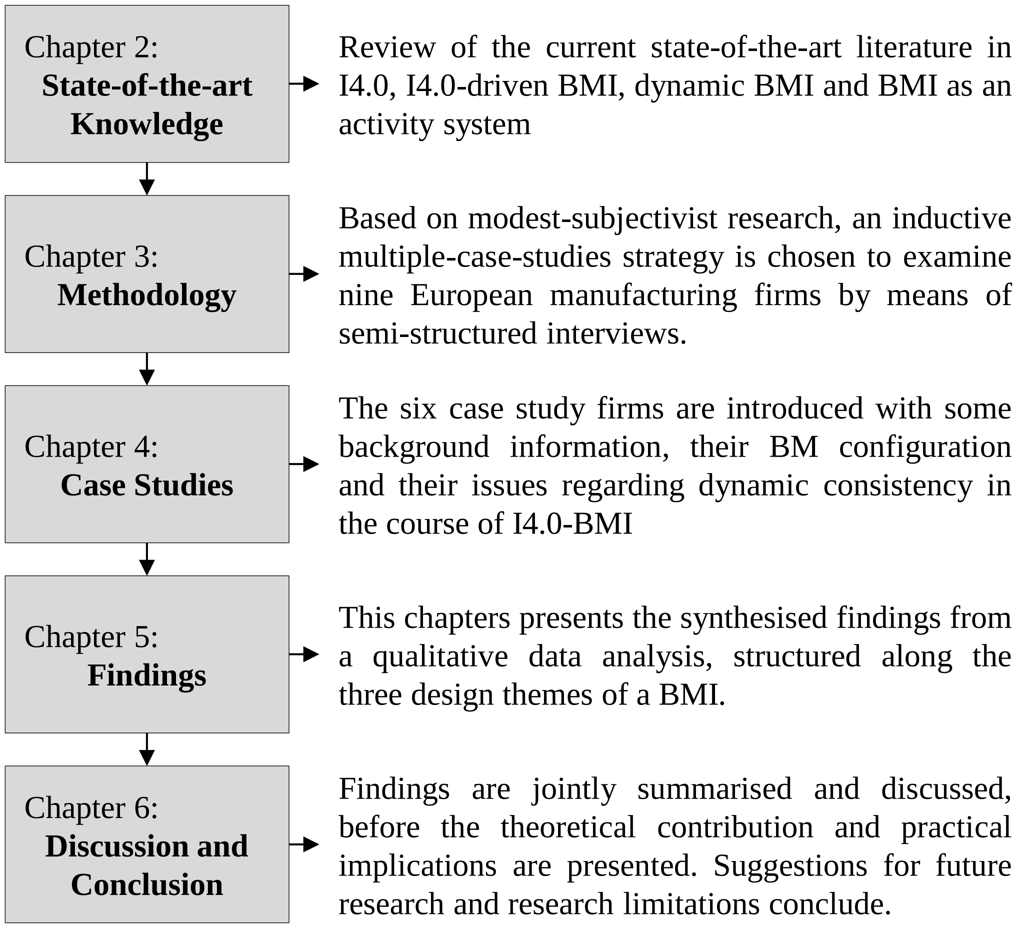

Figure 2. Structure of the thesis

2. State-of-the-Art Knowledge

2.1 Overview

This chapter examines the state-of-the-art knowledge concerning (I4.0) and BMI as the two areas considered relevant to answering the research question of this thesis. Both areas emerged from different fields of research – "Industry 4.0" as a term and research topic emerged in 2011 from a working group of academics and practitioners from engineering and information systems, advising the German Federal Government on their High-Tech Strategy 2020. BMI stems from strategic management literature. Due to the fragmentation of both literature streams, which have started to overlap in some areas, this chapter follows the logical flow depicted in Figure 3.

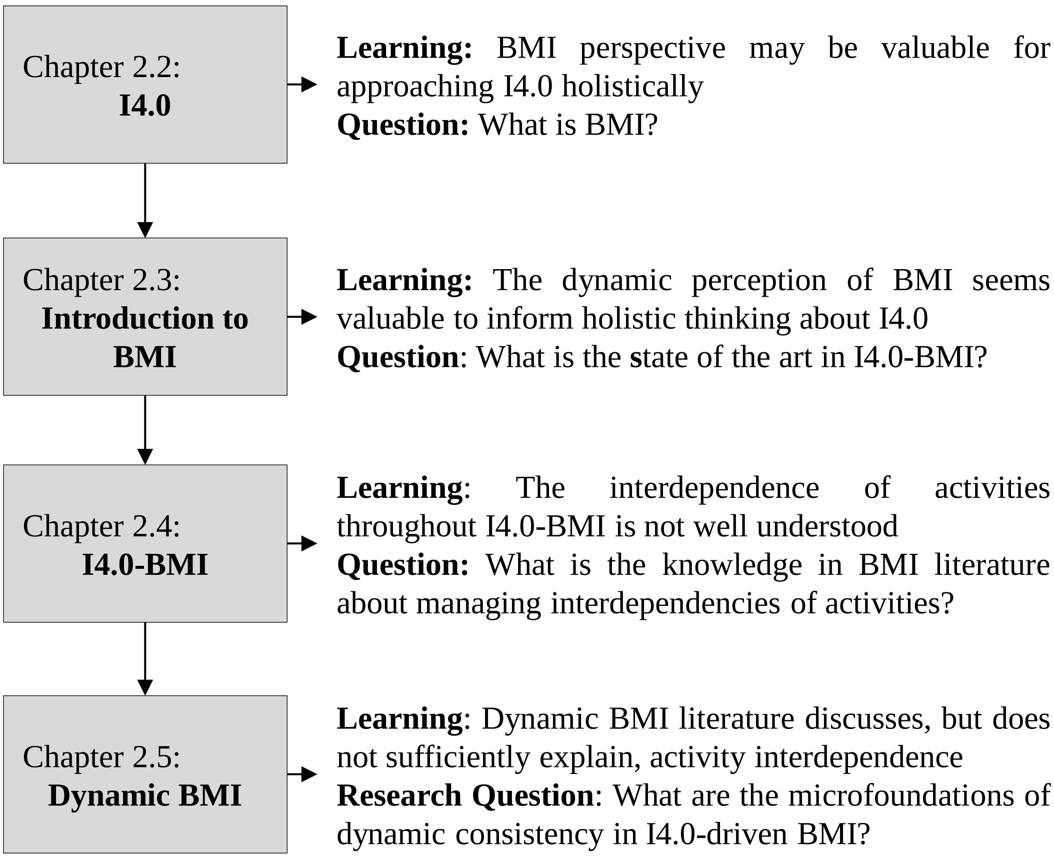

Figure 3. Bodies of literature for the state-of-the-art knowledge

2.2 Industry 4.0

2.2.1 Overview

Governmental initiatives worldwide have started to consolidate developments around the digitalisation of manufacturing industries, to bundle research efforts and provide funding to support manufacturing firms in these highly transformative developments. In addition to I4.0 (Germany), initiatives include Made-in-China 2025, Industrial Internet (USA), Smart Manufacturing (USA), Intelligent Manufacturing Systems (Japan), Factories of the Future (EU) or Future of Manufacturing (UK) (Liao *et al.*, 2017; Schneider, 2018). However, in recent years, academic and industrial publications, alongside Google searches with the term "Industry 4.0", have by far superseded other synonyms including "Industrial Internet (of Things)", "smart manufacturing" (Schneider, 2018). Due to its emergence in the early 2010s, the academic discourse about I4.0 is in its early stage (Schneider, 2018; Xu *et al.*, 2018). At the same time, the underlying approaches and ideas of I4.0 are situated at the intersection of multiple disciplines, including electrical engineering, business administration, computer science, business and information systems engineering, and mechanical engineering (Lasi *et al.*, 2014). As a consequence, a scattered field of research arose, with shortcomings in clear terminological definitions, which several literature reviews attempt to consolidate from different perspectives: industrial information (Lu, 2017), computer management science (Schneider, 2018); engineering and production (Liao *et al.*, 2017; Zhong *et al.*, 2017). In their sum, these reviews provide a profound overview of the discussions in this scattered research landscape.

For the purpose of this thesis, this dispersed body of knowledge can be grouped into three areas of discussion: (1) conceptualising I4.0; (2) operationalising I4.0, entailing its basic building blocks and key enabling technologies; (3) features and potential benefits, including an emerging discussion about I4.0-driven BMI. By far predominant in the literature is the field of technological enablers of I4.0. However, as the motivation and objective for this research project is focused on the mechanisms required for manufacturing firms to organise for I4.0, the large field of enabling technologies is not examined in detail; nevertheless, a brief overview of the most important technologies is included in Section 2.2.3.

2.2.2 Conceptualising I4.0

As part of a new high-tech strategy for the German Federal Government an initiative was founded, supporting the manufacturing sector with the developments subsumed under the umbrella of digitalisation, and coined *Industry 4.0* (Kagermann *et al.*, 2011). For several authors, I4.0 denotes the introduction of the Internet of Things and Services to the manufacturing industry, marking the beginning of a Fourth Industrial Revolution (Kagermann *et al.*, 2013, 2016; Spath *et al.*, 2013). In addition, further information and communication technologies (ICT), including cyber-physical systems (CPSs), industrial information integration, cloud computing, smart devices and business process management, enable the integration of the virtual space with the physical (Hermann *et al.*, 2016; Xu *et al.*, 2018). Much like this definition, the US-based Industrial Internet Consortium labels digitalisation in industry the *Industrial Internet of Things* and defines it as follows: "An internet of things, machines, computers and people enabling intelligent industrial operations using advanced data analytics for transformational business outcomes" (Industrial Internet Consortium 2015, p. 3). While the Industrial Internet Consortium promotes the use of digitalisation for industrial usage in general, the I4.0 initiative focuses predominantly on the manufacturing industry (Xu *et al.*, 2018), recognising in particular the need for a new approach and thinking about BMs in manufacturing firms (Kagermann *et al.*, 2011, 2013a, 2016; Spath *et al.*, 2013; Industrial Internet Consortium, 2015; Bauernhansl *et al.*, 2016).

Neither digital technology nor digital information are particularly revolutionary to I4.0, as both have been around for several decades (Kagermann *et al.*, 2013a; Bauernhansl *et al.*, 2016). However, the ideological principle is to seek completely integrated solutions to digitally integrate industrial ecosystems by applying the vastly progressing ICT technologies and infrastructures to manufacturing (Xu *et al.*, 2018). Comparably new is the possibility to access in real time all the relevant information of a manufacturing value chain based on "the networking of all the entities involved in the value creation process together with the ability to use this data to determine the optimal value stream at any given point in time" (Kagermann *et al.*, 2016, p. 5). Consequently, some distinct principles can be derived that underpin the transformative character of I4.0: (1) A ubiquitous origin of data regarding time, location, quantity and format; fuelled by CPSs, an Internet of Things, data, services, and advanced software suites (Kagermann *et al.*, 2013; Porter and Heppelmann, 2014).

(2) These data are integrated by means of software systems that are interoperable, enabling seamless operations across the boundaries of focal firms (Lu, 2017). (3) Internet-based cloud technologies that enable the bulk storage of, and remote access to, these data (Porter and Heppelmann, 2014; Kiel *et al.*, 2017). (4) Significantly increased possibilities to exploit these large amounts of data using advanced analytics to convert them into valuable information and actions (Industrial Internet Consortium, 2015; Kiel *et al.*, 2016; Müller, 2019).

Applying these aspects to the definition of manufacturing[3], for this thesis, I4.0 can be defined as follows:

> *Industry 4.0 is a socio-technical framework for organising the exploitation of a ubiquitous interoperability of the entire manufacturing value network with the purpose of converting digital information into measurable action plans for sustained competitive advantage.*

2.2.3 Operationalisation – The Basic Pillars of I4.0

In its form as a socio-technical framework for integrating and extending manufacturing value networks at both intra- and inter-organisational levels, I4.0 provides a wide array of solutions for the informatisation of manufacturing industries (Xu *et al.*, 2018). To bridge the gap between the formerly stated overarching definition of I4.0 and the enabling technologies, scholars suggest breaking down the paradigm into higher-order pillars (Kagermann *et al.*, 2013a; Bauernhansl *et al.*, 2016). Though, so far, scholars have not fully agreed on what are the basic pillars of I4.0. Table 1 summarises a selection of frequently used descriptions of the key pillars.

[3]Manufacturing denotes the full cycle, from understanding markets and technologies through product and process design to operations, distribution and related services (University of Cambridge, 2015, p. 16; Brustolin and Jonker, 2012, p. 106)

Table 1. Pillars of I4.0 according to different authors

Author	Pillar 1	Pillar 2	Pillar 3
Bauernhansl *et al.* (2016)	Vertical connectivity	Horizontal connectivity	Real-time optimisation
Brettel *et al.* (2014)	Individualised production	Horizontal integration in collaborative networks	End-to-end digital integration
VDI and ZVEI (2015)	Vertical integration	Horizontal integration	End-to-end engineering
Kagermann *et al.* (2013a)	Vertical integration and linked production systems	Horizontal integration	Digital consistency of engineering along the entire value chain
Smart Factory Task Group of Industrial Internet Consortium (2017)	System-wide visibility	Global supply chain integration	Industrial digital thread

There is a tendency to perceive two of the pillars as vertical integration and horizontal integration. Perceiving horizontal integration (value chain integration) as a pillar of I4.0 acknowledges that the value chain and, more importantly, the value network is an integral element of manufacturing firms' BMs (Demil and Lecocq, 2010; Velu, 2017). A group of scholars regards the third pillar as the consistency of engineering from one end of the value chain to the other (Kagermann *et al.*, 2013b; Brettel *et al.*, 2014; VDI and ZVEI, 2015), whereas Bauernhansl *et al.* (2016) consider the third dimension to be real-time optimisation. Considering the overarching theme of I4.0, which is centred on access, integration and exploitation of real-time data, it is reasonable to consider real-time optimisation as generally inherent to I4.0 rather than as an additional pillar. Generally, the integration and orchestration of all the elements of a BM are seen as crucial for achieving competitive advantage (Zott and Amit, 2010), giving further credentials to the notion of integration along these three perspectives. The following paragraphs provide a brief description of each I4.0 pillar, which are depicted in Figure 4.

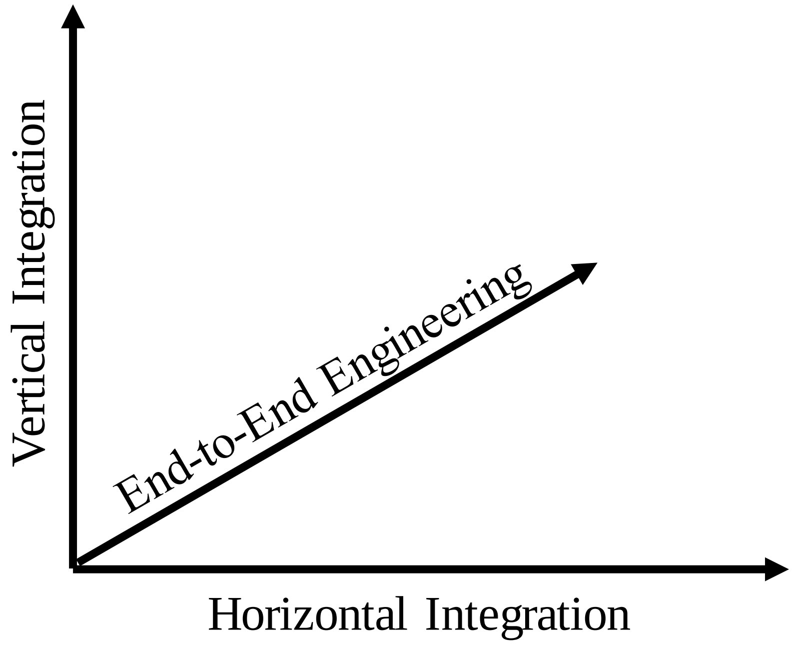

Figure 4. The three pillars of I4.0 (Köbnick et al., 2020)

Vertical integration

Vertical integration has been pursued for several decades, and it denotes the intra-company integration of the means of production across all hierarchy levels of the business towards a cohesive system (Kagermann *et al.*, 2013b; Schneider, 2018). Furthermore, these real-time interconnected systems are integrated with business processes to provide meaningful usage to the business (Kagermann *et al.*, 2013b). The general thinking of vertical integration itself is neither new nor unique to the concept of I4.0. However, a new aspect of vertical integration in I4.0 is the integration of information from things, most notably from products and work pieces, as they were not previously used to provide much data (Industrial Internet Consortium, 2017). As a consequence, the classical automation pyramid transforms towards a network with enhanced communication (Brettel *et al.*, 2014) (Figure 5). The vertical integration in a firm is largely driven through CPSs, the Internet of Things, as well as human–machine interfaces and data analytics coming closer to the shop floor (Kagermann *et al.*, 2013a; VDI and ZVEI, 2015; McFarlane, 2017).

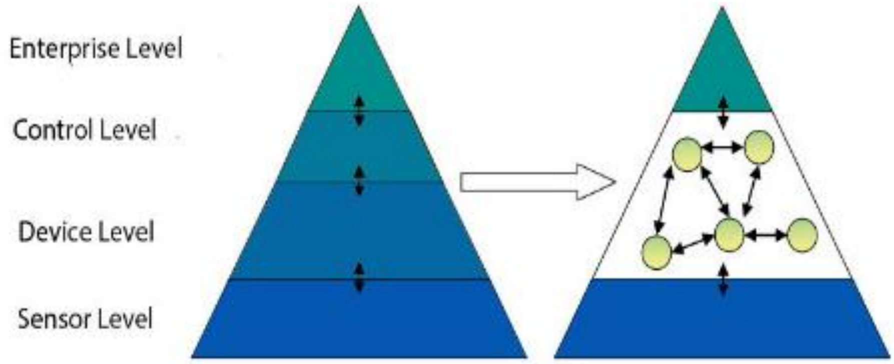

Figure 5. Resolution of the classical automation pyramid with enhanced communication (Brettel et al., 2014, p. 38)

Horizontal integration

Horizontal integration denotes the interconnection of all partners and processes within one factory's wall and beyond, across the entire value chain, between which material, energy or information flows (Kagermann *et al.*, 2013b; Schneider, 2018). A key enabler for horizontal integration is the use of the Internet of Things and Services in the entire value creation system (Bauernhansl *et al.*, 2016). The consequence of pursuing horizontal integration is the dynamic creation of value-adding networks (Kagermann *et al.*, 2013a; VDI and ZVEI, 2015). Despite a decreasing depth of added value in individual factories and firms, horizontal integration still enables the focal firm, via its network, to balance risks and combine resources to expand the scope of market opportunities (Brettel *et al.*, 2014). The Industrial Internet Consortium (2017, p. 5) adds that "importantly, the systems that impact your Smart Factory will not all be internal. External systems from weather networks, suppliers, logistics partners, and technology providers share data with internal systems to drive insight and to coordinate action."

End-to-end engineering

End-to-end engineering is the capability to weave design, manufacturing, engineering and supply chain functions together, for capturing, exploiting and leveraging data both ways across the entire value chain for meaningful use (Industrial Internet Consortium, 2017). This includes technical, administrative and commercial data. As these data are networked, they can flow and be used in inter-company networks, which may result in a seamless convergence of virtual and physical entities (Erol *et al.*, 2016). Data from design and production can, for example, be used for maintenance services in the field, where information and insights are often lacking; in addition, maintenance and usage data can be fed back to production or design for future process and product improvements (Brettel *et* *al.*, 2014; VDI and ZVEI, 2015). By exploiting these data with complex simulations and modelling of the real world, and using data from across the value chain, manufacturing firms can largely improve the overall efficiency of their manufacturing set-up and product quality while reducing asset downtime during service (Industrial Internet Consortium, 2017). Moreover, advanced visualisation and the context-sensitive providence of data via virtual and augmented reality is enabled, easing the collaboration within the value network between humans, software and machines (Brettel *et al.*, 2014).

By considering vertical integration, horizontal integration and end-to-end engineering to be the basic pillars of I4.0, the entire manufacturing system is represented (Kagermann *et al.*, 2013a). As the three pillars represent the internal and external organisational system, accountable for creating and delivering a customer value proposition, they could be considered a central component of the BM, as suggested by Demil and Lecocq (2010).

As noted above, these basic pillars are enabled by underlying technologies and infrastructures that mainly count as ICT; however, these individual technologies do not account for the revolutionary aspect of I4.0. The revolutionary notion stems from the multiple ways to rapidly combine and complement these technologies as appropriate (Porter and Heppelmann, 2014). Although multiple technologies are important, based on the literature, four key technologies shall be discussed:

First, CPSs, as an evolution of embedded systems, are integrated into physical objects, marking a key technology for connecting the virtual space with the physical reality with the aim of ubiquitous accessibility and exploitation of data to establish collaborative systems (Xu *et al.*, 2018). CPSs enable the acquisition and processing of data from the physical reality with an ability to self-control certain tasks and to interact with humans via interfaces (Brettel *et al.*, 2014). They consist of micro-controllers that control sensors and actuators, alongside a networking capability through communication infrastructures to exchange data and information among embedded computer terminals, wireless applications or internet clouds (Lu, 2017; Schneider, 2018).

Second, Internet of Things architectures enable the inter-networking of CPSs via the internet to connect them with other players in a value network for further usage (Zhong *et al.*, 2017). Wireless communication technologies play a significant role for this ubiquitous connectivity of physical objects, software systems, services and humans, as they enable the interconnectivity through remote internet access (Hermann *et al.*, 2016).

Third, these data are increasingly networked via internet clouds that further provide computational services for visualisation and data processing, enabling firms to expand their resources at short notice and purposefully, without investments in further capacities (Zhong *et al.*, 2017).

Fourth, cloud computing is especially valuable for the analysis of the large amounts of data gathered from ubiquitous sources and formats, as conventional processing power in firms is often not capable of processing these large amounts of data, which, moreover, is only required occasionally (Zhong *et al.*, 2017). Furthermore, advanced analytics may uncover hidden patterns or unknown correlations between very different types of data, such as customer preferences, market trends, machine parameters or even weather information (Zhong *et al.*, 2017). Thereby, analytics evolve from being descriptive to predictive and ultimately prescriptive (Hartmann *et al.*, 2016; Diab *et al.*, 2017).

Moreover, other scholars have included further technologies such as additive manufacturing, distributed ledger technologies, robotics and cobotics, and augmented and virtual reality, as auxiliary to I4.0 (Ghobakhloo, 2018). In general terms, the Fourth Industrial Revolution is enabled through a combination of various technologies. For this thesis, the predominant focus is on the four abovementioned key technologies; however, use cases that are primarily based on the key technologies but still use some of these additional technologies will also be considered.

These basic pillars and enabling technologies provide the basis for establishing "collaborative systems involving various communicating agents including physical agents, software agents, and human agents" (Xu *et al.*, 2018, p. 2948). However, a question remains: how do manufacturing firms create and capture sustained value from I4.0 and its associated technologies? This aspect is discussed in the next section.

2.2.4 Features and Potential Benefits

Views differ among authors about how manufacturing firms capture value from the increasing interoperability, virtualisation, decentralisation, real-time capabilities, service orientation and modularity (Frank *et al.*, 2019). Potential benefits can be grouped into three main categories: (1) operational improvements; (2) commercial opportunities; and (3) depolarisation of strategic decisions.

(1) Multiple scholars predict the benefits of I4.0 to be delivered mainly by the exploitation of data for *operational improvements*: by reducing the machine downtime by up to 45%, increasing the production volume by 20–25% (Wee *et al.,* 2015), reducing complexity costs by up to 70% (Bauernhansl *et al.*, 2016), or more generally through increased transparency and speed of decision-making based on real-time data (Müller and Däschle, 2018).

(2) Consideration is given to the emergence of *commercial opportunities* with an anticipated revenue rise of 23% (Hartmann, King and Narayanan, 2015). The main lever is expected to be provided by new product innovations with embedded sensors and actuators (Porter and Heppelmann, 2014). These smart, connected products create possibilities for interaction with the product beyond its point of sale in the form of (individualised) services for customers that yield a superior profit margin for manufacturers (Schneider and Spieth, 2013; Burmeister *et al.*, 2016; Weking *et al.*, 2018; Engländer *et al.*, 2019). In general terms, scholars contend that economies shift from a product- and output-orientated economy towards an economy where an outcome is sold with specific deliverables, such as the specific uptime of equipment (World Economic Forum and Accenture, 2015; Kans and Ingwald, 2016; Martinez *et al.*, 2017). Manufacturing firms who provide these outcome-orientated solutions do take over risk from their customers and turn them into business opportunities that yield higher profit margins (Ehret and Wirtz, 2017).

(3) A group of scholars discuss the *depolarisation of strategic decisions* that reduces the traditional gap between two presumably contrary decisions (Brettel *et al.*, 2014). Through developments along the three main pillars of I4.0, adequate measures are expected to be in place for technically and economically realising the formerly unimaginable manufacturing of a product with a batch-size of one at costs competitive with a mass-produced product (Kagermann *et al.*, 2013a; Burmeister *et al.*, 2016). Moreover, the contradiction between differentiation and cost-leadership strategy is predicted to attenuate (Burmeister *et al.*, 2016; Ibarra *et al.*, 2018; Engländer *et al.*, 2019). Similarly, authors advocate for I4.0 as a moderating mechanism between economies of scale and scope by using plants in low-wage countries, and increasing localisation of production, to provide the flexibility and speed of delivery that are demanded (Brettel *et al.*, 2014; Ibarra *et al.*, 2018).

Beyond these three categories, the literature suggests that companies achieve sustained benefits from investments in I4.0 by taking a holistic approach including the envisioning and executing of radically different ways of working (Westerman *et al.*, 2011; Spath *et al.*, 2013; Schneider, 2018). Different ways of working refers to a socio-technical perspective, in contrast to the substitution or extension of individual assets or processes with new technologies (Dalenogare *et al.*, 2018). Mastering these fundamental changes to a firm's organisational system (Brettel *et al.*, 2014) includes building new skills and competences, and also considering the maturity of the environment to which new technologies are introduced (Dalenogare *et al.*, 2018). Scholars argue that the modification of organisational structures and processes, as well as the development of the necessary employee skills and qualifications, have been understudied in the context of I4.0 (Spath *et al.*, 2013; Erol *et al.*, 2016b). At the same time, manufacturing firms have found it particularly challenging to pursue holistic changes, as few holistic I4.0 best practices exist for reference purposes (Burmeister *et al.*, 2016).

In fact, these substantial changes concern all dimensions of a firm's BM – its components and their orchestration – from a different value proposition, and changes in the organisational systems, to the resource and the competence base (Wee *et al.*, 2015; Demil and Lecocq, 2010; Velu, 2017). Hence, with a considerable consensus among the academic community, scholars from the I4.0 field articulate the need to adopt a BMI perspective for research on I4.0 (Burmeister *et al.*, 2016; Industrial Internet Consortium, 2017; OECD, 2017; Thoben *et al.*, 2017). The BM "provides a holistic perspective that allows managers to take an integrated view on their firm's activities" (Schneider and Spieth, 2013, p. 137). To further elaborate on this specific perspective, the next Section 2.3 briefly introduces the general field of BMI, then specifically examines the current academic discourse on I4.0-driven BMI.

2.3 Business Model Innovation: An Introduction

BMI as a concept and literature stream emerged in the early 2000s as a sub-field of the wider BM research. The notion of BMs can be traced back to the late 1950s. Initially the term was used non-specifically, before it became regularly used in the context of information technology (Wirtz *et al.*, 2016). Though it was not until the advent of the internet, and with it, the birth of the e-commerce in the mid-1990s, that the BM concept became prevalent in the literature field of strategic management (Ritter and Lettl, 2018), with a rapid increase of interest among practitioners and scholars alike (Chesbrough and Rosenbloom, 2002; Zott *et al.*, 2011). In addition to the strategy perspective, a particular driver for the emergence of the BM construct was that incumbent firms experienced great difficulties in managing innovations that were outside their former experience, since their previous beliefs and practices did not apply in these new contexts (Chesbrough and Rosenbloom, 2002; Zott *et al.*, 2011).

Several comprehensive literature reviews have attempted to structure the scattered BM research landscape, which developed from different motives, with disparate understandings of the topic among scholars; cf. Zott, Amit and Massa (2011); Massa, Tucci and Afuah (2017); Ritter and Lettl (2017); Wirtz *et al.* (2016); Schallmo (2013). As these comprehensive reviews contend, an increasing consensus among scholars crystallised to define a BM in line with a definition shaped by Teece (2010, p. 172), who defines a BM as “the design or architecture of the value creation, delivery, and capture mechanisms” of a business. Further, BMs are systems of interdependent activities that transcend the focal firm and span its boundaries (Zott and Amit, 2010; Velu, 2017).

The BM as an activity system provides the architecture for a business to create value for customers and appropriate a share of this value in terms of profit by orchestrating the four main components of a BM, which can be summarised as the 4Vs: (V1) the *value proposition* that a business delivers to customers in the form of its products and services (Richardson, 2008; Demil and Lecocq, 2010); (V2) the *value creation and delivery* system, including the resources, capabilities and processes required to deliver the value proposition (Richardson, 2008; Teece, 2010; Zott *et al.*, 2011); (V3) the *value capture* mechanism that describes how value is appropriated (Richardson, 2008; Teece, 2010; Zott *et al.*, 2011); and (V4) the *value network* of partners for the creation and delivery of value and for capturing shares of the value (Teece, 2010; Zott and Amit, 2010; Velu, 2017).

BM research is discussed from different angles, specifically from strategy, technology and innovation management perspectives (Zott *et al.*, 2011). Foss and Saebi (2017) cluster BM publications into three streams, where BM is seen as either (1) a basis for enterprise classification, (2) an antecedent of heterogeneity in firm performance, or (3) a potential unit of innovation. Following the call in the I4.0 field for taking on the BMI lens to expand the understanding of I4.0, this thesis adopts the view of a BM as a unit of innovation (Zott *et al.*, 2011; Foss and Saebi, 2017).

A central function of a BM from the technology and innovation perspective is to unlock the "value potential embedded in new technologies and [convert] it into market outcomes" (Zott, Amit and Massa, 2011, p. 1032). This perspective entails the (re-) configuration of the BM owing to macro-level impacts, including globalisation and internet technologies (Casadesus-Masanell and Ricart, 2010; Massa *et al.*, 2017) or the blurring distinction between industries that lowers barriers to entry (Wee *et al.*, 2015). One can argue that capturing value from I4.0 for manufacturing firms is accordingly subject to an efficacious adaptation of their BM, as "there is almost no chance of business success [without BM adaptation] – get it right […] and it will contribute to the firm's competitive advantage" (Teece, 2010, pp. 191).

When switching from BM to BMI literature, the main key word is change (Hock, Clauss and Schulz, 2016). Explicit attention on BMI has only emerged in recent years, from academic scholars and practitioners alike, as a given BM cannot be perceived as permanent due to dynamic developments (Schneider and Spieth, 2013). Although BMI in academic discourse can be traced back to the work of Mitchell and Coles (2003, 2004a, 2004b), it is only relatively topical that it has become an outgrowth of the BM literature. Recently, Foss and Saebi (2017) provided an extensive examination of the literature on BMI, finding a lack of construct clarity with gaps in identifying conditions that preceded BMI, alongside missing contingencies and gaps in the understanding of BMI outcomes. Complemented by work of Schallmo (2013), Schneider and Spieth (2013) and Spieth *et al.* (2014), these reviews bring some structure to the scattered academic discussion.

Table 2. Selected definitions of BMI

Reference	Definition
Mitchell and Coles (2004a)	"By [BMI], we mean [BM] replacements that provide product or service offerings to customers and end users that were not previously available. We also refer to the process of developing these novel replacements as [BMI]." p. 17
Santos *et al. (*2009)	"[BMI] is a reconfiguration of activities in the existing [BM] of a firm that is new to the product/service market in which the firm competes." p. 14
Johnson (2010)	Seizing the white space "calls for the ability to innovate something more core than the core, to innovate the very theory of the business itself. I call that process [BMI] […] [BMI] is an iterative journey." p. 13 & p. 114
Demil and Lecocq (2010)	"The observable sign of BM evolution is a substantial change in the structure of its costs and/or revenue – from using a new kind of resource, developing a new source of revenues, re-engineering an organizational process, externalising a value chain activity – whether [triggered] deliberately or environmentally. Usually such changes also lead to cost/revenue *volume* changes, but these aren't, in themselves, BM changes […] it's *structural* changes in these dimensions that are the first 'symptom' of BM evolution." [emphasis in original] p. 235
Amit and Zott (2012)	BMI can occur in three ways: (1) by adding novel activities, also perceivable as new activity system '*content*'; (2) by linking activities in novel ways, also perceivable as new activity '*structure*'; (3) by changing one or more parties that perform any of the activities, also perceivable as new activity system '*governance*'. p. 44
Evans and Johnson (2013)	"[BMI] often requires that multiple functions – not just technology and manufacturing – actively participate in their own reinvention." p. 52
Velu (2015)	BMI "involves systematic change across the value proposition, value creation and value capture approaches." p. 3
Burmeister *et al.* (2016)	"We define BMI as the (dynamic) generation process and initial implementation of a (static) BM, which is new from the perspective of the company or target market." p.128
Foss and Saebi (2017)	"We define BMI as 'designed, novel, and nontrivial changes to the key elements of a firm's [BM] and/or the architecture linking these elements.'" p. 201

* BM: Business model; BMI: business model innovation

The BMI literature can largely be distinguished into two disparately evolving perspectives: dynamic and static (Spieth *et al.*, 2014; Foss and Saebi, 2017). Authors that take a *static* stance view BMI either as new types of innovative ventures resonating from organisational change processes or as a source of firm performance. Authors taking a *dynamic* perspective view BMI as an organisational change process that requires specific capabilities, leadership or learning mechanisms. This thesis adopts the dynamic perspective to deepen the understanding of I4.0 for manufacturing firms, as I4.0 scholars explicitly call for research into the implications of modifying organisational structures and processes alongside the development of necessary employee qualifications in the realm of I4.0 (see also the detailed account on dynamic BMI in Section 2.5).

With reference to Table 2, a working definition of BMI shall take the dynamic perspective; the key essence of dynamic BMI are substantial (Demil and Lecocq, 2010), systematic

(Velu, 2015), structural changes (Demil and Lecocq, 2010) to the key elements of a BM (Evans and Johnson, 2013; Foss and Saebi, 2017) or the linkage between the key activities (Amit and Zott, 2012). Considering the working definition and four key components of a BM, a working definition of BMI for this thesis can be as follows:

> *A BMI is a designed, novel change to the key elements of a firm's BM or the architecture linking these elements. These changes to the activity system may affect key activities within the value proposition, value creation or value capture mechanism itself, linkages between activities, or changes in the value network comprising a change of activity ownership.*

This working definition inherits an important notion for the remainder of this thesis – although large parts of the BMI research have focused on new BMs within start-ups (Santos *et al.*, 2009), this thesis perceives BMI as changes to an existing BM of an incumbent manufacturing firm.

With a working definition in hand, and I4.0 scholars' call for a BMI perspective on the I4.0 phenomenon in mind, now the existing literature on I4.0-triggered BMI is examined to gain a better understanding about the progress of the discourse. Then the dynamic BMI literature that contributes to the discussion about I4.0-driven BMI is studied.

2.4 Industry 4.0-driven Business Model Innovation

Although the interest of scholars in the interface of the two phenomena BM(I) and I4.0 is increasing, literature discussing specifically this field is nascent and largely scattered (Kiel *et al.*, 2016; Müller, Buliga, *et al.*, 2018; Schneider, 2018). I4.0-driven BMI attracts scholars from multiple disciplines, including information systems, engineering, management and innovation, though many studies only touch loosely on the topic of discussion.

Based on a systematic literature screening, the literature can be grouped into three main themes: (1) definition and boundaries of I4.0; (2) impact of I4.0 on BM elements; (3) approaches to I4.0-driven BMI. The remainder of this chapter is organised along these three themes, concluded by a brief discussion about the shortcomings of this literature on I4.0-driven BMI.

2.4.1 Definition and Boundaries

With the public spread of the World Wide Web in the 1990s, companies developed new ways of doing business, widely discussed using the term *e-commerce BM* (Spieth *et al.*, 2014). E-commerce BMs mainly focus on new distribution channels alongside revolutionary ways in which companies interact with their supply chain partners, customers and employees (Bärenfänger and Otto, 2015; Luz Martín-Peña *et al.*, 2018). The revolutionary, wide-ranging character of e-commerce BMs, which is similar for digital BMs, originates from the properties of digital data, that (1) can be replicated with the same quality at merely zero marginal costs, (2) can be communicated via the internet in near-real-time speed across the globe (Iansiti and Lakhani, 2014; Brynjolfsson and McAfee, 2016). By means of the new Internet Protocol IPv6 in combination with CPSs, smart objects arise with the ability to ubiquitously communicate and cooperate with one another, thus creating a networking of resources, information, objects and people (Kagermann *et al.*, 2013a; Luz Martín-Peña *et al.*, 2018). The increasing incorporation into operational activities and business management practices enables fundamentally different ways of working for manufacturing firms (Luz Martín-Peña *et al.*, 2018).

As the examination of the concept of I4.0 has demonstrated, the Internet of Things is a central component of the I4.0 paradigm. Further key aspects include CPSs and end-to-end engineering. Based on the working definitions of I4.0 and BMI for this thesis, an I4.0-driven BMI is an organisational change process in a manufacturing firm that is driven through the revolutionary essence of digital technologies and takes advantage of them – for internal operations as well as for enhancing products and services (cf. digital BM in Bärenfänger and Otto, 2015).

Accordingly, an I4.0-driven BMI is a significantly new way to propose, create or capture value along the manufacturing value chain by extending, complementing, merging or substituting primarily physical resources, information, objects, processes and human labour. It embodies the fundamental properties of digital technologies – replicability with the same quality at near zero marginal costs, communicable across the globe in near-real-time (Brynjolfsson and McAfee, 2016).

2.4.2 Impact of I4.0 on BM Elements

The main point of discussion in academic literature is the impact I4.0 may have on the individual components of a manufacturing firm's BM. Referring to the three BM design themes – content, structure and governance (Amit and Zott, 2001) – several studies discuss changes to the content of a BM through I4.0-driven BMI. In recent years, a few empirical studies have explicitly examined the impact of I4.0 on BM components. In their review on I4.0 and BM(I), Kiel *et al.* (2016) found that studies at this intersection are predominantly about impacts and changes associated with key resources and key activities, followed by the value proposition. New target customers, alternative revenue models, cost structures or distribution channels play a subordinate role in concurrent academic discussion (Arnold *et al.*, 2016; Kiel *et al.*, 2017). Below is a discourse organised along the 4Vs, i.e. the four BM components.

Value proposition

A basis for subsequent changes in value propositions are smart, connected products. These are products equipped with a selection of sensors, actuators, processors, connectivity and cloud interfaces and were named "smart, connected products" in Porter and Heppelmann's (2014) widely recognised work. The possibility to remotely interact with these smart, connected products opens up an infinite range of highly customised services based on simulations, data mining and data analytics (Kagermann *et al.*, 2013a; Porter and Heppelmann, 2014). Accompanied by these innovative services, products and services increasingly fuse to provide customers with solutions on the basis of agreed outcomes instead of separated product and service sales (Arnold *et al.*, 2016; Kiel *et al.*, 2017). Intensified customer interactions, for and based on highly individualised products and services, pave the way towards a batch size of one, accounting for the ubiquitous trend of individualism (Burmeister *et al.*, 2016). Some authors perceive these developments as logical pathways towards new customer segments and markets (Ibarra *et al.*, 2018; Müller, 2019). Similarly, new value propositions are expected through improved delivery of existing products and services, for example through direct customer delivery by the manufacturer – skipping retailers – named B2B2C by Burmeister *et al.* (2016).

Value creation

Given the changing value propositions as outline above, manufacturers' value-creating activities need to become more flexible, especially being able to create individual product-service bundles and produce them as a batch size of one (Brettel *et al.*, 2014; Arnold *et al.*, 2016). The integration and interoperability of employees, machines, systems and products on the basis of real-time access to information along the entire value chain play a key role in this flexibility (Kagermann *et al.*, 2013a). Interoperability serves as a basis for a flexible customisation, as a real-time picture of orders and processes is available (Arnold *et al.*, 2016). An individualisation of products and production can be achieved by a focus on modularisation (Burmeister *et al.*, 2016; Ibarra *et al.*, 2018), as well as a virtualisation through advanced simulations (Brettel *et al.*, 2014). Input for individual customer demands is further generated from using ubiquitous sources and types of data, including information and data directly obtained from customers, but also through the analysis of data sources including publicly available social networks or new customer touchpoints (Kiel *et al.*, 2016; Ibarra *et al.*, 2018).

Despite the technological impact on the value creation and delivery system, multiple scholars explicitly point out the importance of human beings for such flexible value creation processes, especially with respect to our creativity for problem solving and our decision-making ability (Kiel *et al.*, 2016). However, to account for the required speed of action for rapid customer deliveries, these skills need to shift from a supervisor level towards the shop-floor and engineer level (Müller, Buliga, *et al.*, 2018), requiring an increased need of college-level education (Kiel *et al.*, 2017) or continuous learning and training on the job (Spath *et al.*, 2013).

Essential skills include specific domain knowledge for the increasingly important IT infrastructure, networks and the like, to realise and ensure both inter- and intra-company connectivity (Müller, Buliga, *et al.*, 2018; Müller, 2019), as well as to build knowledge around data sourcing, data processing and data analytics as well as data-based decision-making (Arnold *et al.*, 2016; Kiel *et al.*, 2016). Intertwined with these skills, software knowledge is especially important for the development of user interfaces to improve human–machine interactions (Kagermann *et al.*, 2013a).

Value network

Rapidly changing value propositions, and the value creation of individualised products and services, force manufacturing firms to seek alliances for being able to react swiftly but profoundly, with partners upstream and downstream, as well as entirely new partners (Kiel *et al.*, 2017; Müller, 2019). Manufacturers treat customers increasingly as equal partners, resulting in intensified communication and collaboration in various fields, including product conceptualisation for a co-creation of value to enable individual solutions (Schuh *et al.*, 2014). Similarly to the developments on the customer side, firms intensify their collaboration with key partners, mostly to complement their existing capabilities with data or software, to jointly develop products and services that are individual to customers or can be individualised by them (Müller, Buliga, *et al.*, 2018). The shift towards smart and connected product-service solutions, new distribution channels and alternative methods for customer interaction further result in changes of the supply chain structure, including power shifts within the supply chain towards actors that have access to sensitive customer data (Weking *et al.*, 2020). The latter are predominantly fuelled by the access to real-time information spanning company boundaries (Kiel *et al.*, 2016).

Value capture

Despite the significant changes expected in manufacturing firms' value propositions with remote, data-based services and products as a service, as well as an increasing collaboration with partners, considerations about changing value capture mechanisms are largely underrepresented in manufacturing firms and academic literature alike (Arnold *et al.*, 2016; Burmeister *et al.*, 2016). However, as the revenue mechanisms seem to remain widely untouched by manufacturing firms, they may fail to appropriate their share of additional value created (Müller, 2019). The main facets for capturing value from I4.0 are more efficient operations, lower development costs and also lower transaction and complexity costs (Bauernhansl *et al.*, 2016; Weinberger *et al.*, 2016; Müller, Buliga, *et al.*, 2018). However, while these facets mainly consider the utilisation of isolated I4.0 solutions to optimise the current flows of materials and information, they neglect the potential to generate new revenue flows based on smart, connected products, smart services, or a more flexible manufacturing set-up. Changes may include the cycle of payments from one-off to continuous in the form of subscriptions, or revenue models like pay-per-feature or pay-per-output, rather than the entire product being paid for (Ibarra *et al.*, 2018; Müller, Buliga, *et al.*, 2018; Weking *et al.*, 2018). Other authors even describe increasing costs based on investments in data quality, obtaining key resources and large expenses for IT (Arnold *et al.*, 2016; Müller, 2019).

The discussion about the changes that I4.0 brings to a manufacturing firm's BM provides limited support for managers in manufacturing firms in how to choose what "change" is suitable for the focal firm. Moreover, these content-focused studies examine changes to the BM components driven by I4.0 mostly in isolation, with limited consideration of the implications that changes in one BM component may have on other activities in the BM, or how manufacturing firms may innovate their BM holistically based on I4.0 principles. Research clearly lacks a more systematic discussion of the holistic implications that the new value propositions driven by I4.0 have for the other three BM components, and how manufacturing firms may holistically manage the changes and interdependencies (Demil and Lecocq, 2010) to appropriate sustainable value from their I4.0 activities.

2.4.3 Approaches to I4.0-driven BMI

Another stream of studies discusses how manufacturing firms should approach I4.0-driven BMI. This stream of literature can be grouped into three main areas of discussion: BM transformation processes; maturity models and other tools; and organisational aspects.

BM transformation processes

Several studies propose specific processes for innovating a manufacturing firm's BM based on I4.0 principles. Some studies suggest performing a generic analysis of the current BM, then generating ideas, and developing and implementing a new BM (Rudtsch *et al.*, 2014; Kaufmann, 2015; Burmeister *et al.*, 2016; Sathananthan *et al.*, 2017). In contrast, other approaches emphasise the importance of a firm's position within its ecosystem for developing ideas for changing the BM (Paulus-Rohmer *et al.*, 2016; Kölsch *et al.*, 2017). Comparing the proposed transformation approaches, only a few acknowledge the need to incorporate a feedback mechanism in a BMI process to account for emerging difficulties, and the need for a change-management process for the organisation (Paulus-Rohmer *et al.*, 2016).

However, all approaches have in common that they describe formal processes following a rather project-orientated nature, neglecting that a BM underlies constant change, requiring continuous adaptation of the BM components and their interdependencies, which is a strategic task (Demil and Lecocq, 2010).

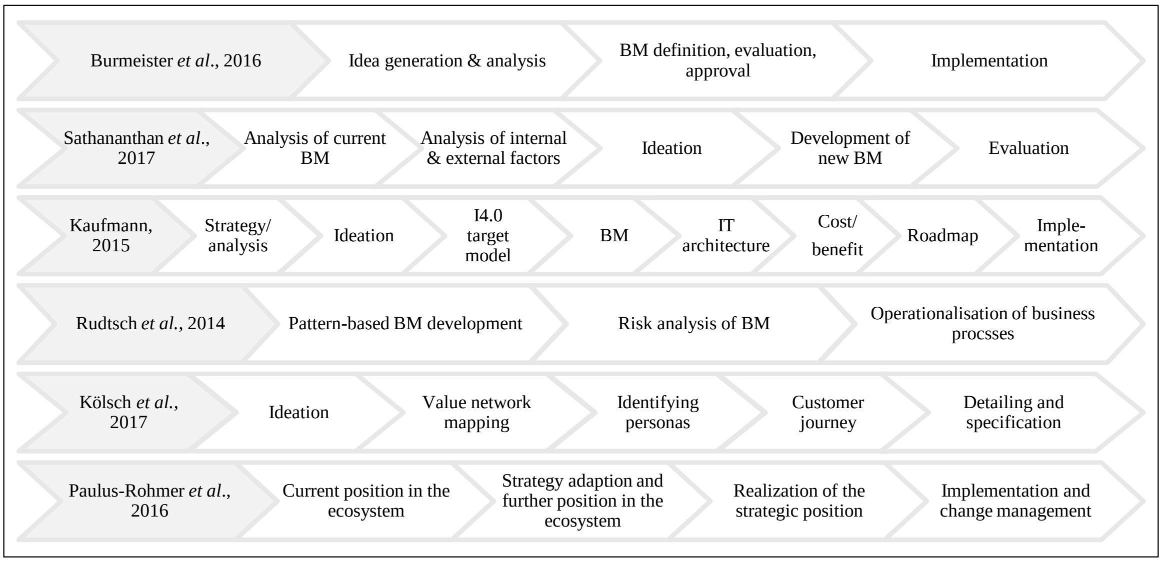

Figure 6. Selected I4.0-driven BM transformation approaches according to different authors

Maturity models

Some authors propose stepwise guidance for the implementation of I4.0 by means of maturity models that provide steps for progressing in various dimensions (Kaufmann, 2015; Schuh *et al.*, 2017). Such maturity models are tools to assess the current I4.0 ability of a manufacturing firm in various disciplines and map it against a predetermined ideal ability level. Hence, for each discipline, pre-fixed, discrete steps to improve performance are proposed. However, these models do not take on a specific BM lens; merely for isolated aspects of a BM, with a strong focus on value-creating activities, systematic I4.0 development trajectories are proposed. One study attempting to develop a maturity model that integrates I4.0 and BM was presented by Rübel *et al.* (2018). Their study lies out interesting, has however significant methodological shortcomings. They do not provide evidence, how dimensions were derived or detailed; neither based on academic literature nor through empirical evidence.

The outlined BM transformation approaches and maturity models may provide limited assistance to manufacturing firms in terms of high-level process steps on their way towards their I4.0-driven BMI. However, without explicitly noting it, all approaches take a static view on BMs. As they take this static view on BMs, they fail to capture the interdependence of activities, which is especially important when new technologies and other changes are introduced in specific components of the BM, as they have an impact on other components.

Organisational aspects

The literature barely provides insights on organisational implications for I4.0-driven BMI. Only two studies provide some evidence for organisational aspects that support I4.0-driven BMI. An empirical in-depth case study of a medium-sized manufacturer's I4.0-driven BMI attempts denotes the change of existing processes, extensive communication and managers as important aspects of I4.0-driven BMI (Müller, Traub, *et al.*, 2018); however, despite mentioning these organisational aspects, it also takes a rather static view of BMI and does not provide further details or an explanation of how these organisational aspects link to other aspects of an I4.0 journey. The second study takes a static view of BMI and regards it as the process of developing and initially implementing a BM that is new to a firm (Burmeister *et al.*, 2016). It does provide evidence that developing new I4.0-BMs should be facilitated by a dedicated I4.0/BMI team that is led by top management with sufficient power and breadth of control. Moreover, a culture like a start-up with a good cross-functional collaboration is seen as supportive for developing new I4.0-BMs.

In summary, the examined approaches to I4.0-driven BMI barely provide insights into achieving alignment across activities during the process of innovating an existing BM in the course of I4.0, which is, in particular, due to their rather static view on BMI. Accordingly, these approaches are insufficient to answer the posed research question on dynamic consistency.

2.4.4 Section Discussion and Summary

While the existing literature provides detailed accounts for content-related changes to incumbent firms' BMs driven by I4.0, few insights about organisational aspects that discuss structural or governmental changes peculiar to I4.0-driven BMI or the interdependencies of activities have been found.

Despite most studies taking a static view on BMI, many remark on the importance of the interrelation between the activities and components in the context of I4.0-driven BMIs and demand holistic perspectives (Arnold *et al.*, 2016; Kiel *et al.*, 2016; Ibarra *et al.*, 2018; Müller, Kiel, *et al.*, 2018).

However, only two studies explicitly examine the notion of interrelation. Kiel *et al.* (2017) distinguish direct and indirect relationships, e.g. a change in the value proposition directly triggers changes in the value configuration. Only the latter then directly triggers change in a firm's core competencies. The second study, conducted by Prem (2015), claims that a development triggered by I4.0 in one BM component generates causal effects in other components in turn. To support his claim, Prem presents a graphical BM depiction showing causal relationships between BM components based on induced I4.0 changes. These relationships are derived from 15 examples of BMIs based on digitalisation. However, these BMIs lack an adequate description; the author merely presents his own assessment of affected components, without any description of how these were derived. Additionally, this study lacks a profound analysis and discussion of the claimed causal relationships. Hence, the study sets out an interesting idea, but lacks methodological rigour.

The academic literature lacks a comprehensive review of I4.0-triggered BM changes, as not a single article examined I4.0-triggered change on all nine dimensions of the BM canvas (Kiel *et al.*, 2016). In addition, Arnold *et al.* (2016) report that I4.0-infused changes to the core activities are mainly observed in manufacturing activities and the intensification of customer interactions, but rarely in other BM activities. This claim is reflected in the nearly non-existent attempt of manufacturing leaders to think about new revenue models, different distribution channels, new target customers or alternative sourcing models for a changing cost structure (Arnold *et al.*, 2016).

In summary, existing (I4.0-) BMI approaches, such as the widely used static BM canvas, fall short of encompassing the complexity of the interdependence between BM components and actors across the ecosystem (Klein *et al.*, 2017). In particular, with respect to Demil and Lecocq's (2010) thinking about dynamic consistency, the current body of knowledge provides almost exclusively static views on I4.0-driven BMI. Although the studies revealed the existence of direct and indirect relations, authors' advice for manufacturing firms focus on ideas how to use I4.0 to answer challenges within single BM elements. The literature remains silent on providing manufacturing companies with insights into how they can actively manage consistency among their BM components (i.e. determine what factors should be considered to determine the consistencies in the BM system) and, more importantly, provide ways of resolving inconsistency.

2.5 Dynamic Business Model Innovation: A Complex Activity System

The literature examination of I4.0-driven BMI showed a lack of understanding of the complex interactions between BM components and their constituting activities in an I4.0-driven BMI (Ritter and Lettl, 2018), and a lack of understanding of organisational aspects that may support an I4.0-driven BMI. In addition, the I4.0 related Section 2.2 and Section 2.4 revealed that digitalisation is a complex undertaking for manufacturing firms, as most changes in multiple dimensions of a firm take place at the same time, requiring a holistic management throughout the organisational change process (Kagermann *et al.*, 2013a).

In particular, the emerging stream of literature around the dynamic BMI perspective and perceiving a BM as an activity system, as adopted for this thesis (see Section 2.3), may inform the understanding of how interdependencies of activities in an I4.0-driven BMI can be managed. Two distinct and acknowledged literature reviews clustered the BMI field and denoted the dynamic BMI perspective as a promising field to advance understanding of organisational changes processes (Schneider and Spieth, 2013; Foss and Saebi, 2017). Studies taking a dynamic perspective view BMI as an organisational change process that requires specific capabilities, leadership or learning mechanisms (Foss and Saebi, 2017). The static perspectives discussed in the literature, including theorising about the scope and novelty of BMI, achieving construct clarity, the outcomes of BMI with respect to financial performance, or the development of new BMs in start-up firms (Spieth *et al.*, 2014; Foss and Saebi, 2017; Ritter and Lettl, 2018), were found to be less helpful in informing the understanding of interdependencies in an ongoing BMI process.

Following Baden-Fuller and Morgan (2010), any of these BM(I) views focusses on different characteristics and thereby produces a different set of classes and possibilities for classification that may change over times, similarly to ideas and knowledge about things in the world develop over time. Similarly to knowledge that develops over time, some scholars view a BMI rather as a cognitive structure (Foss and Saebi, 2017), that provides the theory of how firms create value, position themselves in an ecosystem, and how they organise themselves (Doz and Kosonen, 2010). Viewing a BMI as a cognitive schema therefore essentially focusses on the cognition of managers (Foss and Saebi, 2017). The underlying principle of this cognitive perspective is that managers do not hold real systems in their mind when they take decisions, but rather *images* of real systems (Massa *et al.*, 2017). These images are modelled by manager's cognition and link the physical domain to an economic domain (Chesbrough and Rosenbloom, 2002).

Understanding these interdependencies among the activities in an I4.0-driven BMI requires a holistic perspective on the respective BM. The articulated holistic nature of BMI in incumbent firms is reflected in an emerging academic debate on perceiving dynamic BMI as a complex system of interdependent activities (Demil and Lecocq, 2010; Zott and Amit, 2010; Velu, 2017); particularly the consideration of changes in interlinked, boundary-spanning activities and their interdependent effects, whereby BMI connects elements of corporate strategy, technological capabilities and innovation processes of a business (Spieth *et al.*, 2014). The following sections present a discussion of BMI as an activity system, followed by insights on how dynamic BMI may inform the understanding of how manufacturing firms manage the interdependencies across their BM throughout an I4.0-driven BMI.

2.5.1 BMI as an Activity System

Originating from discussions in strategic management, the perception of a BM as a set of activities was only recently introduced by Zott and Amit (2010), defining an *activity* in a focal firm's BM as "the engagement of human, physical, and/or capital resources of any party to the BM […] to serve a specific purpose toward the fulfilment of the overall objective." Activities serve as the basis of understanding what a business does, and as such are the building blocks of the BM and therefore central to all other perspectives (Ritter and Lettl, 2018). This follows the notion of Porter (1991), who states that the elemental role of firms is to configure their activities and understand how they interrelate. Since activities are orchestrated and interrelated, a set of interdependent organisational activities of a specific firm may be defined as an *activity system* – this includes activities carried out by the firm, its partners, vendors or customers, and may also be extended beyond the boundaries of the firm (Zott and Amit, 2010). The purpose of the activity system is to make economic sense, since it constitutes the logic for the value creation and appropriation of a share of the created value (Ritter and Lettl, 2018).

A complex system

Taking into account the delineation of a BM into an activity system highlights the complexity of a BMI as it encounters major holistic changes to an incumbent firm's established activity system (Casadesus-Masanell and Ricart, 2010). A system is complex, once the interactions among the activities of the systems, and the interaction between the system and its environment, are of such a nature, that the system cannot be fully understood by analysing the activities. This definition is in contrast to a complicated system that can be described in terms of its individual activities (Uhl-Bien *et al.*, 2007). Key to the understanding of such activity systems is the notion of interdependencies, as Uhl-Bien *et al.* (2007, p. 310) nicely explain: "interaction alone is insufficient for complex functioning; the agents in a system must also be interdependent. While interaction permits the movement and dynamic interplay of information, interdependency creates pressure to act on information. Interdependency's potency derives from naturally occurring (emergent) networks of conflicting constraints." Two or more activities that are interdependent influence each other in the sense that some change in Activity A imposes a change in Activity B (see Figure 7). The imposed change may have a positive, neutral or negative effect. As negative effects are based on conflicting constraints, a reduction of these conflicting constraints may lead to a higher degree of alignment between these activities, which is also acknowledged to lead to an optimisation of the BM (Porter, 1991; Ritter and Lettl, 2018). When a BMI achieves a higher degree of alignment, it consists of a coherent set of reinforcing selections (Morris *et al.*, 2005). Negative effects or mismatches occur when activities have contrary adverse or conflicting effects on other activities (Berends *et al.*, 2016).

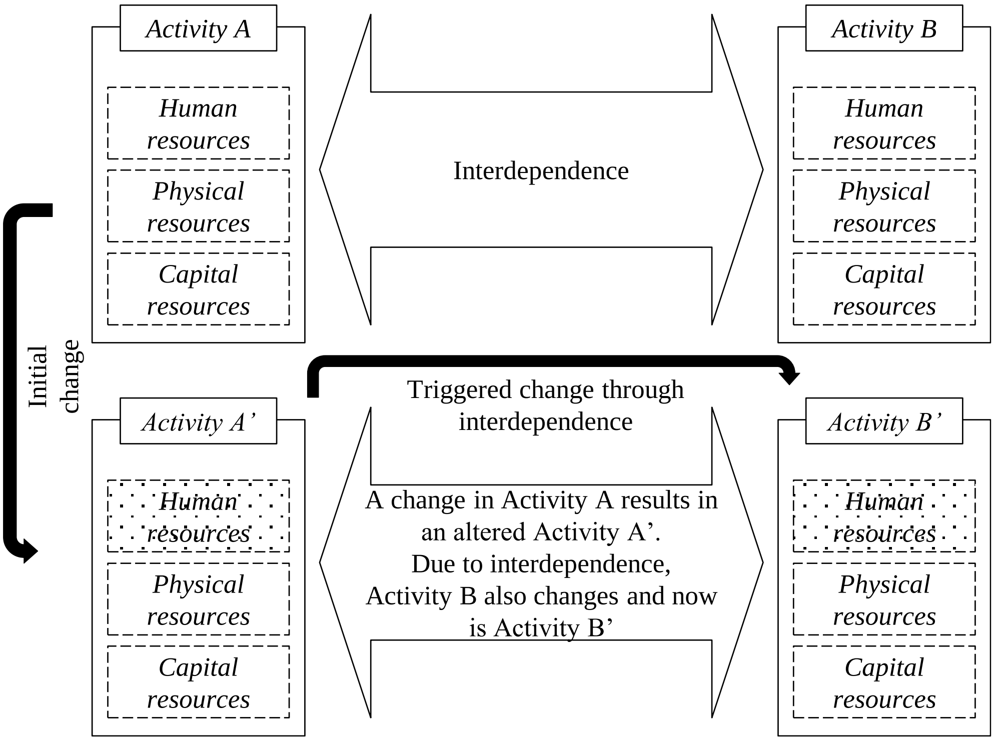

Figure 7. Sketch of activity interdependence in an activity system; author's own depiction

BMI considered as a complex system

Following Levinthal (1997), Fleming (2011), and Simon (1962, 1973), a BMI can therefore be conceptualised as a complex system (cf. Foss and Saebi, 2017). Siggelkow (2011) adds that two elements are interdependent if the value of one activity depends on the presence of the other activity, which clearly holds true for a BMI. Moreover, two activities mutually reinforce each other if the value of both activities is raised by the presence of the other activity – the two activities are then complementary to each other (Siggelkow, 2011). This interdependency is what classifies activity systems, and hence BMIs, as complex systems (Velu, 2017). The system perspective encourages one to "look at the forest of interdependencies and not only the trees" when changing the BM (Halecker and Hartmann, 2013). In other words, a system perspective encourages systemic, holistic thinking rather than a concentration on isolated choices (Zott and Amit, 2010), making the perspective of BMI as an activity system a promising lens to inform the posed research question that incorporates the difficulty of manufacturing firms to holistically integrate I4.0 in their BM, beyond the mostly observed isolated choices.

Another effect of the interdependencies in a complex system is that there is not only one optimal solution as demonstrated by Levinthal (1997). Rather, there are likely to be several optimal configurations of activities with a nearly equivalent performance (cf. equifinality in complex systems theory), which, in a sense, is in line with the notion of dynamic consistency as the continuous search for the best configuration (Demil and Lecocq, 2010), and Porter's (1991) finding that the specific configuration of a firm's activities forms the basis of competitive advantage.

Besides the interdependency of elements, and with specific regard to perceiving BMI as a complex system, Velu (2017) further defines four key characteristics of complex systems that apply to BMI: (1) *Distinctions* can be made among BM components, thereby the boundary of a BMI can be distinguished. (2) *Sub-systems* can be distinguished, as activities and BM components are organised in higher-level sub-systems, whereby the entire system and also the sub-systems can be classified as systems. This enables a micro- and macro-level perspective for understanding and analysing the entire complex phenomenon. (3) *Relationships* exist between the parts of the system, in the form of feedback loops, correlations or causalities. (4) *Perspectives*: the parts of the system and their relationships can be perceived from different perspectives, giving them different meanings at different times.

BMI defined as a complex system of activities

Following this distinction, BMI as an activity system further comprises the four distinct BM components, as interdependent organisational sub-activity systems with a focus on the focal firm and its partners for creating and capturing value (Zott and Amit, 2010; Velu, 2017). These four sub-activity systems are, namely, the 4Vs: value proposition, value creation, value capture and value network. BMI as an activity system is further characterised by three design elements that provide different perspectives on the BM and the BMI, as depicted in Figure 8: content, structure and governance (Amit and Zott, 2001; Zott and Amit, 2010):

(1) The activity system *content* relates to the selection of activities that are performed, answering the questions of what activity arrangements ensure appropriate exchanges of material goods and information, and what resources and capabilities enable this.

(2) The activity system *structure* refers to the linkage of the activities, answering the questions of how the activities are interlinked, in what sequence and of what importance, and how material and information are exchanged to achieve alignment across the activities to strive for similar objectives;

(3) The activity system *governance* refers to who performs the activities and who holds decision-making authority to change flows of information and materials for (re-) linking activities, or to change the selection of activities. Moreover, governance is about the incentive system for actors in the system.

In addition to these three commonly used design themes, Santos *et al.* (2009) proposed "organisational units that perform the activities" as a fourth aspect. However, as activities comprise human resources, organisational units can be considered as inherited in activities.

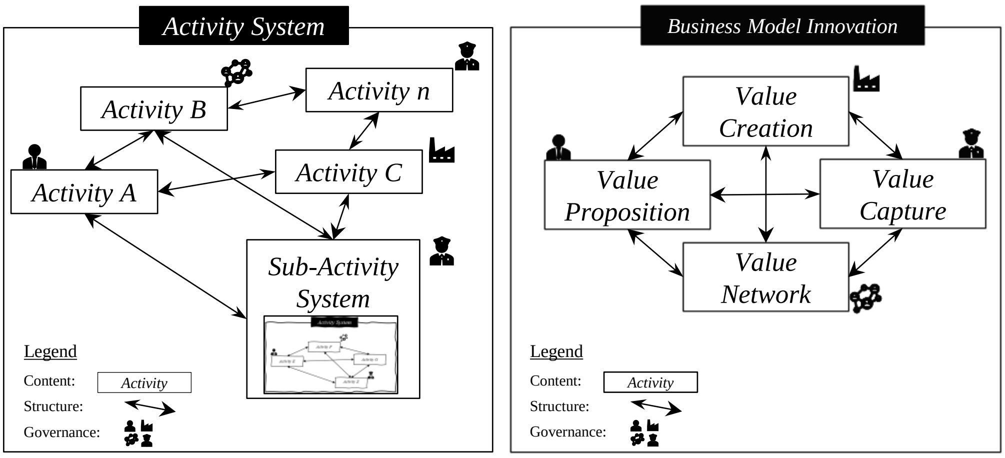

Figure 8. Schema of the business model as an activity system; based on synthesised ideas of Velu (2017), and Zott and Amit (2010)

Changing a complex system

The change of these complex systems, as encountered by BMI with possible changes in multiple dimensions that may yield an optimal configuration, can usually be either architectural or modular (Foss and Saebi, 2017). Modular changes imply changes within the boundary of a BM component (e.g. changing the mechanism by which value is created or changing the sub-system by which value is captured). Architectural changes refer to fundamental changes in the architecture of a BM. The architecture is a metaphor for the interplay between the single components of a BM, which ideally should be aligned with each other. Siggelkow (2011) defines four architectural change processes: (1) *thickening*, reinforcing of existing activity by elaborating new activity; (2) *patching*, creating a new core activity and its reinforcement by new elaborating activities; (3) *coasting*, no further elaboration of a new core activity in a given period; and (4) *trimming*, deleting a core activity and its elaborating activity. Following Siggelkow (2011) further, core activities are those that interact with many other current or future activities. Accordingly, the notion of interaction among activities plays a key role in identifying these core activities. Other authors present a similar typology, translated to BMI, that further accounts for the importance of interactions as every BMI involves a reconfiguration of activities: (1) *relinking*, defined as an alteration in the connections between organisational units that currently perform certain activities; (2) *repartitioning*, defined as a change in the physical, cultural, or institutional boundaries of the organisational units that currently perform certain activities; (3) *relocating*, defined as a change in the distance – physically, culturally, or institutionally – between organisational units that currently perform certain activities; (4) *reactivating*, defined as an alternation of the set of activities that constitute the current BM of the firm (Santos *et al.*, 2009).

As both typologies indicate, the scope of a BMI often entails both changes, modular and architectural, at the same time (Foss and Saebi, 2017). Likewise Velu (2015, p. 3) argues that BMI "involves systematic change across the value proposition, value creation and value capture approaches", and Evans and Johnson (2013, p. 52) add that "business model innovation often requires that multiple functions – not just technology and manufacturing – actively participate in their own reinvention." These descriptions of BMI point to the complexity that comes with any changes in a firm's BM, as the entailed reconfigurations have implications for multiple internal and external processes and stakeholders.

Adapting a system of tightly coupled activities in response to environmental changes is a challenge for incumbent firms. On the one hand, a strong interdependence of activities is prone to increased inertia and resistance to change as the resources have been developed and honed; on the other hand, a tight coupling might increase managements' sensitivity to optimally configure their activities (Zott and Amit, 2010; Siggelkow, 2011). Thus, finding a balance between remaining flexible and being perfectly aligned is challenging but essential (Velu, 2017; Ritter and Lettl, 2018). Demil and Lecocq (2010) therefore argue that in a BMI, continuous work to align activities is crucial due to the constant change imposed upon them. They term this ongoing process *dynamic consistency*.

The systematic (re-) alignment of activities that goes along with holistic thinking about BMI was found largely absent in manufacturing firms in their attempts to capture value from I4.0 (Arnold *et al.*, 2016; Burmeister *et al.*, 2016; Müller, Buliga, *et al.*, 2018). Hence, particularly for the context of I4.0, the perception of a BMI as an activity system provides valuable insights; I4.0 principles not only change activities and their interlinkage inside a firm, but moreover widen the scope of innovation beyond a focal firm based on changing flows of digital information that consequently also change flows of physical material goods (Amit and Zott, 2001). Constant, complex organisational change processes are consequential if firms deem it a priority to stay competitive over time (Demil and Lecocq, 2010). The notion of BMI as an activity system and the view of dynamic BMI in general have only recently emerged. Nevertheless, several studies discuss organisational aspects that contribute to understanding the mechanisms that drive or hinder innovating an incumbent's BM. The following section sheds light on the state of knowledge in this area.

2.5.2 Dynamic BMI

Against the backdrop of new technologies, it is important for manufacturing firms to realise that new technologies need to be combined with innovation of their existing BM (Chesbrough, 2010). However, manufacturing firms have shown a low degree of reception regarding a continuous review and thinking about BMI in the context of progressing digitalisation, especially regarding the alignment of activities across the activity system (Burmeister *et al.*, 2016; Kiel *et al.*, 2017; Müller, Buliga, *et al.*, 2018). Beyond the specific context of I4.0, manufacturers' knowledge about innovating their BM in response to externally exposed opportunities and threats is also premature (Saebi *et al.*, 2017); and I4.0 is perceived as a threat and an opportunity for manufacturing firms at the same time. The existing state of knowledge on dynamic BMI can be grouped into four areas: (1) a need for a continuous process of changing and innovating the BM; (2) outlining (anti-) drivers of BMI; (3) procedures for pursuing BMI; and (4) organisational aspects that foster or hinder BMI. The following paragraphs discuss each area.

(1) Continuous BMI process

Several studies highlight the importance of a continuous process of BMI in companies, as BMs do not emerge fully-formed, but are subject to a continuous process of discovery, adjustment and fine-tuning (Dunford *et al.*, 2010). Similarly, authors emphasise a general significance of continuous incremental changes to the BM (Sosna *et al.*, 2010); although this form of simultaneous experimentation implies lower initial growth rates, it then facilitates long-term survival based on enacting variety in a resource-effective manner (Andries *et al.*, 2013). Simultaneous experimentation is similar to the concept of dynamic consistency: Demil and Lecocq (2010) introduced this concept to advocate for continuous work on the alignment of BM components as they mutually influence each other. Hence, firms and managers need the ability to constantly identify and understand the consequences of changes in one component on other components of a BM and the overall performance (Cavalcante *et al.*, 2011). Specifically, in new-technology projects manufacturing firms tend to focus on the development and commercialisation of innovative applications and thereby neglect profound analyses on the effects on the firm's BM (Cavalcante *et al.* 2011). Baden-Fuller and Haefliger (2013) nicely elaborate on this issue by stating that managers need to spend time on understanding the complexity of this interplay between technology and the dimensions of a BMI.

(2) (Anti-) drivers of BMI

Engaging in BMI is subject to certain drivers and antecedents. Due to a firm's path dependencies, including a dominant BM logic, complementarity of assets or contingent events, BMs are often closely aligned and therefore create a self-reinforcing mechanism that makes it more difficult for incumbent firms to change their BM (Bohnsack *et al.*, 2014). These path dependencies can also be seen as root causes, whether companies perceive an external development, such as I4.0, as a threat or an opportunity. The likelihood of engaging in BMI was found to be dependent on the perception of the external aspects (Saebi *et al.*, 2017): the more severe an external threat was, the more likely firms innovated their BM, whereas perceiving the external development "merely" as an opportunity was associated with upholding the status quo. Moreover, Saebi and colleagues found that the strategic orientation of the firm plays a significant role for the decision to engage in BMI. Market development orientation yields higher propensity to change the BM, as it already denotes the development of routines and processes to effectively respond to external events. Not surprisingly, firms that pursued a rather defence-orientated approach by seeking to offer lower prices or focusing on reducing operational costs were significantly less likely to engage in BM changes. This is explained with reference to prospect theory, that managers are more likely to take risk in situations of threat than opportunity. However, the applicability of prospect theory is challenged by empirical longitudinal case study evidence about sustainably growing firms (Achtenhagen *et al.*, 2013). The authors of that case study propose managers take one or a mix of three strategizing actions to kick-start the BMI for sustained value creation, regardless of what environmental conditions prevail: first, combining organic growth with strategic acquisitions; second, focusing on simultaneous expansion along different dimensions, i.e. not only diversification of products, but also considering other BM dimensions such as new markets and distribution channels; third, combining cost-efficiency with a high-quality focus.

(3) Procedures to pursue BMI

Despite the drivers to engage in BMI, some authors have focused on implications for the actual process of innovating the BM. Cavalcante (2014) identified a pre-stage, which precedes any BMI, and is supposedly crucial for the subsequent success of the BM change. In this pre-stage, multiple challenges require an answer, and companies can experiment with new processes that might become future core processes, before anything gets changed. Once a firm has embarked on innovating the BM, the alignment of the BM with the strategic and operational management model of a firm should be closely considered (Basile and Faraci, 2015). The management model in Basile and Faraci's definition comprises objectives, people, activities and decision-making, which is included in the view of the BMI as an activity system as proposed for this thesis, inspired by Amit and Zott (2001) and Zott and Amit (2010). Another study examined a firm's development from a service firm to a hybrid product firm towards a product firm, proposing that, over time, BMIs in a firm follow precisely this sequence (Willemstein *et al.*, 2007).

However, these procedures for pursuing BMI seem to view BMI as a project rather than a continuous process as proposed by the notion of dynamic consistency (Demil and Lecocq, 2010). Considering the fast-paced innovation cycles driven by digitalisation, which includes selected and emerging changes, the dynamic consistency view as an ongoing fine-tuning process promises more valuable insights to sustainably and holistically approach I4.0-driven BMI.

(4) Organisational aspects

Despite the drivers of BMI and different procedures to pursue BMI, a line of literature discusses organisational capabilities supporting firms in innovating their BM over time. This perspective might yield interesting complements to the notion of continuous BMI in general, and dynamic consistency in particular. In principle, the discussed organisational aspects may be grouped into three: (a) experimenting and learning; (b) leadership and culture; (c) flexibility of resources.

(a) Experimenting and learning: Continuous and wide-reaching practices should span the whole organisation to transform the firm into a continuous nucleus of experimenting and learning, as this ensures over the long term a dynamic BM (Achtenhagen *et al.*, 2013; Cavalcante, 2014). Particularly important for this is an openness towards failure as a source of learning (Sosna *et al.*, 2010) and opportunities for knowledge transfer between groups of people (Mason and Leek, 2008) as well as a sourcing of information from various sources (Velu, 2017). However, such openness might be jeopardised by hard knowledge transfer mechanisms that often exist in incumbent firms, i.e. specific routines and structures for how and to whom knowledge is transferred (Mason and Leek, 2008).

(b) Leadership: One can imagine leadership and culture to be important aspects for successful BMIs in incumbent organisations that are often trimmed towards efficiency and avoidance of failure to ensure high-quality operations. Incumbents find it difficult to incorporate such experimental routines, which is why authors advocate for an active and clear leadership to form a strong corporate culture and employee commitment (Dunford *et al.*, 2010; Achtenhagen *et al.*, 2013). Alignment of cultural beliefs with formal practices and routines may foster experimentation and cooperation within a firm's ecosystem (Dunford *et al.*, 2010). Doz and Kosonen (2010) regard unity among the top leadership as crucial for taking fast and bold decisions without being caught in win-or-lose politics. Moreover, firms are more receptive and successful in their BMI approaches, when top management actively engages in resolving presumable organisational paradoxes, in fields including rules, knowledge and relationships (Ricciardi *et al.*, 2016), and when top management is able to receive and create new idiosyncratic meanings about the BM (Velu, 2017).

(c) Flexibility of resources: Due to the dynamics required for a BMI process, it seems inevitable for several authors that resources and capabilities need to be flexible, in the sense that they need to be reconfigured and reorganised rapidly (Doz and Kosonen, 2010; Achtenhagen *et al.*, 2013). This is especially true against the backdrop that the presumably small changes with which a BMI is started may well transform the core logic of an entire organisation, embracing holistic, system-wide changes that may simultaneously include major changes to the value creation and value capture mechanism (Sosna *et al.*, 2010).

Having examined the literature on dynamic BMI, one can conclude that the initial question of how manufacturing firms may manage the interdependencies across their activity system throughout an I4.0-driven BMI largely remains open. The current literature does not provide enough insights into what mechanisms support firms in achieving dynamic consistency. Most studies propose single aspects that deserve consideration during the process of innovating a BM, a comprehensive collation of mechanisms that are needed to ensure alignment on a continuous basis can hardly be derived from the existing literature in this field. Only one study was identified that attempted to explain the concept of dynamic consistency by proposing a framework to measure dynamic consistency (Kranich and Wald, 2018). However, this framework does not sufficiently explicate the microfoundations of what generally determines the consistency between two activities, neither in general, nor specifically for I4.0-driven BMI. The model assumes causal relationships that serve as mediating variables. As an example, the value proposition was identified to be a starting point of BMI, followed by customer value adjustments that lead to changes in value creation. Moreover, Kranich and Wald propose discrete item scales for each BM dimension and consequently draw on a pre-set possibility of configurations. However, the core of BMI is the innovative nature to develop new configurations that might not have occurred anywhere or within the industry and that may not seem obvious or consistent. Mostly, these configurations are based on a unique choice of sets of activities (Siggelkow, 2001). Therefore, the factors that determine whether activities are complementary should be examined, as this allows general measurement, even of new configurations and over time.

While the BMI literature highlights the need to achieve continuous alignment over time among BM components and their underlying activities, it remains largely silent in further operationalising this specific idea of dynamic consistency. Although some organisational aspects for successful BMI were proposed, the literature does not sufficiently explain the understanding of how firms manage the complex interdependencies of activities, especially against the fast-moving developments pushed by digitalisation.

3. Methodology

3.1 Overview

This chapter discusses the methodological choices taken for this thesis with their underlying rationales and their suitability for addressing the posed research question: *What are the microfoundations of dynamic consistency in I4.0-driven BMI?*

3.2 Basic Scientific Considerations

To a certain extent, all qualitative researchers – and, in fact, all humans – are philosophers, as we are guided by rather abstract principles (Denzin and Lincoln, 2003, p. 33). These principles combine beliefs about the nature of reality (ontology) with the relationship between the inquirer and knowledge (epistemology), and thereby shape rationales, beliefs, and how the researcher sees the world and acts in it (Denzin and Lincoln, 2003). Accordingly, these principles form the basis for the logic of inquiry that will answer the given research questions.

3.2.1 Philosophical Assumptions

Philosophical assumptions form the theoretical foundation for the present research, and influence the chosen methodology followed by specific methods and techniques. For a researcher, it is essential to understand one's own philosophical presumptions for several reasons (Easterby-Smith, Thorpe and Jackson, 2015, p. 46): (1) to understand the epistemological position to sense the reflexive role in different research methods; (2) to understand what evidence is required, how it is to be gathered and analysed, and how these design choices influence the answers to the research question; (3) to guide decisions on appropriate design choices and inherent limitations. As qualitative researchers examine the world in action and embed their research in it, they are likely to experience constraints against the social world (Denzin and Lincoln, 2003) which can be better examined and discussed with the consciousness of one's own view of reality (ontology) and knowledge (epistemology), which shall be discussed subsequently.

Ontological assumptions

In principle, ontological assumptions determine the beliefs about the nature of (social) reality, and what kind of being a human is; whether there is any objective reality or whether reality is subjectively created by one's cognition (Denzin and Lincoln, 2003; Blaikie, 2010; Easterby-Smith *et al.*, 2015). These assumptions make claims about the kinds of social phenomena that may exist, their conditions of existence, and their interdependence (Blaikie, 2010). Due to the fundamental nature of these questions, different schools of philosophy have strongly diverging views (Blaikie, 2010; Robson, 2011; Easterby-Smith *et al.*, 2015). The following classification of Easterby-Smith *et al.* (2015) distinguishes four different ontologies on a spectrum between realism and nominalism (Table 3).

Table 3. Ontological assumptions

Ontology	Realism	Internal realism	Relativism	Nominalism
Truth	Single truth	Truth exists, but is obscure	There are many truths	There is no truth
Facts	Facts exist and can be revealed	Facts are concrete, but cannot be accessed directly	Facts depend on viewpoint of observer	Facts are all human creations

Source: (Easterby-Smith, Thorpe and Jackson, 2015, p. 50)

Realism as one side of the spectrum denotes the belief that there exists a reality driven by immutable natural laws (Guba, 1990). Nominalism, at the other end of the spectrum, argues that (social) reality is no more than a creation of people through language and discourse (Easterby-Smith *et al.*, 2015). The stance taken for this research will be discussed in detail in Section 3.2.2.

Epistemological assumptions

Epistemology is the study of the nature of knowledge, what kind of knowledges are possible, and how we gain knowledge about the reality of the physical and social world (Blaikie, 2010; Easterby-Smith *et al.*, 2015). As with the ontological position, the epistemological position can be determined on a spectrum between the two traditional epistemological stances in the social sciences: positivism on one side and social constructionism on the other (Table 4) (Easterby-Smith, Thorpe and Jackson, 2015, p. 51). *Positivism* regards facts and values as distinct and holds that scientific knowledge comprises observable facts, whereas *constructionism* denotes that most aspects of a social reality are constructed by subjective perceptions, neglecting the view of an objective reality. This form of sense-making of the world is facilitated by sharing experiences via the medium of language.

From these two fundamental philosophical discussions, it is clear that these assumptions are mutually dependent and that the epistemological view depends on how reality is seen (Holden and Lynch, 2004). The following section therefore connects these two perspectives into a research paradigm that serves as a basis for the subsequent choices of the present study's design.

3.2.2 Research Paradigm

According to Guba (1990), the basic set of personal beliefs about reality and knowledge guides a researcher's actions, and is often called a "paradigm". The research paradigm followed resonates from the positioning within the ontological and epistemological assumptions discussed in Section 3.2.1 and can be located on a continuum, with objectivism and subjectivism as the two polar opposites (Holden and Lynch, 2004) (Table 4). Other names for the objectivist view include quantitative, scientific or positivist. Similarly, subjectivism is also discussed as qualitative, phenomenological, humanistic or interpretivist (Morgan and Smircich, 1980). Table 4 merges the ontological and epistemological assumptions into an overview that highlights the dependency of decisions regarding ontology and epistemology.

This research project examines the evolving phenomenon of how manufacturing firms approach BMI in the course of I4.0. BMI can further be perceived from multiple perspectives, as the reality is not singular; rather, different stakeholders of these processes have different perspectives that emerge through the interaction of people in their regular working environment. From this, the paradigm of the present research can be derived as taking a relativist ontology (Easterby-Smith *et al.*, 2015). The examination of activity interdependencies within a BM mostly entails the observation and enquiry of processes and relations which are often intangible, alongside some insights on tangible assets such as machinery or engineering artefacts. The reality of these processes is predominantly constructed through the interaction of the researcher with the respective stakeholders of these processes by means of questions (Denzin and Lincoln, 2003); based on this relativist ontology, a constructionist epistemology is advisable.

Given its relativist ontological and constructionist epistemological stance, the chosen research paradigm can be called a *modest subjectivist* approach, providing guidance for the subsequent methodological choices. This approach is based on a rather relativistic ontology that goes hand in hand with the view that knowledge is constructed on the basis of language, culture, human intuitions, and subjective thoughts (Johnson and Onwuegbuzie, 2004).

Table 4. Philosophical assumptions and their convergence into research paradigms

Paradigm	Objectivist ◄			► Subjectivist
Ontological Assumptions	Realism	Internal realism	Relativism	Nominalism
	Social reality as a concrete structure	Social reality singular, but evidence is always indirect	Social reality not singular, but multiple perspectives	Social reality as a creation of human imagination
Epistemology / Methodology	Strong positivism	Positivism	Constructionism	Strong constructionism
Aims	Discovery	Exposure	Convergence	Invention
Starting points	Hypotheses	Propositions	Questions	Critiques
Designs	Experiments	Large surveys, multiple case studies	Cases and surveys	Engagement and reflexivity
Data types	Numbers and facts	Mainly numbers with some words	Mainly words with some numbers	Discourse and experiences
Analysis / Interpretation	Verification / falsification	Correlation and regression	Triangulation and comparison	Sense-making and understanding
Outcomes	Confirmation of theories	Theory-testing and generation	Theory generation	New insights and action

Adapted from Easterby-Smith *et al.* (2015, p. 54), (Easterby-Smith *et al.*, 2015) Holden and Lynch (2004), Morgan and Smircich (1980, p. 493)

3.2.3 Research Strategy

The modest subjectivist stance chosen for this research project guides the choices made for the research strategy. The research strategy defines the logic of inquiry for answering the research questions (Robson, 2011; Denzin and Lincoln, 2003). According to Blaikie (2010), four research strategies can be determined (Table 5).

Table 5. Research strategies

	Inductive	Deductive	Retroductive	Abductive
Aim	To establish descriptions of characteristics and patterns	To test theories, to eliminate false ones and corroborate the survivor	To discover underlying mechanisms that explain observed regularities	To describe and understand social life in terms of social actors’ meanings and motives
Start	Collect data on characteristics and/or patterns; Produce descriptions	Identify a regularity that needs to be explained	Document and model a regularity	Discover everyday lay concepts, meanings and motives
Finish	Relate these to the research questions	Test hypotheses by matching them with data explanation	Establish which mechanism(s) provide(s) the best explanation in that context	Develop a theory and elaborate it iteratively

Source: Blaikie (2010, p. 84)

I4.0, and specifically I4.0-driven BMI, emerged due to rapid technological and social change. As the literature examination has shown, the body of knowledge lacks patterns and characteristics for the dynamic alignment of activities in I4.0-driven BMI. Accordingly, the research question sets out to examine procedures and interdependencies between activities and actors in a socio-technical system. For establishing a description of these explicit or implicit social characteristics or networks of regularities, an inductive research strategy is most suitable (Flick, 2009; Blaikie, 2010). The present research project accordingly draws on an inductive research strategy to seek answers to the stated research question.

3.3 Research Design

With the research design paradigm and strategy having been discussed and chosen, the study design is now conceived to connect the theoretical paradigms and the strategies of inquiry with the methods for collecting empirical material (Denzin and Lincoln, 2003). In the process of choosing and justifying technical decisions for the research project, the research design is to remain clearly focused on the research question (What are the microfoundations of dynamic consistency in I4.0-driven BMI?) and which information will best answer it (Blaikie, 2010). This includes finding out the most suitable way to gather data about a focused social setting (Mack, 1970).

3.3.1 Social Setting

Given that the research question seeks to examine the microfoundations of dynamic consistency in I4.0-driven BMI, the social setting for this research projects needs to fulfil the following primary criteria:

- As I4.0 is considered the application of digitalisation in manufacturing industries, the social setting must be manufacturing industries.
- As indicated by the term, the concept of BMI examines how firms innovate their BM, i.e. the core logic of how they do business. Accordingly, another criterion for the social setting is manufacturing firms.
- The research question seeks to examine the alignment of activities across an I4.0-driven BMI. Hence, firms invited to participate in this research study must have started to undertake significant changes to their BM, triggered by I4.0.

Based on these considerations, the European manufacturing sector is one promising social setting to inform the research question. Moreover, it accounts for 15% of the total value-add in the EU (Veugelers, 2017), while having a share of more than 50% of the EU's total expenditure on business enterprise research and development in 2014 (Germany: >85%). As these numbers indicate, manufacturing industries are among the most innovative sectors in Europe. Given that I4.0 has emerged from a German federal governmental initiative that is funding research and driving the application of I4.0 in Germany, and proposing the same for Europe, the European manufacturing sector can be regarded a suitable social setting for seeking answers to the research question.

Other aspects hold synergetic potential to support the choice based on the primary criteria: As I have more than six years' professional experience in relevant jobs in both the automotive supplier industry and the machinery and equipment industry, it seems beneficial for the research to build on this expertise and professional network. In addition to this personal experience, the automotive industry represents Europe's largest industry, with more than 7% of the entire EU's GDP (European Commission, 2020), and automotive suppliers account for more than 75% of the entire industry's global spends on innovation (VDA, 2018). Closely attached to the automotive industry is the machinery and equipment manufacturing industry – the second biggest industry in the manufacturing sector (Eurostat, 2019) . As digitalisation is a major driver for innovation in both industry sectors, they are presumably a good starting point to inform the understanding of the posed research question.

3.3.2 Data Sourcing Approach

For each research paradigm, a considerable diversity of approaches and designs exists (Blaikie, 2010; Easterby-Smith *et al.*, 2015). Case study research, for example, is one suitable approach, based on the modest subjectivist research paradigm and the inductive research strategy (Creswell and Poth, 2018). Case study research is well suited to investigating a particular contemporary phenomenon within its real-life context; the case is the situation, the individual, the group or the organisation one is interested in (Yin, 2014; Robson and McCartan, 2016). Moreover, the case study approach allows researchers to retain a holistic and meaningful insight into real-life events, such as organisational and managerial processes, to understand their complex social nature (Yin, 2003). The latter applies to the aim of this research project, seeking a better understanding of the interdependencies of activities in an I4.0-driven BMI that emerged during the literature review in Chapter 2. This phenomenon is a contemporary one that is studied best within manufacturing organisations that embraced an I4.0-driven BMI process, which is the natural setting of the phenomenon (Blaikie, 2010; Creswell and Poth, 2018). Case study research is known to consider these aspects, as it allows in-depth inquiries into processes with multiple stakeholders, and allows the researcher to collect detailed information by using a wide array of data collection methods (Yin, 2003, 2018; Creswell and Poth, 2018).

Table 6. Case study schools of thought

	Positivist (Yin)	Positivist and constructionist (Eisenhardt)	Constructionist (Stake)
Design	Prior	Flexible	Emergent
Sample	Up to 30	4–10	1 or more
Analysis	Cross-case	Both	Within case
Theory	Testing	Generation	Action

Source: Easterby-Smith et al. (2015, p. 92)

Depending on the epistemological perspective, case study research can be designed in three main ways, as depicted in Table 6. Although Easterby-Smith *et al.* (2015) distinguish three different schools of thought, they also denote the loose transitions among them. However, as this study takes a considerably modest subjectivist perspective, the constructionist school of Eisenhardt (1989) is adopted for this research.

This research sets out to generate a better understanding of what factors are to be considered for continuously aligning the components of an I4.0-driven BMI. As the BMI processes and the underlying mechanisms and activities vary across manufacturing firms but may follow mutual patterns, it is vital to develop an in-depth description and analysis of multiple manufacturing firms' BMs, given that that this phenomenon is not a unique or critical case, for which single case studies might be more suitable (Yin, 2003). By showing different perspectives of the phenomenon through the examination of multiple case studies, theoretical generalisation may be achieved (Robson and McCartan, 2016; Creswell and Poth, 2018). Eisenhardt's (1989) approach accordingly serves well, as not only insights into multiple BMs are required, but also insights from multiple stakeholders of every BM. The latter has been found as one of the major constraints of concurrent research on I4.0-driven BMI, as methodological approaches mostly focused on one informant in each company (e.g. Burmeister *et al.*, 2016), or used survey approaches that did not study the phenomenon in its natural context (e.g. Müller *et al.*, 2018).

3.4 Multiple Case Studies Approach

3.4.1 Unit of Analysis

The definition of one "case" for each research project depends on the research question posed (Creswell and Poth, 2018). As the focus of this study is on I4.0-driven BMI, per definition of I4.0, the phenomenon in focus is on manufacturing organisations and, more precisely, on a manufacturing firm's I4.0-BM. A BM is defined as a firm's set of activities across multiple dimensions to gain a sustainable competitive advantage, which is accordingly unique to every manufacturing firm; in fact, every BM is unique, and a (manufacturing) firm may run multiple BMs. Having stated the latter, the unit of analysis for this study is *one* I4.0-BM of a manufacturing firm, which has been subject to an innovative transformation process towards a "new" BM. Comprised in this definition are organisational and managerial activities that are relevant to the innovation of the BM.

Following the modest subjectivist philosophical stance, cases are well suited to generate theory.

3.4.2 Case Selection Approach

When building theory, cases are chosen for theoretical reasons with the goal of choosing those that are likely to replicate or extend the emergent theory (Eisenhardt, 1989). It is therefore advisable to seek theoretical generalisation by selecting cases that may provide different perspectives on the subject of investigation (Robson and McCartan, 2016; Creswell and Poth, 2018). Regarding sample size, Eisenhardt (1989, p. 545) suggests four to ten cases, subject to theoretical saturation, which means that more cases are added until no more substantial insight is discovered (Blaikie, 2010). In line with the modest subjectivist stance, the approach to examine multiple BMs is well suited to generate theory, as social reality is not singular, but has multiple perspectives. This is important as the development of theory is subject to comparison between cases, which is why Yin (2018) suggests a literal and theoretical replication logic for the selection of cases. Thereby, literal replication aims to select cases with minimal differences predicting similar results in single case studies, whereas theoretical replication maximises differences in anticipation of contrasting results. The validity of the inquiry is accordingly controlled by the case selection.

With I4.0 as a contemporary phenomenon bringing rapid technological and social change to manufacturing organisations, and Europe as a prominent geographical area in which many firms undertake significant changes to their BM triggered by I4.0, it is vital to gain access to and insights into manufacturing firms who fulfil the following criteria for answering the stated research question:

(1) Firms must be manufacturing firms with their main research and development, engineering, and production locations based in Europe.

(2) Firms must have started utilising I4.0 principles and thus have changed their BM. Different maturity levels of I4.0 adoption across the examined firms would be preferred.

(3) The focus on interdependencies requires close insights into the heart of an organisation, the key mechanisms of how value is created and captured, involving

multiple stakeholders. The firm must therefore grant access to a minimum of five interview partners, including multiple senior employees.

(4) To account for unexpected differences or homogeneity within one industry, the aim is to have manufacturing from two different manufacturing industries.

Considering the former aspects, alongside Eisenhardt's sample size and Yin's logic of replication, this research aims to examine three to four cases chosen based on the literal replication logic, which shall then be complemented by two or more cases that extend the obtained insights.

By means of theoretical sampling, theoretically eligible cases were screened for their informative potential to replicate or extend theory by filling conceptual categories informing the research question (Eisenhardt, 1989). Publicly available reports and databases were screened for insight into which manufacturing companies have changed their BM driven by I4.0. Moreover, the personal network of manufacturing firms was contacted, and academics from the university with a strong industrial record were asked to suggest companies that meet the above targets. In total, 32 manufacturing firms were identified and selected as potential case firms in terms of location, industry and overall suitability, based on recommendations from informants or publicly available information. An initial contact with each firm was made either via an introduction through an informant or directly via email, LinkedIn or personal phone call. This process proved challenging for two main reasons:

(1) To answer the research question, access to senior persons in the organisation is necessary, as interviewees with a good general overview of the firm's processes and procedures are likely to be able to provide multiple perspectives on the firm's BMI process (Corley and Gioia, 2004). As the participation for this research project involves a minimum of five different senior interviewees per manufacturing firm, access and consent of a senior person must be granted. Further information on this is given in Section 3.4.3. on units of observation and data collection.

(2) All companies invited to participate required confidentiality agreements to be signed. This may be because I4.0-driven BMI has not been widely disseminated across manufacturing companies.

Of the 32 contacted firms, nine agreed to participate in this study. Four automotive suppliers that were particularly interesting for the research question were primarily selected as case study firms (Saunders *et al.*, 2015). To reduce and explain possible contradictions, theoretical replication was sought by selecting machine and equipment manufacturers, as BMs and approaches to I4.0 are likely to differ in other industries, with potential to enrich the insights from the initial sample. Three other firms were chosen as pilot case studies. See Table 7 for further information, and Chapter 4 for detailed information about each case study firm.

3.4.3 Data Collection Approach: Unit of Observation and Semi-structured Interviews

Following Eisenhardt (1989), case studies typically entail a combination of data collection methods. In accordance with the modest subjectivist stance, the rationale here is to pursue triangulation using multiple data collection methods to provide stronger support for the emerging theory. Multiple sources of evidence were gathered and triangulated, including semi-structured interviews, documents, notes and direct observations (Yin, 2018). The primary source of data was semi-structured interviews, group discussions (i.e. workshops) and direct observation. Table 7 gives an overview of the scope of the conducted interviews.

Table 7. Overview of case studies with semi-structured interviews as source of primary data

Industry / Location HQ	Firm pseudo-nym	Revenue [million EUR]	No. of employees	No. of interview partners	Total interview time [min]	Pages of interview transcripts	Pages of interview notes
ME[1] / IT	Alpha	80	300	9	790	237	--[3]
ME[1] / DE	Beta	1,200	4,000	9	725	44	73
ME[1] / DE	Gamma	690	2,500	10	725	--[4]	39
A, S / DE	Delta	800	1,000	5	386	79	7
A / DE	Epsilon	850	4,000	10	640	95	32
ME / NL	Zeta	400	2,000	9	629	203	3
A / [2]	Eta	2,000	8,300	6	404	111	--[3]
ME / DE	Theta	1,400	4,000	6	460	19	34
A / HU	Iota	481	1,800	8	458	160	1
	Total			72	5,217	948	189

A: Automotive supplier; ME: Machine and equipment manufacturing; S: Steel
[1] Pilot case study
[2] Country not to be disclosed – German-speaking, European country
[3] All interviews were voice recorded
[4] No authorisation for voice recordings

Regarding the selection of interviewees, a view of several stakeholders involved in the I4.0-BMI process is necessary to build a valid account of the alignment mechanisms involved. Moreover, adding further interviewees should be pursued until theoretical saturation is achieved (Blaikie, 2010). Other authors find it difficult to estimate *a priori* how many participants are likely to be needed to reach data saturation and suggest a sample size of 5–

25 for semi-structured, in-depth interviews (Saunders *et al.*, 2015). Depending on the homogeneity of the accessible interviewees in each case study firm, this present study aimed for a minimum of five interviewees per firm from different functions, accompanied by snowball sampling when conducting the research; i.e., each interviewee was asked who else should be interviewed to gain a holistic picture of the I4.0-driven BMI process. To ensure that multiple perspectives on a BM are covered, a minimum of five stakeholders were interviewed which provided broad data saturation. All interviewees were contacted by email giving a broad outline of the research project's motivation and objectives. As Table 7 demonstrates, all conducted cases contain 5–10 individual informants, with all interviews lasting on overage more than 70 minutes to allow different topics to be explored thoroughly (Taylor and Bogdan, 1998). All interviews were conducted by the author of this thesis, most of the interviews were conducted in person, but occasionally telephone interviews were conducted instead. Firm Gamma did not grant permission for audio-record. The researcher therefore took extensive electronic notes during the interviews. Shortly after each interview, the notes were re-read, and short key points were extended with a view to the essential points made by the interviewee. These notes were then included into the case study database and analysed similarly as the transcribed documents. Table 8 gives an overview of interviewees' seniority, positions included COO and managing director; directors of production, IT, supply chain, finance, high-performance manufacturing technologies, sales, and innovation; heads of advanced manufacturing, industrial engineering, and smart factory; and managers of digital transformation, open innovation, and cost engineering. A full list of interviewees and duration of the interview can be found in Appendix A.

Table 8. Overview of interview partners

Position	Delta	Epsilon	Zeta	Eta	Theta	Iota	Total
Executives	-	-	-	1	-	1	2
Director	4	3	3	2	3	3	18
Head	1	-	1	2	1	4	9
Manager	-	4	2	1	1	-	8
Project leader	-	2	1	-	1	-	4
Senior engineer	-	1	2	-	-	-	3
Total	5	10	9	6	6	8	44

Semi-structured interviews were guided by predetermined questions and topic areas that were modified during the interview based on the researcher's perception of what was most appropriate for that particular interviewee – questions were omitted, additional ones included and time spent on each question varied (Robson, 2002). Following a brief introduction describing the researcher’s background and the motivation of the research project, all interviews began with a set of open-ended question about the interviewee’s background, position and duty within the firm, and their general perception of I4.0 within the firm. Depending on the flow of conversation, further topic areas were examined. In general, all topic areas were attempted to be covered with each interviewee. Table 9 provides details about the topics covered and the associated questions.

The interview guideline was first developed based on the earlier literature review and was then tested and refined in three pilot case studies, as advised by Yin (2003). The posed questions were adapted to the terminology of the respondent and the specific firm. In addition, the guide was mainly used as a reminder to cover all relevant topics – in the vast majority of interviews, the main aspects were covered by a smooth flow of conversation based on the first four questions, supplemented by smaller questions on topics not covered by the respondents’ statements.

In addition to the semi-structured interviews, every case study contained a workshop (i.e. group discussion) with the interviewees, which was held once all interviews had been conducted and analysed. For these workshops, feedback was prepared for the firm by means of a data-gathering framework that was created based on I4.0-driven BMI literature as well as emerging themes throughout the interviews. The framework was used to indicate the performance of the case study firm in up to 25 different areas, including vertical integration, level of digitalisation of products and services, approaches to collaboration, and others. By analysing the interviews and reflecting on the factory visits, the firm’s current status in each of the 25 areas was indicated by the researcher on discrete scales of A to F.

The main purpose of this data-gathering framework was to facilitate a discussion among the group of interview partners about the alignment of their BMI activities. As the workshop participants represented a cross-section of the firm’s functions, they were well equipped to discuss interdependencies of activities across the BM. Following a dynamic systems mapping approach, the workshop participants were asked to firstly individually assess what activities had an impact on each other. These individual assessments were then discussed and indicated on a large-scale print-out of the obtained performance results: what activities had a positive or a negative impact on one another, i.e. which activity needs development with regard to overall BM consistency. The individual assessment that preceded the group discussion was established to reduce the risk of group-level biases.

Comments and topics of this group discussion were noted down and included in the case study database for further content coding. Based on this exercise, a roadmap with prioritised actions was derived and given to the firm by way of recognition for their participation in the research project.

Given the feedback of the participants, the workshop approach, including analysed interviews, dynamic systems mapping and a roadmap, indicated the potential for further use as a management tool. Participants especially regarded their cross-functional team as agreeing on issues of BMI and I4.0, providing a solid basis for discussing the firm's current performance in different areas. Moreover, consideration of the impacts of different activities on each other highlighted multiple needs for improving the performance of those activities that were negatively affecting others.

Table 9. Guiding questions for semi-structured interviews

Topic	Guiding Question
General	- What is your description of Industry 4.0 in your firm? - What is your description of your firm's BM? What role does Industry 4.0 play? - Which initiatives and projects in your firm, that you know of, would you classify as related to Industry 4.0? - What were the challenges, what went well, what would you do differently in hindsight?
Value proposition	- What key dimensions do you consider important to describe the value proposition you are offering your customers? What has changed in the context of digitalisation? - What are product configurations regarding "intelligence" and connectivity? - What do your customers value most? - What would further improve your value proposition?
Value creation and delivery	- What key aspects do you consider important to describe the value-creating activities? What is your firm's core know-how? - What is your approach to operational excellence? - How do you manage operational, process and planning data? - Can you describe the product development process and how relevant information is distributed to design, engineering and production? - What would further improve your value-creating activities?
Value capture	- What are the value capture mechanisms of your firm? - What are the most important costs? What is your description of your cost structure? - What concrete thoughts or discussions have you had about sharing or monetising data? - What would further improve your ability to capture value?
Value network	- Can you describe your approach towards external partnerships? - Can you describe your relationship with customers and suppliers? - How could you further benefit from partnerships?
Miscellaneous	- What further dimensions in your area of responsibility may benefit from the use of digitalisation? - What other activity or function within your firm would benefit most from an increased usage of digitalisation? How? What are the preconditions? - What is important to digitalisation in general, or to your firm specifically, that we have not covered so far? - Whom else should I talk to?

In addition to substantial insights from interviews, direct observation was carried out, studying the natural technical environment during extensive shop-floor visits, including informal conversations with many blue-collar workers and technicians at each site. Moreover, secondary data were added to the case study database, including company presentations and annual reports. These pieces of evidence were further included in the coding process. An example of firm internal documentation is illustrated in Appendix D. Further details are shown in Table 10.

Table 10. Further sources of primary and secondary data

Data	Source	Data collected
Primary	Documentation	- 2–3 pages of notes for each of the nine workshops, including feedback from participants on the general approach, satisfaction with the findings, questions asked, etc.
	Direct observation	- For each case, at least one factory visit of >2 hours was conducted - For each case, a 2-hour workshop with the interviewees and selected executives was held to present and discuss consolidated findings from the interviews and factory visits
Secondary	Archival data	In total, more than 500 pages of supporting documents, including: - Annual reports - Information about companies from their webpages - Published articles, news, news releases, reports about firms retrieved from Factiva - Reports from industrial agencies (including VDI, VDMA, acatech, Fraunhofer) discussing the case study firms - Internal company presentations - Internal company documents

3.4.4 Data Analysis

Section 3.2.3 outlined this thesis's strategy to build theory from induction by describing patterns of interdependencies among activities in an I4.0-driven BMI. To establish this description of characteristics, theoretical data coding as an approach to data analysis was adopted. This approach was first introduced by Glaser and Strauss (1967) in the course of the discovery of the grounded theory and further developed by Corbin and Strauss (1990, 2008). Grounded theory is a research methodology to construct theory by inductive reasoning. Long-standing debates circled around Glaser and Strauss' objectivistic idea of data representing a "real" reality and their approach to beginning empirical investigations without any *a priori* ideas to prove or disprove (Glaser and Strauss, 1967). This research project is informed by a modified approach to grounded theory, introduced by Corbin and Strauss (2008, 2015), that acknowledges that a researcher brings his own philosophies, experience, professional background, and interests into the research process and enters fieldwork with a focus (Corbin and Strauss, 2008). In line with the modest subjectivist research paradigm taken, this research follows Strauss and Corbin's view of enacted truth through the interaction of the researcher with the research setting and the obtained data

(Mills *et al.*, 2006). Despite the philosophical controversies, data coding is a process of analysing qualitative raw data in the form of field notes, interview transcripts, etc., to raise it to a conceptual level. Coding involves interacting with data, asking questions and making comparisons to eventually derive and develop concepts from these data (Corbin and Strauss, 2008).

The adopted coding approach for this thesis is informed by Corbin and Strauss and consists of multiple iterative rounds of coding to refine the emerging themes and concepts (Corbin and Strauss, 2008). It is supported by a software suite for qualitative data analysis, namely MAXQDA 2018. Coding was started with open coding, where codes were used as labels to attribute a symbolic meaning to chunks of information obtained during the study (Miles *et al.*, 2014). Thereby, the data were interpreted based on the researcher's understanding of the events (Denzin and Lincoln, 1998; Corbin and Strauss, 2008). Building on the open coding, second-cycle coding was then used to develop thematic patterns by organising, relating and synthesising the first-order codes into more condensed and analytical second-order themes (Miles *et al.*, 2014), described as axial coding by Corbin and Strauss (2008). In a third round of coding, the second-order themes were further synthesised into aggregate, overarching dimensions that are the basis of the emergent framework. These techniques were not carried out in a linear or sequential fashion, but formed a recurring process that continued until a clear understanding of theoretical relationships emerged and additional interviews did not reveal any new data relationships (Corbin and Strauss, 2008; Gioia *et al.*, 2012). The final data structure is presented in Annex B, which summarises the second-order topics on which the dynamic consistency mechanisms are built.

3.5 Rigour and Quality of Research Design

Making a relevant, credible and interesting contribution to the body of knowledge is at the heart of every research project. The previous sections described the methodological approaches selected to achieve this aim. Yin (2003) and Easterby-Smith *et al.* (2015) propose several aspects that help researchers to assess the quality and rigour of their research project. Table 11 displays the five most relevant aspects alongside the contingency approaches taken in this research.

Beyond these prominent tests to judge the quality of a study's design, a researcher's behaviour with respect to ethical considerations is crucial to ensuring a qualitative and rigorous research project. Miles *et al.* (2014) urge researchers to reflect on a set of ethical matters; these, with the author's reflections, are as follows:

- *Informed consent*: All interviewees were informed in writing before each interview that the interview shall be recorded. Explicit permission of every interviewee was obtained before voice recordings were started.
- *Honesty and trust:* The intentions of interviewing informants and observing production sites were clearly stated in writing when case study firms were first contacted. Non-disclosure agreements were signed with the majority of firms.
- *Privacy, confidentiality and anonymity*: The abovementioned trust was established by granting anonymity for every informant and the firm. Moreover, when interviewee quotes were shared with another firm, the consent of every interviewee was obtained. Information that had revealed interviewees' identity was rephrased or omitted in interview transcriptions.

Finally, the data was interpreted fairly throughout; when contrary findings occurred, these were considered and discussed in the findings chapter, both within- and cross-case.

Table 11. Approaches applied to ensure rigour and quality of research design

Quality and rigour aspect	Aim	Applied approach
Construct validity	Establishing correct operational measures for the studied concepts	- Multiple informants for each BM - Triangulation of two sources of primary data with secondary data - Extensive, dialogic review about findings with informants; directly and during workshops
Internal validity	Ensuring correct inferences are made; mostly valid for explanatory or causal studies only	- This study is exploratory in nature; however, to ensure correct inference during analysis, interviewee explanations were cross-examined on differences and often cross-checked with informants
External validity	Defining the domain to which a study's findings can be generalised	- Applied literal and theoretical replication logic for selecting multiple case studies - The two most relevant manufacturing sectors in Europe were examined
Reliability	Ensuring that the operations of the study can be repeated with the same results	- Systematic case study protocol was established during three pilot studies and followed throughout the six case studies - Multiple case studies were conducted - Interviews were voice recorded and transcribed thereafter; detailed notes were taken for transcribed interviews as well as for those that could not be recorded - Notes, transcriptions, codes and secondary information were stored in a case study database

3.6 Chapter Summary

This chapter laid out the modest subjectivist perspective of the thesis on the reality of nature and knowledge as the basis for research design choices. Based on these, an inductive research strategy was chosen to describe patterns of activity alignment in an I4.0-driven BMI, operationalised by a multiple case study approach. Six European manufacturing firms, operating in the automotive supplier sector and the machine- and equipment manufacturing sector, were selected using replication logic. Theoretical data coding as the method of choice for analysing data was explained, followed by measures to ensure the rigour and quality of the research design.

4. Case Studies

4.1 Overview

This chapter provides details of the six examined manufacturing firms that were used as case studies to obtain evidence from a primary source to answer the earlier posed research question. Table 12 provides an overview of these firms. Sections 4.2, 4.3, 4.4, 4.5, 4.6 and 4.7 introduce the case studies Delta Steel, Epsilon Racing, Zeta Home, Eta Drive, Theta Heating and Iota Electric, respectively. Each case study is narrated in a descriptive format, starting with the firm's products and services and competitive advantages, and followed by their I4.0 visions, strategies and projects that set out to change the firms' activity systems, i.e. their BMs. Their newly emerging I4.0 BMs are discussed, thereby giving consideration to the dynamic consistency of the I4.0-driven BMI. Finally, Section 4.8 summarises this chapter.

Table 12. Overview of selected case studies

Firm acronym	Industry/ Location HQ	Revenue [million EUR]	No. of employees	Main product
Delta Steel	A, S / DE	800	1,000	Precision steel strips
Epsilon Racing	A / DE	850	4,000	Automotive suspension
Zeta Home	ME / NL	400	2,000	Home stairlifts
Eta Drive	A / [1]	2,000	8,300	Automotive chassis systems
Theta Heating	ME / DE	1,400	4,000	Underfloor heating systems
Iota Electric	A / HU	481	1,800	In-car entertainment systems

A: Automotive supplier; ME: machine and equipment manufacturing; S: steel
[1] Country not to be disclosed – German-speaking, European country

4.2 Delta Steel

Background information

Delta Steel is a precision steel manufacturer based in Germany. With 1,000 employees, Delta Steel produces customised, high-quality, hot-rolled precision steel strips and special profiles for the global automotive sector and the mechanical engineering sector. Customers primarily manufacture safety-critical components and highly stressed and wearing parts for vehicles. Founded in 1846, Delta operates one steel processing plant and a small steel cooking plant in a joint venture, generating a yearly revenue of about 800 million Euro. Delta is headed by two executive officers who chair a board of eight directors.

BM description

Delta's interviewees consistently described their BM as "the pharmacy of steel", referring to a high degree of flexibility, delivery speed and small lot sizes as desired by customers. High quality was described as a basic product characteristic, but customers demanded more than "just" high quality. More than 70% of the entire production volume has a batch size of one, accounting for one steel coil, with every coil being customised to specific dimensions and material properties. According to Delta, a batch size of one for customised steel is extraordinary for the following reason: one batch of steel from a steel cooker with a custom-made material specification has a quantity of about 270 tonnes, which is also roughly the smallest batch size that steel makers usually sell to customers. However, Delta sells batches as small as 10 tonnes, although they must always produce 270 tonnes, realised by holistic planning procedures across the entire customer spectrum that allows material specifications to be grouped by individual orders rather than customers. These very small lot sizes, in combination with a rapid delivery, constitute a unique selling point that allows Delta to charge a premium price. This BM was enabled by substantial changes made to the previous BM, which will shall be discussed next.

I4.0-related changes to the BM

Delta Steel is widely recognised as one of the first examples of an I4.0 lighthouse in terms of vertical and horizontal integration, established before the term I4.0 was popularised. In the realm of the 2008 global financial crisis, Delta started to plan significant changes to their BM. They started intensive discussions and workshops with their customers to find out what customers demanded, needed and desired, and why customers bought at Delta. They found that customers most desired high flexibility and a short lead time. To meet customer desires, a vision was developed to become the "pharmacy of steel", indicating small lot sizes, custom-made, and delivered at short notice for a premium price. To achieve this vision and thereby meet customers' demands, Delta laid out a comprehensive strategy: (1) a continuous-improvement program with a focus on preventive maintenance and set-up time reduction, aiming at high availability of equipment and the accommodation of small lot sizes; (2) a re-engineering of their entire business process landscape, comprising both technical and administrative processes (this, with the first aspect, provided the foundation of the new strategy); (3) an interoperability with customers by horizontal integration of ERP systems; (4) a vertical integration of processes from device-level to enterprise planning into a central data lake to achieve a high-resolution digital picture of their own operations.

A central data lake was supposed to serve as the basis for interoperability with customers, source for rapid decision-making and process improvements based on the use of data analytics. At the same time, the technological foundation was laid for more flexibilisation in the factory, realised by an upgrade of production equipment to the latest control systems and further automation-related changes. Due to their wide reach and their significance, these changes were only completed in early 2014, taking six years from the initial idea to completion. One of the last “official” sub-projects was the launch of a business intelligence platform, providing workers and management with granular and individualised real-time reports and analytics about their areas of responsibility, based on the central data pool. The platform has so far been used for more than half a dozen (mobile) apps to improve flows of information and materials across the business, from a customer app to a maintenance app or an app for the information of the plant’s firefighters.

Issues regarding dynamic consistency

One significant misstep at Delta during their BMI was that the vision and aims of changes made were not sufficiently communicated across the company. In particular, many projects took place in the “machine room” of the firm, without visibility, and increased the workload for many employees who now had to work on sub-projects as well as their main jobs. Moreover, the increase in flexibility also required production staff to move some shifts to the weekends, although sometimes not all shifts were run during the week – employees were upset and thought this was due to bad production planning.

Another problem highlighted was that when the business intelligence platform was first started, many discussions among employees and heads of functions arose, caused by mismatching key performance indicators (KPIs) in the new system and the legacy system, i.e. paper notes and spreadsheets. The first change to stop these discussions was the board’s decision to only use and believe in the new system data; the second was a process to develop mutual semantics for KPIs across the business to bring everyone onto the same page.

4.3 Epsilon Racing

Background information

With more than 4,000 employees, Epsilon Racing develops and manufactures innovative high-tech product solutions for suspension technology for premium cars and racing cars. Markets served include original equipment and aftermarket parts. An executive board of three people governs five plants globally plus a research and development centre based at their headquarters in Germany, generating an annual revenue of 850 million Euro.

BM description

Epsilon Racing's core competencies are in product development, demonstrated by their position as the number one partner for large premium cars and racing car teams in developing new technical solutions. Based on this technological strength and their strong brand in niche-segment racing cars, Epsilon set out to grow their revenue since 2013 by serving the small- and medium-size premium car market and thereby experienced fierce growth. However, pampered by Epsilon Racing's engagement in the niche markets, customers apply pressure on Epsilon to also deliver bespoke products in small batch sizes for the volume-intense medium-size premium car segment. The resulting number of product variants is not only difficult to manage with respect to the supply chain but finalising the product design of each variant is subject to extensive product testing. For several years, Epsilon Racing tried to continue satisfying customers with superior product innovations, but did not reconfigure their value-adding activities to account for process stability to deliver the highest quality in large volumes. Having realised this mismatch, Epsilon started to reorganise the firm in 2014/2015, which also included the launch of Six Sigma and lean management as a means to achieve operational excellence for satisfying customers.

I4.0-related changes to the BM

Two specific projects based on I4.0 principles were initiated in 2014/2015, aiming to address the challenges described above.

First, Epsilon's director of technology and innovation initiated a project to build simulation capabilities to enable a near-complete digital twin of their product that is able to simulate the dynamic function of that product throughout its life cycle to reduce the scope of testing. In a joint research project with an OEM (original equipment manufacturer) car maker, this purely digital simulation is complemented with a digital/physical simulator of the relevant automotive system, including a simulator of road environments half the size of a football pitch. Moreover, Epsilon Racing aims to reduce the scope of variants through a modular component architecture, which is enhanced by a software system. These two arrangements aim to create and deliver the demanded customer value of flexibility and speed, and at the same time improve the internal efficiency of operations by improving the flow of information based on linking procedures in product development, engineering and production.

Second, to manage and improve the quality, dependability and reliability of operations, Epsilon's director of operations initiated the introduction of a global MES software solution. The aim of the MES software was to capture the process data for every product throughout the entire value chain; process data may include insertion pressures, audio testing profiles, torques, required machining times, etc. Equipped with a QR code, an individual genealogy is created in a SSOT database. According to Epsilon, capturing the process data of every product is unprecedented in their market segment; competitors only capture process data for entire batches. These process data from every process step will be used to have full traceability of the product and, more importantly, Epsilon aims to improve product quality by using artificial intelligence algorithms to unravel unknown patterns between process steps. For example, the algorithms might be used to determine if a specific test pattern from a single component can predict how susceptible to error the assembled system will be.

Issues regarding dynamic consistency

Interviewees, including three directors and the CEO's assistant, commented on a lack of business vision alongside a common approach towards digitalisation, indicating a lack of leadership. This lacking direction has resonated in isolated I4.0 projects, as described above, that have great potential to be closely aligned with each other to improve business value and customer experience.

4.4 Zeta Home

Background information

Headquartered in the Netherlands, Zeta Home is a leading supplier and technology pioneer in their market, developing, producing and selling customised stairlift solutions for private homes. Globally, more than 2,000 employees in two locations manufacture bespoke, customised customer solutions, generating an annual turnover of 400 million EUR.

BM description

Zeta Home manufactures mechatronic product systems that provide assistance to elderly people, or people with walking impairments, who face difficulties moving in their own home. Up to the point at which customers contact Zeta Home, they have always had evaluated other options that may prevent them from buying Zeta's product (e.g. removal of stairs, steps or other structural differences in height), as it is often a visible confession, to themselves and others, that they are getting "old and frail". As customers do not desire the type of product Zeta Home sells, they do not usually contact Zeta until an acute accident happens, which usually includes hospitalisation. It is such incidents that trigger the customer to contact Zeta, despite their moving difficulties usually having built up over months or years. Products are custom-made, designed and produced based on precise measurements of the surroundings in customers' houses. They get permanently installed as "inventory" in customers' houses, fixed to stairs. Product sales are almost exclusively initiated through newspaper and Google adverts, and potential customers contact Zeta Home almost always by phone. For sales and service, Zeta relies on a mix of their own staff and service contractors. Having established an emotional sales strategy, customers are always personally visited 1–2 days after their initial call. The delivery time from the first personal visit to the installed product is, on average, more than 42 days. Along with the product, Zeta or their service contractors sell maintenance services to customers, ensuring a yearly check-up and support in case of malfunctions. The product's end of life always corresponds to the customer's end of life.

I4.0-related changes to the BM

From extensive customer surveys in 2014 – 2015, Zeta Home found that customers value product reliability (uptime) over rapid delivery (a measure from order to installed product). However, further analysis suggested that a delivery time of 14 days from order to ready-to-use installation of the product is desired by customers. Accordingly, Zeta set up a cross-functional project team including sales, design, engineering, production and IT to evaluate the changes required to enable 14-day delivery. Based on ramp-to-ramp value stream mapping with support from external consultants, the project team identified redundant and superfluous flows of information between salesmen, design, engineering and production as the main contributor to delivery time. Once production documents were generated, production took only 2 days, as the factory equipment already supports computer-aided manufacturing, enabling machines to directly read computer-aided design (CAD) drawings. Zeta generated ideas to achieve their 14-day delivery target, resulting in two interlinked projects: (1) streamlining the entire flow of information by setting up a new IT system that integrated all IT systems from sales to production, either by substituting old IT systems or by making existing systems interoperable; (2) replacing a measurement system for the customer's environment based on a tape measure and camera with a newly developed and patented measurement solution based on Microsoft's HoloLens, which scans the customer's environment and generates a CAD file. By means of these two projects, Zeta managed to cut down delivery time to 14 days in most countries.

Issues regarding dynamic consistency

Reducing the delivery time to 14 days has not yet been possible in all countries, as country sales organisations are independent profit centres that are responsible for logistics and shipping. Consequently, some countries have optimised their transport from the factory to customers based on costs, and not on time, meaning that the flow of material here is not optimal due to a misalignment of incentives across functions. Nevertheless, the disturbed flow of information between salespeople and production has been identified and solved due to the 14-day-delivery project. The root causes for this disturbed flow of information were manifold, from non-standardised sales processes in every country to isolated IT systems in sales, design and production that could not communicate with each other, as well as employees who did not use the IT systems provided but relied on paper and pen. Moreover, measurement of the customer's environment was performed by a salesperson using a tape measure and a camera; they would then complete multiple paper documents to configure the customer's product, and send this via mail or email attachment to a drawing engineer who prepared a drawing. The drawing would be sent back to the salesperson for approval, and finally to a manufacturing engineer.

Moreover, the workshops conducted during this research project highlighted possibilities for introducing further smart, connected sensors into the lift, for advanced services – a pilot project to equip lifts was started only a few weeks after the case study report was presented to the board of directors.

4.5 Eta Drive

Background information

Based in a German-speaking, central European country (country cannot be named due to non-disclosure agreement), Eta Drive serves as a Tier 2 and Tier 1 supplier of safety relevant mechatronic chassis systems for the global automotive industry. A global footprint of 8,300 employees in 17 manufacturing sites and four research centres accounts for an annual revenue of 2 billion EUR. Eta Drive has undergone rapid growth in recent years, fuelled by new product developments that make security-relevant mechanical components redundant with the use of software. These products are core components for autonomous vehicles. The growth has been realised by a cost-sensitive industrialisation including the ramp-up of multiple new production facilities in Asia, Eastern Europe and North America.

BM description

Due to the overall developments in the automotive sector towards autonomous driving, electrical drive systems, and an increased focus on new "mobility BMs", the entire industry faces the challenge of massively investing in radically new product-service innovation. At the same time, OEMs have drastically increased cost pressure on suppliers for current and future serial products. Eta Drive has managed to meet both of these challenges thanks to the long-term thinking of their executive board, who have always put attention on expanding the firm's product and skill portfolio, from purely mechanical components in the early 1990s, to mechanical systems, followed by mechatronic components, to today's product systems. This continuous innovation was financed by a distinct focus and strength on both technical industrialisations, by engineering and patenting their highly automated machine systems, and on operational excellence through Six Sigma and lean production. The latter is demonstrated by Eta Drive's multi-award-winning production system, which was developed in-house, in the style of the Toyota Production System.

I4.0-related changes to the BM

Triggered by the challenges discussed above, the executive board set up a cross-functional project team, responsible for developing a digital way forward for the business in 2013/2014. After an intensive learning journey with consultants, technology ventures and internally, Eta Drive developed their vision of establishing a global digital factory by 2025, referring to a global real-time connectivity of all factories and the ability to control and manage these factories from one central location. To achieve this vision, two major projects were launched. The first is a MES-MOM platform project to establish a global manufacturing execution system (MES) and manufacturing operations management (MOM), interoperable with the global ERP system. Its aim is to integrate and interlink all obtainable data (product quality data, operating data from equipment, order planning and scheduling data, data from products in their usage phase) into one SSOT. Data are made usable by a layer of software applications writing into and reading from this SSOT. This project began in 2014 and the pilot of the MES-MOM platform was successfully launched in September 2019 in one plant. The second major pillar to realise a digital global factory is the development of a systematic product life-cycle management software platform – like the MES-MOM platform, but focused on product development and engineering data. This project started in spring 2017. Both software platforms are planned to be fully interoperable by 2025.

Issues regarding dynamic consistency

In general terms, the case study revealed only a few inconsistencies, as the two major projects set out to integrate large parts of the activity system closely and the leadership team showed significant passion for driving digitalisation and cognitive skillsets. However, the current revenue model is fully based on product sales and bespoke product design services. Triggered by discussions during the workshop, in the course of the case study, Eta Drive’s COO took the proposed options for alternative revenue models as the ignition to start a project with his CEO colleague for discussing alternative revenue streams with customers. Moreover, the data-gathering framework of this thesis was officially included in Eta Drive’s yearly strategy update workshops. One of the most significant synergies seems to lie in advancing end-to-end engineering in the form of simulation capabilities, as this holds opportunities for a greater customisation of products and more rapid product ramp-up, both due to decreased product-testing efforts. However, developments in this space are subject to substantial investments and as such, the improvement of simulation capabilities was sacrificed for the benefit of other projects.

4.6 Theta Heating

Background information

Theta Heating is an internationally active manufacturing firm in the field of sanitary and heating technology, including underfloor heating systems with its headquarter in Germany. Theta is a world market leader in their segments, providing innovative product solutions for the private and public sectors. Globally 3,600 employees at ten locations generated 1 billion EUR turnover in 2015; by 2017, more than 4,000 employees had generated over 1.4 billion EUR turnover, indicating fierce organic growth that was even reported to have accelerated in the past two years (figures later than 2017 were not shared; as Theta Heating is family-owned, data are not publicly available to date).

Five business units report to the executive board: (1) the technology business unit, including research and development alongside product development and design; (2) the supply chain business unit, including manufacturing engineering, production and logistics; and (3) three sales units that split global sales areas among them. The business unit heads all serve as executives on the board, complemented by a CEO, CFO and several members of the owner family. Seven central functions, including digital transformation and administrative functions, report to the executive board as well.

BM description

Theta's BM is characterised by a wide range of premium products for installation solutions that are produced to stock. Products predominantly include mechanical components, about 80% revenue, but increasingly also mechatronic system solutions that bundle mechatronic components with electronic control units. Theta manufactures to the highest quality standards and has a vertical business integration of nearly 100%, excluding raw material production. However, Theta develop their own raw material, so most products are manufactured with patented materials that are exclusively supplied to Theta. In addition, Theta also develop their own electronic sensors, actuators and software. They operate a large variety of manufacturing technologies, including foundry, electronics development and production, with a focus on metal-cutting technology. Theta's quality standards are backed by a strong focus on operational excellence including lean production and Six Sigma. Product sales is exclusively a three-stage distribution – installed in buildings, customers are both end users and craftspeople, including plumbers and other building workers. Included in their focus on quality is a quality of services, operationalised by a large network of service technicians providing support service to craftspeople.

I4.0-related changes to the BM

In 2016, Theta established two dedicated teams for digital transformation and I4.0. The digital transformation team is staffed with five people reporting into the executive board, aiming at developing digital service solutions and new BMs based on the wide range of products. The I4.0 team is based in the supply chain business unit aimed at increasing efficiency in Theta's own operations by means of machine connectivity and data analytics. Moreover, in 2018, the technology business unit launched an open innovation office at a technical university aimed at infusing product development with university collaboration.

Issues regarding dynamic consistency

These three distinct structures to drive innovation in general, and digital innovation in particular, are acting without a shared vision or consistent strategic pathway regarding digitalisation, leading to overlapping activities. Coordination between these teams is only based on the drive of individuals. Interviewees reported a focus on EBIT (earnings before interest and tax) margin and growth as the determining factors. Besides concepts, the digital transformation team and the open innovation office had, up to the time of the case study, not had any approved projects. The I4.0 team started to develop a new MES solution in-house, prototyped in two pilot areas in one production plant. Six months after completing the case study interviews and workshops, the entire digital transformation team had left the company, including the director of digital transformation, although the team was not officially disbanded.

4.7 Iota Electric

Background information

Iota Electric is an automotive supplier based in Hungary, founded in 1987. With about 1,800 people, Iota Electric manufactures customised electronic components for the global automotive sector, including in-car entertainment systems. In recent years, it has particularly focussed on key components for hybrid and fully electric vehicles. Iota was acquired in 2002 by its mother firm, which was founded in Germany in the late 1800s. Iota Electric is headed by a managing director who chairs a board of four directors alongside four factory heads. In parallel with a steep increase in growth of the automotive industry in Eastern Europe, Iota has also grown significantly, more than doubling its production value from 100% in 2010 to nearly 240% in 2018 (revenue 2018: 481 million EUR with 1,800 employees). Moreover, the specific region where Iota Electric is based sees an unemployment rate of only 2%. Iota's managing director reported significant challenges in meeting the demand for new personnel due to the continuing rise of production value and departure of workers seeking new jobs elsewhere due to the low unemployment rate.

BM description

Iota's core competencies are technology-driven, customer-made product development and the rapid industrialisation of large-volume serial productions against the highest standards of quality and reliability. A strong focus on operational excellence, including lean production and Six Sigma, is complemented by a high degree of automation with dedicated process technology exchange mechanisms across the locations of their mother firm. In recent years, Iota Electric managed to balance two fundamental strategic avenues, giving them a very strong position in their market segments: product differentiation through new product innovation and cost leadership through strong industrialisation. Based on their close customer relationships, Iota anticipated the shift towards electric vehicles and started to closely collaborate with customers and suppliers to develop new technical solutions for electric vehicles around 2010. Iota's product range has changed significantly during the last few years from a pure electrical components manufacturer to a provider of solution systems.

I4.0-related changes to the BM

To strengthen their leading position on the product innovation side, a software development centre with hundreds of data engineers and software developers was established in 2017 in Eastern Europe to master data that are generated by the products in the field. Moreover, to further drive the efficiency and productivity in their factories, Iota established an I4.0 vision for their factories. This vision essentially entails two distinct pillars: (1) introduction of a company-wide MES system as a SSOT for manufacturing process data. (2) Establishment of a cross-functional I4.0 team, who is responsible for identifying and executing projects that utilise the database of the MES system, and who introduces cobotics, robotics, additive manufacturing and automated guided vehicles into the factories.

Issues regarding dynamic consistency

Generally, a high degree of consistency was observed, supported by Iota receiving a prestigious I4.0 “Factory of the Year” award in 2018. Nevertheless, the use of end-to-end engineering, in the form of weaving together product design functions and production, is rather rudimentary.

4.8 Chapter Summary

In this chapter, the six in-depth case studies and their BMs were presented together with the changes that these manufacturers have made to their BM using I4.0 principles. The next chapter examines the results of the investigation of these six companies, the main themes that arose, and similarities and differences between the six cases that are valuable in answering the research question of this paper.

5. Findings

5.1 Chapter Overview

In the previous chapter, each case study was described individually based on its I4.0 journey and its resulting BMI. This chapter collectively substantiates findings across these case studies to identify common patterns, and thereby answer the research question: "What are the microfoundations of dynamic consistency in I4.0-driven BMI?" Thus, this chapter operationalises the idea of dynamic consistency by dismantling its impact on the three design themes of an activity system: content, structure and governance.

Sections 5.2, 5.3, 5.4 elaborate on the findings and provide evidence about how a manufacturing firm achieves dynamic consistency. The findings suggest manufacturing firms should: (1) organise their I4.0-driven BMI with a value focus on data and software as a catalyst to enhance existing domain and customer experience; (2) structure their I4.0-driven BMI activities through an active flexi-directional interlinkage of cyber and physical activities; (3) govern their I4.0-driven BMI through agile working ensembles. Next, Section 5.5 argues that the activity system perspective on BMI does not sufficiently explain the notion of dynamic consistency. Rather, it was found that crucial aspects for the dynamic consistency of an I4.0-driven BMI are related to viewing the BM from a cognitive schema perspective. A proactive mindset with integrity as the cognitive foundation sets out rather intangible mental modes, including behaviours, beliefs and habits, that are imperative for creating and running a dynamically consistent I4.0-driven BMI – depicted as a plinth, without which the activity system loses its footing (Figure 9).

With reference to the applied content coding technique, each section first explains the aggregate dimension that represents the respective mechanism for operationalising dynamic consistency, as depicted in Figure 9. The second-order themes and first-order concepts associated with this aggregate dimension are subsequently explicated. For a detailed data display and additional data support see Appendix B and Appendix C. A summary of the chapter is provided in Section 5.6.

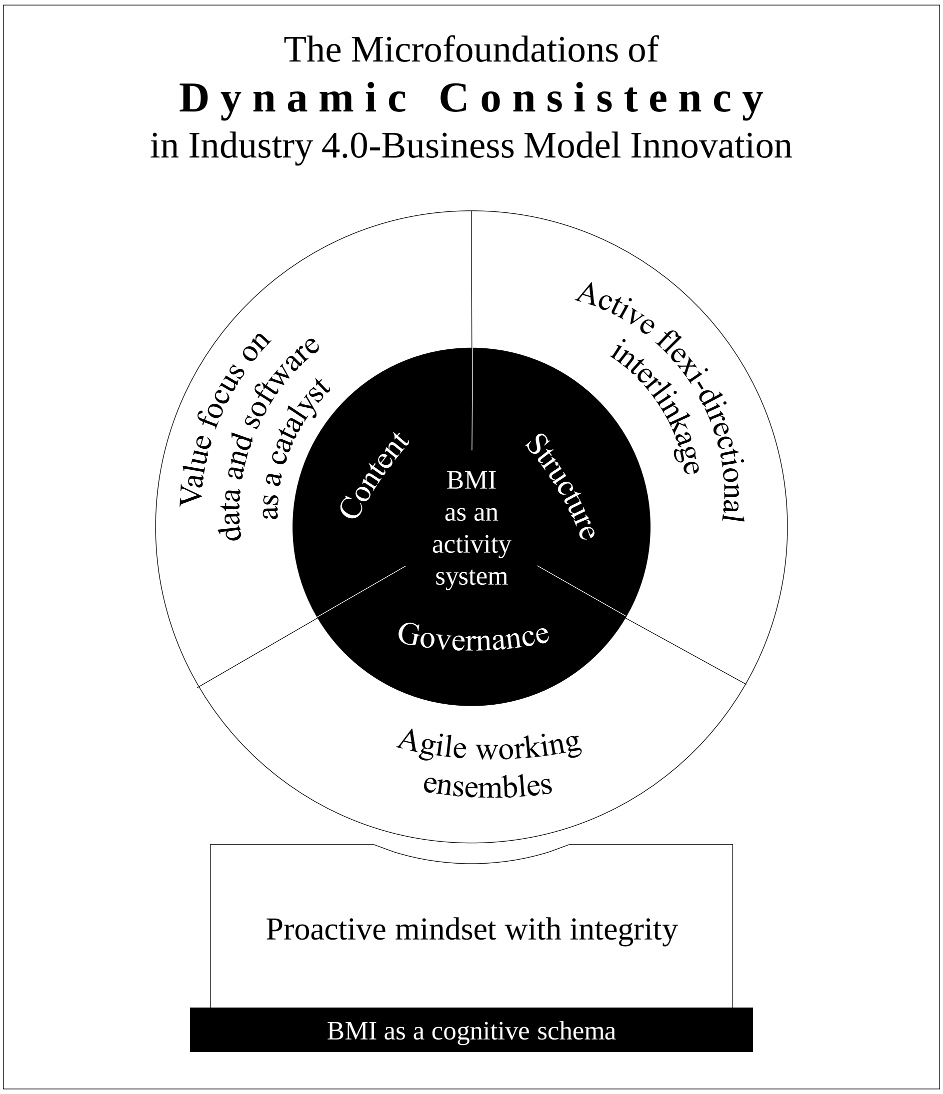

Figure 9. Synthesis of the findings: the microfoundations of dynamic consistency for Industry 4.0-BMI

5.2 Content – Value Focus on Data and Software as a Catalyst

The findings suggest that in the wake of the Fourth Industrial Revolution, manufacturing companies are concentrating their activities on: (1) leveraging data and software as a catalyst to enhance existing domain expertise and customer experience; (2) digitalising product and service offerings; (3) cloning physical activities coherently into digital. More specifically, data and software are used by manufacturing firms to enhance the flow of material goods and information in their existing fields of expertise or to tap into new fields of expertise, both on the product-services side and on the value-adding side. Improving the information flow and/or the physical flow of goods by reorganising activities through leveraging data and software follows the higher goal of increasing customer experience for a sustained competitive advantage. Not all examined manufacturing firms showed the full spectrum of this value focus; nevertheless, this chapter describes its principles.

Across the case studies examined, manufacturing firms attempted to utilise digital solutions to rearrange their activity system to optimise flows of materials or information, focused on their customers. The dense interplay between customer needs, product-service offerings, value-adding activities and digital solutions is nicely represented by a remark made by Eta's COO about their journey to develop a new product for autonomous vehicles: *"Based on the customer drive towards autonomous driving, we have developed new competences, mostly software, and launched these new products. However, ramping up production efficiently and achieving scaling effects is crucial to being correspondingly competitive, with economic purchase prices and own value chains. This will provide further financial leeway to build expertise in data fusion of all vehicle sensors, which is currently done by the automakers."* Similarly, Delta's director of IT explained how the customer, product, manufacturing and digitalisation are centrally linked in Delta's BM: *"Quality, small lot sizes, speed and loyalty – customers want all at the same time. Our action must be a reaction to the customer. Hence, we are aiming to establish flexibility and volatility as a new, additional product-service feature. […] For me, the potentials of the toolbox Industry 4.0 have to serve the business model and thus the customer."*

The remainder of this chapter is organised by following the three mechanisms of value focus: Section 5.2.1, leveraging domain expertise with data and software as a catalyst; Section 5.2.2, digitalising product-service offerings; Section 5.2.3, cloning physical activities coherently into digital. The data structure for the aggregate dimension, termed the value matrix, is presented in Figure 10. For data reporting, key quotes are displayed in the according sub-sections and quotes that mapped to the first-order categories are provided in additional tables.

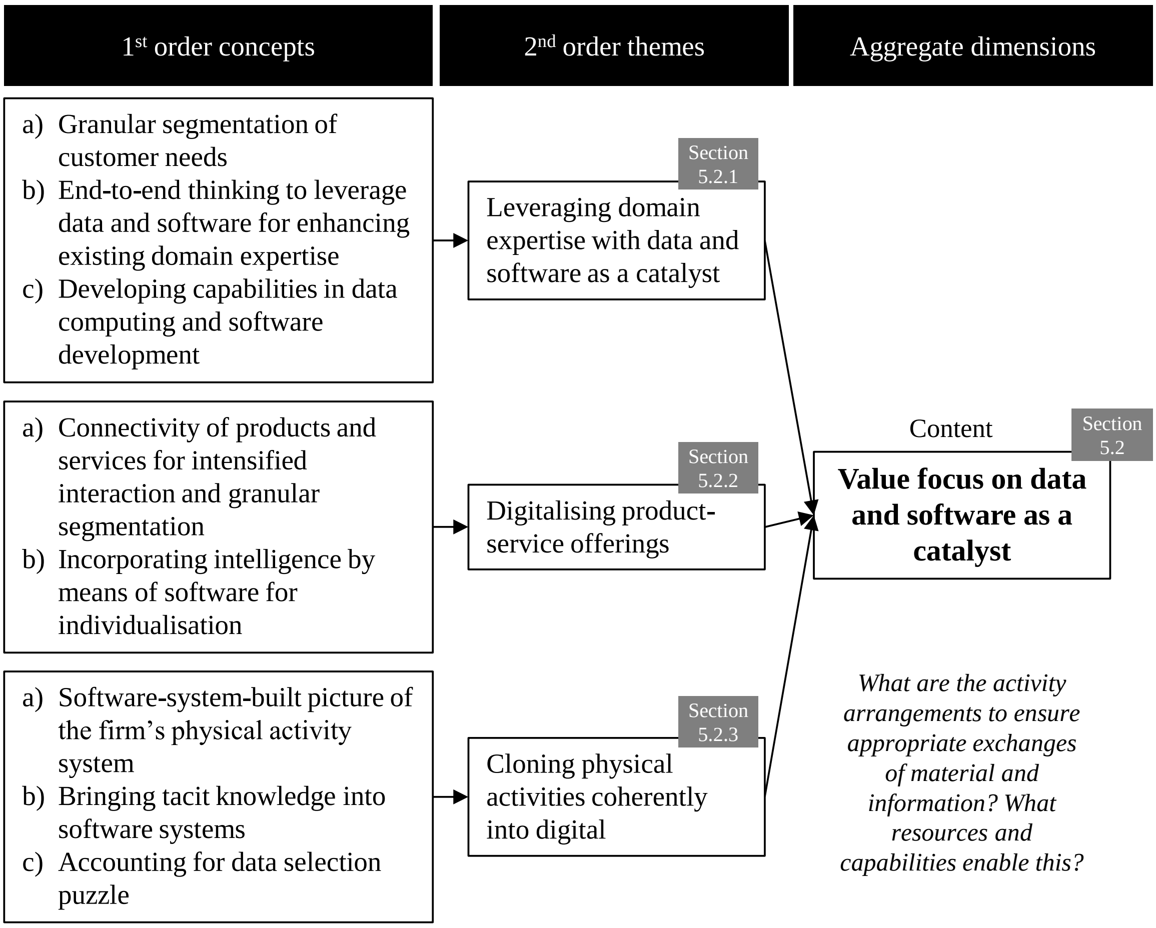

Figure 10. Coding synthesis: factors crucial to achieving dynamic consistency in an I4.0-driven BMI content view

5.2.1 Leveraging Domain Expertise With Data and Software as a Digital Catalyst

This section is based on a finding that emerged across the entire sample of case study firms: the (re-) organisation of activities in an I4.0-driven BMI is focused on the granular segmentation of customers – dominated by leveraging data and software as a catalyst to better comprehend individual customer needs and to (better) realise flexible, individual-customer solutions based on this segmentation through improved flows of information and materials. Figure 11 depicts the role of data and software as a catalyst that leverages existing domain expertise in various fields, connecting customers, products and services, and value-adding activities. Based on the findings, the leveraging of data and software for enhancing the existing knowledge base can be grouped in to the following three aspects: (a) granular segmentation of customers' individual needs through data-supported and software-facilitated information; (b) end-to-end thinking to leverage data and software for enhancing existing domain expertise; (c) developing capabilities in data computing and software development to increase flexibility and responsiveness.

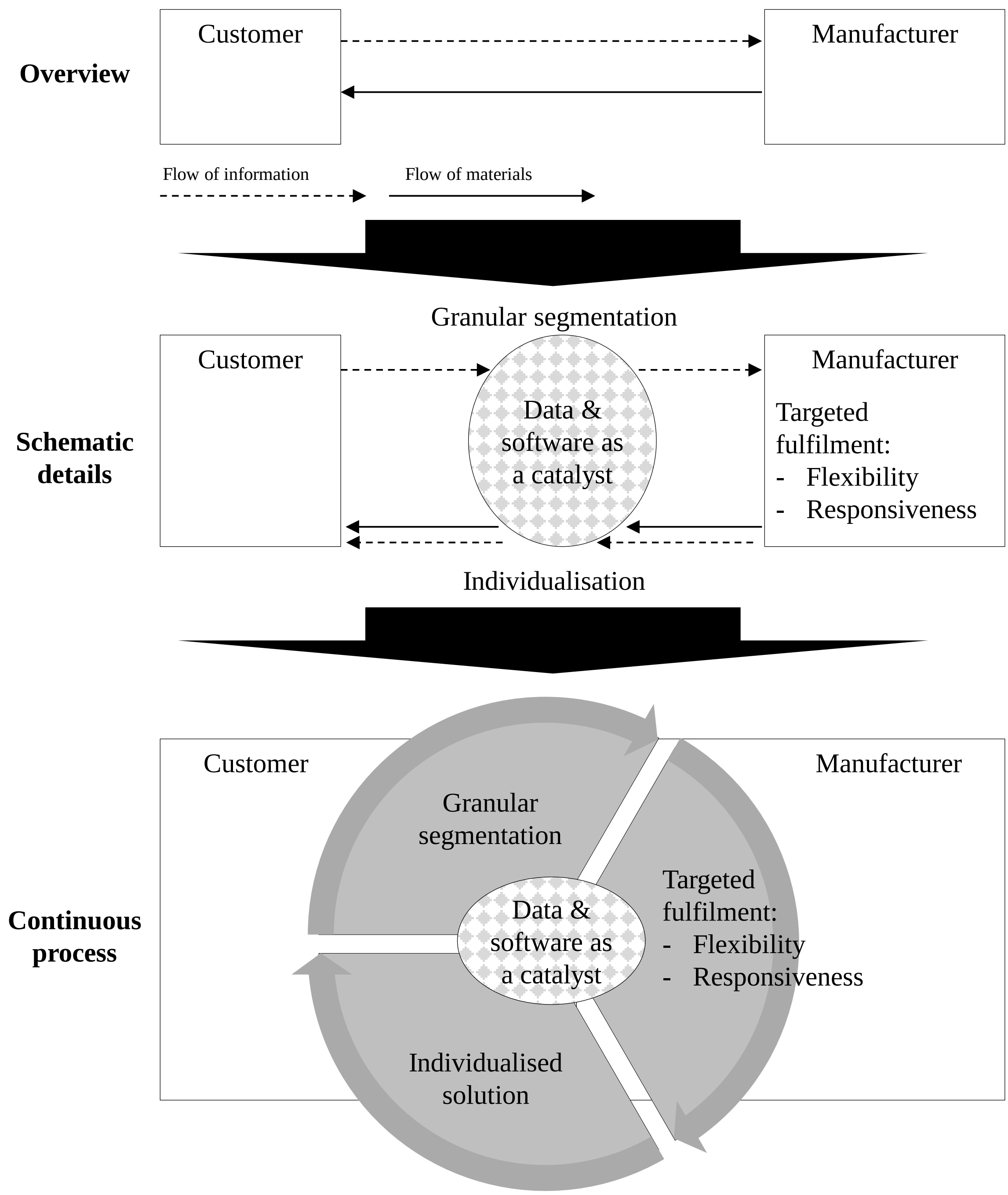

Figure 11. Schema depicting the leveraging of existing domain expertise with data and software as a digital catalyst: Manufacturers are advised to concentrate on customers by leveraging data and software to enrich existing domain expertise and thereby enable unconventional solutions in value-adding activities and product-service offerings to enhance customer experience.

(a) Granular segmentation of customer needs

Customers' needs are to be understood as more than customers expressing what product or service they require; it is to understand the job each customer desires to do for satisfying his very own customers (Christensen *et al.*, 2016). Although not all the examined firms followed a rigorous approach to better understanding customers' needs for more granular segmentation, some case studies showed approaches that demonstrate the principle of how a thorough understanding of customers' needs and the software-based facilitation of the underlying data is the basis for reorganising the flow of information and physical materials to then enhance customer experiences with individual solutions. In short, the general principle observed across the case studies is that data and software are leveraged as a catalyst to granularly segment customer needs.

About a decade ago, the steel manufacturer Delta started customer surveys and intensive dialogues with their customers to examine what they needed, what they valued, and how Delta could help them satisfy their own customers in turn. Delta's director of sales and production planning explained their approach as follows: "*We have always listened very strongly to our customers and we still do. We have a very close relationship with our customers. Through so-called development dialogues, we explore exactly how we have to evolve so that our customers can evolve to have an advantage in the market*." From this intensive and thorough examination, Delta learned that the most desired customer needs were flexibility and speed in the form of rapid product delivery – the option to order small lot sizes and change product orders shortly before the aimed delivery date. Based on these needs, Delta set out to change their BM from delivering large batch sizes in weeks to offering small batch sizes of one, delivered in days. They call this BM a "pharmacy of steel", indicating the ability to granularly segment customer needs into the smallest desired unit, and the ability to respond swiftly to changing customer requirements.

The basis of Delta's BM is, among others, to pool data as diverse as customer orders, their applications and their customers' applications, supply material specification, internal operations data, and a myriad other data into one central database for further use. This enables the granular segmentation of customers (and their orders), and to achieve a responsiveness that allows the flexible and rapid response to this fine-grained segmentation through individualised customer solutions, alongside other things achieved through a re-grouping of individual orders. Delta reached this by improving flows of information on the basis of fully interoperable ERP, MES and business intelligence software systems that led to better flows of physical goods, down to the quantity of one, within Delta's factory and between suppliers, Delta and customers. Delta's director of controlling and business excellence pointed out the changed flows of information and material, based on data: "*Data themselves do not have any value, but the information I draw from them and the different ways of working due to data are so valuable*." Many data are used to provide customers with real-time insights about their current orders as well as capacity utilisation for further order bookings. This focus on data and advanced software solutions to process and optimise the flow of information for a fine-grained segmentation "*helps us to strengthen our ties with our customers by providing them with insights into our processes,*" as Delta's director of sales and production planning reported. The same applies to new, customer-specific value propositions in the course of the "pharmacy of steel" BM, which are only enabled by the ubiquitous real-time flow of information within and between software suites.

Similarly, Eta's COO noted that data become increasingly important in discussions with their customers: "*Currently, they are very keen on getting data.*" Eta has not recently engaged in fully innovating their value propositions based on data and software. Nevertheless, compared to Delta, Eta started to realise the importance of data and software for attaining benefits based on changed flows of information or materials within their own manufacturing environment and to prepare more individual solutions, rapidly delivered. The latter is evident in their MES-MOM and PLM projects that aim to shorten product development times and make operations more efficient and responsive, as Eta's director of high-performance manufacturing technology explained: "*We must have our design data in our PLM software machine-readable. Once all tolerances are machine-readable, I can simply compare existing designs with new customer requirements, and further read these data with my production machines, without someone typing them into a CNC [computerised numerical control] code. Moreover, once a customer requires changes, I can immediately incorporate them in the system and introduce them into our worldwide production facilities.*" A further example for fine-grained segmentation, flexible and responsive fulfilment and customer-specific solutions is Zeta's innovation towards their 14-day delivery BM.

Data analysis clearly demonstrates the role of data and software as valuable assets for the reorganisation of activities, as data and software are the backbone of any I4.0-related change to a manufacturer's BM.

(b) End-to-end thinking to leverage data and software for enhancing existing domain expertise

The findings suggest that, to utilise the undisputed power of data and software, manufacturing firms need to embrace end-to-end thinking. In particular, ideas for interesting data combinations and impactful use cases that may have the potential to improve the flow of information or materials are often subject to detailed domain expertise.

The findings indicate that it is important to sensitise the entire manufacturing organisation to the power and importance of gathering, linking, analysing and interpreting all different types of data, as anyone may have ideas for the missing piece in a data puzzle. The understanding of data in combination with existing domain expertise enables the discovery of new information about the flow of materials, the creation of new combinations of (non-) digital products and services, or "simply" more effective and efficient flows of material and physical goods.

All the examined firms gather and store large amounts of data that may be useful for advanced data analytics to specifically improve internal processes, but possibly also the value proposition offered to customers. However, as Iota's director of IT remarked, it is not enough to have an I4.0 team or a task force for data analytics; both exist at Iota, but from his point of view, "*The person who can gain should generate ideas, because they know the process, not the big data tools out there, so they need to generate ideas for how to improve the processes by means of digitalisation; the solution can come from someone else.*" His statement underlines the fact that data, and the software to process and analyse them, are not enough for optimising exchanges of information and materials. The existing domain experts need to acknowledge and embrace their contribution for optimising the I4.0-driven BMI, particularly for generating ideas to improve existing processes, products and services to better serve customer needs.

To accommodate an internal flow of information and ideas, firms must also embrace the need for a rigid, software system-based facilitation of data, as Iota's director of supply chain management and planning pointed out: "*We often tend to blame the 'stupid' SAP system, and start to work in Excel again, but we need to put more effort into the quality of our data within the SAP system, [then] we would not have a problem with it.*" Improving the flow of information and materials with respect to the entire activity system is not possible with the industry-predominant export of data from SAP into Microsoft Excel, as information is not non-redundantly up to date. Therefore, semi-optimal decisions regarding the flow of physical materials might also be taken.

These examples demonstrate the importance of everyone's contribution in a manufacturing firm to advance the I4.0-driven BMI by means of data- and software-based improvements as the core of Industry 4.0. Only when everyone generates ideas and facilitates their data and information in the provided software systems can the flow of information and materials be optimised for holistic steps forward.

(c) Developing capabilities in data computing and software development

To enable the fulfilment of granular customer segmentation, and to encounter flexible and swift responses to customer changes, a basic level of in-house capabilities in the domain of data computing and software development is crucial for manufacturing firms. Several firms, including Epsilon, Eta, Theta and Iota, have identified this need and started to build up expertise in this field.

Eta's digital factory project manager and head of performance management reported, "*We have established a near-shore Centre of Excellence for software development in Eastern Europe with about 800 developers […]. In the beginning, we had support from consulting firms, but we are currently transforming our development activities from external to fully internal, to have the full expertise in-house. Because every day that an internal team member solves problems is worth gold compared to an external person who walks away with this know-how.*" Eta's software centre is responsible for various tasks, including the support service for the MES-MOM software platform, alongside its development and the connectivity of new machines and plants into the platform, but also the development of software apps for specific use cases that run on the MES-MOM platform. All these tasks contribute to increasing Eta's flexibility and responsiveness, as changes to the flows of information and materials can be implemented rapidly in the corresponding software systems. These responsibilities at Eta match with Iota's approach. Epsilon, Delta and Theta took similar approaches on a smaller scale.

The diversity of skills that may be required ranges from machine integration and connectivity, as observed at Eta, Iota, Delta, Epsilon and Theta, to the programming of robots and cobots, as observed at Eta and Iota. Despite the specific type of software development, Iota's head of smart factory underlined the general importance of building capabilities in the chosen data and software field. With regard to the cobot programming skills of his Industry 4.0 team, he remarked, *"The most important thing is the knowledge! And I think it's the most expensive and the hardest part of the story to get guys on board who have at least the basic knowledge that we can further develop […]. In my Industry 4.0 team, it's mandatory for everybody to learn robot and cobot programming.*"

Building up these in-house capabilities is of great importance, as all the manufacturing firms as well as the literature discussed above reported an accelerated speed of customer changes and technical developments in the context of I4.0. Due to the rapid speed of digitalisation and the corresponding ubiquity of data in day-to-day business operations, in-house capabilities in data computing and software development can be considered an elemental support function, like purchasing or controlling. By building a basic set of in-house capabilities, manufacturing firms enable themselves to react swiftly to these changes, by adapting their flow of information and materials through amending their software suites.

This section demonstrated the importance of leveraging data and software as a digital catalyst. First, to use data and software to better understand customer needs to granularly segment them; and, moreover, to sensitise the entire manufacturing organisation so that everyone can have an impact and contribute to capturing value from combining data and software with existing domain expertise. Finally, in-house expertise in software development and data computing is critical to ensuring the timely reorganisation of activities for a continuously optimised exchange of information and materials.

The findings further suggest an explication of the principle of leveraging data and software, providing a more detailed account of how customer experience can be improved by using digital solutions to enrich conventional product and service offerings, and to improve the value-adding activities. The former is discussed in Section 5.2.2 and the latter in Section 5.2.3.

5.2.2 Digitalising Product-Service Offerings

The previous sections outlined the general notion of leveraging data and software as a catalyst for reorganising the activity system to achieve more granular segmentation of customers. A crucial aspect of ongoing and reinforcing granular customer segmentation is the creation of digital (unconventional) product-service offerings that enable the targeted fulfilment of fine-grained segmentation, and additionally reinforce the data basis for this granular segmentation – a reinforcing feedback loop: traditionally, manufacturing firms tend to have their domain expertise in the design, engineering or production of physical products. Beyond products, services – and specifically product-service offerings – increasingly serve as a manufacturing firm's vehicle to enhancing customer experience, fuelled by the possibility to ubiquitously connect things to the internet. Although not all examined manufacturing firms have specific product-service offerings in place yet, the findings indicate a general principle that digital solutions based on sensors, actuators, connectivity, data and software are central elements that set out to change manufacturers' activity systems. The findings imply two major concepts that often tend to converge: (a) connectivity of products and services for intensified interaction; (b) incorporating intelligence by means of software for individualisation

(a) Connectivity of products and services for intensified interaction and granular segmentation

The findings show that manufacturing firms seek to improve customer experience and the organisation of activities by improving flows of information and materials based on a connectivity of products and services. The observed examples can be grouped into four categories: (1) using the generated product data to sell to other companies, as done by Delta Steel and thought about by Epsilon Racing; (2) using data from the field to optimise operations; (3) offering improved customer experiences through advanced, post-purchase individualisation for their customers via over-the-air software updates, observed at Epsilon Racing and Eta Drive; (4) compensating for an existing feature by software, leading to a higher value appropriation, as done by Zeta Home.

(1) Epsilon Racing, for example, produces components for automobiles that directly interact with the environment. For many years, Epsilon's products have been equipped with different types of sensors and actuators to adjust their product to specific environmental conditions or customer desires. Moreover, as Epsilon's director of operations described, "*We have digitally enhanced our products by leveraging existing sensors and adding new sensors to provide real-time environmental data that is being acted on accordingly. This not only is an enhancement of the existing product, but also offers big opportunities for further services, e.g. by selling these anonymised data to public authorities for better road maintenance.*" The connectivity not only enables Epsilon to granularly segment their customers based on their usage patterns, but also allows them to make targeted improvements and create individual solutions for specific customer segments, and additionally generate revenue with granular data about environmental data, i.e. precise localisation of road conditions.

(2) Eta Drive plans to utilise their existing product sensors to get feedback from their products during their usage phase: "*By using data of the millions of our products that are on the road every day, machine learning and other artificial intelligence technologies enable us to act and create a closed loop for developing our products faster and better*" (Eta's director of high-performance manufacturing technology).

(3) Eta Drive will also offer an improved customer experience by the opportunity to "*easily update our products in the field with new software or new control parameters, for example in response to environmental conditions that surround our customer,*" according to Eta's director of high-performance manufacturing technology. In addition, Epsilon's MES implementation project manager added, "*Our product for the US market has a chip that enables remote identification of this specific product. Once this product has any malfunction, the chip notifies us that the product needs changing.*"

(4) Zeta Home developed a new augmented reality interface, with the Microsoft HoloLens and an iPad, for their customers to virtually interact with their specific product configuration. Until recently, it was merely glossy brochures that gave an idea of how Zeta's product looked in its designated environment; Zeta's connected HoloLens- and iPad-based solution changed this fundamentally. According to Zeta's senior design engineer, "*The added value was that we can even put the HoloLens on the customer themselves and they could see a real-time visualisation of the product in their own environment at home.*" Beyond the HoloLens being an additional sales argument due to a better product visualisation, Zeta uses the connectivity of the HoloLens and an iPad to offer their customers improved, targeted services due to a better flow of information between the customer and Zeta. This includes a shortened delivery time, from several weeks to only 14 days, alongside a 50% reduction of necessary sales visits, from two to one.

Evident is a predominant logic of digital-enriched product and service offerings to incorporate connectivity for a more intense interaction during a product's usage phase and with the individual customer, serving as a basis for providing more advanced, more individual data-based services to these customers. As these examples demonstrate, connectivity serves as a nucleus to innovate the BM for an improved customer experience.

(b) Incorporating intelligence by means of software for individualisation

Beyond the connectivity of products, firms increasingly work to incorporate a notion of intelligence in their products and services using software in the form of (semi-) autonomous decision-making and advanced insights based on bulk data analysis that allow individualised services and functionality for each customer. Not many examples were observed in the case studies; however, the general principle of an incorporated intelligence in products and services enables firms to improve the flow of information in their products as well as between their products and other actors, with potential benefits impacting flows of physical goods as well.

As discussed earlier, Eta Drive's products have incorporated many sensors that provide continuous flows of data that are analysed and used to make decisions, as Eta's director of high-performance manufacturing technology noted: "*Our products are extremely intelligent; we are acting in real time on multiple environmental influences and at the same time ensure a 99.99% reliability. We invested much work and resources here.*" Eta Drive's product is a key component for autonomous vehicles and accordingly required (semi-) autonomous decisions to be taken based on sensor data. Epsilon Racing has similarly developed their product to incorporate (semi-) autonomous decision-making algorithms: "*Our newest product is smart and intelligent throughout, with condition monitoring and app-based individualisation. However, the question remains as to how much value-add this brings to our customer.*" This remark by Epsilon's manager of cost engineering raised an important question of whether it really improves customer experience and, if so, how it pays off for the manufacturer. The value-add of a digital solution is a crucial consideration, as manufacturers only appropriate value beyond their conventional domain expertise if it adds value for the customer or is advantageous for value creation through insights from the field or higher efficiency in manufacturing. However, as Epsilon's remark and the scarcity of further examples may indicate, manufacturing firms in the B2B market seem to find it more difficult to envision customer value-adds beyond purely technical features.

Zeta Home, as a supplier to consumers, reports a clearer position regarding value-add: "*With the new HoloLens software solution, it is now possible to show our customers what the product looks like in their own environment. This clearly helps in our customer's decision process in favour of our product – seeing an augmented reality simulation of our product in the real customer environment, and not just a nice colourful brochure*" (Zeta's HoloLens project manager). It can be argued to what extent Zeta's solution should be considered intelligent, but based on augmented reality technology, it provides a way to simulate the full function of the specific, individualised product in its designated environment, without any further human intervention.

This section demonstrated the potential held by connectedness and intelligence incorporated into products and services to optimise the flow of information and the flow of materials in a manufacturer's activity system, especially with respect to a granular segmentation of customer needs and their targeted, individual fulfilment. Regarding an appropriate organisation of activities in an I4.0-driven BMI, the findings indicate connectedness as a nucleus for further changes to the BM, through service offerings and other new value propositions to improve customer experience. Moreover, the presented examples demonstrate that manufacturers use data-based insights from products and digital product compensation to improve their value creation and delivery systems that are mostly based on "physical" domain expertise in design, engineering or production. The specific relevance of data and software for increasing the flexibility and responsiveness of the value-adding activities shall be discussed in further detail in the next section.

5.2.3 Cloning Physical Activities Coherently into Digital

As indicated in the preceding section, digital enrichments for products and services may also have implications for improving the value creation and delivery system. Beyond this cross-fertilisation, distinct activity (re-)organisation in the value creation and delivery system on the basis of data and software usage may further improve the flow of information and materials within the I4.0-driven BMI. In particular, an organisation of activities that systematically replicates physical, mental and social activities and processes, as a form of digital cloning, yield great potential to improve the flow of information, and likely also materials. The findings indicate three aspects relating to I4.0 that enable manufacturing firms to improve their exchange of information and materials within their value-adding activities. Some aspects were evident in all examined firms, others in advanced firms only. The following sections are organised to discuss these three aspects: (a) software system-built picture of the firm's physical activity system; (b) bringing tacit knowledge into software systems; (c) accounting for a data selection puzzle.

(a) Software system-built picture of the firm's physical activity system

Interviewees indicated that a software system-built picture of the firm's non-digital activity system enables a much more streamlined, timely and therefore appropriate flow of information. A more appropriate flow of information increases the firm's responsiveness and flexibility to serve granular segmented customer needs and thereby contributes to a better alignment of activities. "Software system-built picture" refers to a software-based facilitation of activities to ensure that information is in a machine-readable format to be processed by other software suites. Such information can be replicated instantly, is (globally) transferable to be available at short notice wherever needed, and activities become transparent. All the case study firms started to replicate their core physical value-adding activities into software systems. However, their progress differed and not every firm took a systematic approach. Structured approaches were observed at Zeta Home, Delta Steel and Eta Drive:

Zeta Home replicated their entire sales process, encompassing multiple aspects and manual human tasks, into digital. Zeta set out to speed up and streamline this process by improving the flow of information through reducing the impact of humans involved, redundancies, and media-breaks between paper-based and computerised documents. Zeta's senior project leader for 14-day delivery noted that they aimed to bring the entire process from sales to production into one software suite: "*We wanted to bring the entire process into our own [software] portal with our own configurator, into one central place where our sales organisations could enter the product configurations, attach the additional information required to manufacture it, and production can just use this information to produce the product.*" Eventually, Zeta managed to reduce their standard product delivery time from more than 42 days to just 14 days (from order placement to product installation) – almost exclusively due to a software system-based facilitation of information flow.

Another example was observed at Delta Steel, who introduced a business intelligence software based on a large SSOT that provides real-time information about all operational, planning and financial processes within the firm. Again, formerly paper-based processes and siloed information now flow within a software system. More specifically, formerly invisible information about physical material flows became visible through the digital replication of the physical processes, available in-house and for customers, enabling rapid actions if required: "*Our technicians can see why the power consumption goes up at their machine. They now control operations with this information. The ideal state of digitalisation leads me to recognise much sooner if I have a problem, and I can then define much faster the measures to solve it,*" as Delta's director of controlling and business excellence described their steel production process, which is now controlled, among other variables, by detailed live data about electricity consumption.

As the examples of Zeta and Delta demonstrate, the virtual replication of physical processes in a software system, with timely information about these physical processes, greatly impact the responsiveness and coherence of the entire I4.0-driven BMI. The transparency that is gained through a software system-built picture of the physical world helps firms to take rapid decisions and to improve their processes by changing the flow of materials and information. Such improved flows enable a better alignment of activities to each other by facilitating granular customer segmentation and the required flexibility to act on these granular insights.

However, some manufacturers are facing ambivalence from employees with a system-based picture of their processes. Individual employees often do not use the provided software systems for their work. Presumably, at first sight their work is slightly easier if they do not use the system; for example, they may find the user interface inconvenient. However, considering the entire activity system, this individually optimised workflow causes misalignment in the overall system due to an interruption of the appropriate flow of information, as the following by example by Epsilon's director of manufacturing process engineering indicates: *"If I can see at the push of a button that in one factory, 10–20% of the equipment is not utilised, then I can argue, based on data, that product volumes should be shifted to that factory. Today our planners only have bits and pieces in Excel, but these data are not connected to our SAP. Moreover, in SAP we don't have forecast data for the next 2–3 years, because [the people in] sales are doing this in their Excel spreadsheets only. We only have a fine-tuned plan for the next 1–3 months in SAP. If I want to properly utilise SAP to use my machinery at each location, I need to remain in the system and cannot switch to Excel".*

A consequent reliable, near real-time clone of the physical world significantly helps manufacturers to align their activities on a continuous basis. The ability to combine and analyse different types of operational and business data enables decisions to be taken based on overall system optimisation; this may have negative effects for individual activities, but the overall coherence, and therefore performance, can be optimised by data-based decision-making. Moreover, the timeliness of information enables cause analyses, which would be much more difficult or impossible afterwards. Manufacturers improved existing flows of information, but also created new flows of information about their physical processes, which put them in a position to better serve customer demands and thereby increase customer experience. Delta Steel's reorganisation of their value-adding activities was the cornerstone for their "pharmacy of steel" BM (the physical product itself did not change), neatly indicating an increasing integration of product-service offerings and value-adding activities.

(b) Bringing tacit knowledge into software systems

The findings indicate a concept closely related to the system-built picture of the physical activity system, which contributes to a better responsiveness and flexibility, and thereby consistency, of the internal activity system – trying to capture mental and social aspects in a digital format and thereby transform the tacit knowledge of employees into machine-readable data. An example nicely demonstrating this concept was raised by most examined firms – bringing the knowledge of their production planners into a software system. According to the case study data, production planners tend to use their custom-made spreadsheets to plan activities such as production sequences, rather than the provided software systems.

For example, Iota Electric faced problems with their production scheduling process. As Iota is an automotive supplier, they are quite dependent on their customers. Given that, they must often agree to commercial contracts that demand extraordinary flexibility regarding the volume of produced and delivered products within a week. Essentially, the automakers may increase, decrease, change or cancel orders up to 24 hours before the scheduled start of production, imposing high stress on Iota's production scheduling process. This stress led to an examination of how a new software suite may help capture tacit knowledge, as Iota's director IT explained: "Ma*ny conditions for planning, such as changeover sequences, etc., are not pictured in the software system, only in the heads of the production planners. And the biggest issue is that customer requests or orders are dynamically changing. So that means within a day they can change what they want twice. That is the reason why we have started a benchmark process for a better software solution that supports the kind of big flexibility and changes that are required*." Bringing this tacit knowledge of the production planner into a software system, and thereby improving the flow of required information, is crucial to Iota being able to meet customer demand on time, as the flow of physical materials is dependent on this information.

A further example demonstrates another aspect where the systematisation of tacit knowledge may benefit manufacturing firms – the exchange of information and knowledge among experts across a firm, based on transferring tacit knowledge into explicit knowledge. Believing in the power and benefits of exchanging the latest knowledge among experts, Iota Electric established an intranet-based system to facilitate this exchange, named NetTech, bringing together "*engineers who have the domain knowledge, who are experienced and really know how to handle the process. The NetTech is a big advantage. I really like it, and I force my engineers to take part in this NetTech. That means that* *technology knowledge centres are available all around the world*" (Iota's head of industrial engineering). Due to the impact of human variance, Iota incentivises their engineers to participate in their global technology exchange network, to digitally share information for specific technologies, complemented by face-to-face seminars among themselves.

(c) Accounting for a data selection puzzle

Beyond physical activities and tacit knowledge, the findings reveal a third aspect that manufacturing firms should consider for ensuring flexibility – accounting for the data selection puzzle of the "unknown unknowns" in their software suites. It was observed throughout the study that manufacturing firms found it difficult to determine and agree on what data they should sense and include in their software systems and data lakes. The findings suggest that manufacturers should be open to including unexpected, *a priori* unknown sources of data in their system and account for this possibility beforehand. At the same time, they should not be afraid to "slack" in the beginning.

For example, when Theta Heating discussed what data should be included from which machine in their MES system with the underlying SSOT, they said, *"We realised we should first not listen to the employee, but try to make sense of the data. But surely then we need to analyse it together with the domain expert*" (Theta's Industry 4.0 project manager). However, they realised that this approach is too cumbersome, as everyone they asked about which data should be included had a different opinion. Accordingly, they started to capture data that were easily accessible by the machines' PLCs (programmable logic controller), to then analyse it with domain experts. In their iterative process of determining what other data are important to include into their data lake, they then found out, for example, "*that temperatures are important, and several parameters regarding the individual employee – no one had thought of them until then"* (Theta's Industry 4.0 project manager). Similar discussions were observed at Epsilon Racing and Iota Electric, and most examined firms found it difficult to agree on whether they should define beforehand what data should be gathered or whether they should simply gather as much data as possible. Nevertheless, Theta's example nicely demonstrates how formerly unknown factors can impact the coherence of the activity system. In Theta's case, they were able to optimise the flow of materials, saving 1–1.5% of the direct manufacturing costs, purely by acting on this additional information about the current temperatures.

The general dilemma faced by all manufacturing firms about what data should be selected and sensed is suitably expressed by Eta Drive's head of advanced manufacturing, who commented on the topic as follows: "*This is an equation with many unknowns. No one can afford to record everything. When I say 'everything', I really talk about everything. But some people want to define first what benefits one has from sensing all the data, but one can't define everything.*" His quote matches with observed approaches that domain experts should determine, what data about a process are critical to measure and to include in a database and what data granularity is needed. This initial set of data can then be complemented by data that are considered relevant later on – an approach somewhat similar to a puzzle; one needs to start the puzzle to identify the missing pieces, as Theta's temperature example demonstrates.

Closing remarks on content

Leveraging data and software to granularly segment customers, to enhance digitally product-service offerings, and to increase responsiveness and flexibility by digitally cloning physical activities, human knowledge and knowledge exchange, are critical aspects for the reorganisation of activities in an I4.0-driven BMI. Accelerated feedback loops based on real-time data alongside the reduction of uncontrolled human intervention provide a fruitful source to continuously optimise the flow of information and materials for higher flexibility and responsiveness, as positive and negative interdependencies can be seen much quicker due to the increase in transparency. The findings provide evidence of how manufacturing firms improve value creation efficiency through new or more advanced information about the flow of physical goods; improve their effectiveness by substituting or complementing formerly non-digital procedures with digital ones; or enable new value proposition, including customised offerings.

In brief, manufacturing firms are advised to focus on leveraging software and data to granularly segment customers and realise a flexible and responsive creation of individualised product-service offerings through a systematic coherence of cyber and physical, together contributing to a dynamically consistent activity system.

5.3 Structure – Active Flexi-Directional Interlinkage

In the context of Industry 4.0, manufacturing firms organise their activities according to a value focus on data and software as a digital catalyst to enrich their conventional domain expertise and customer experience. The previous Section 5.2 indicated that digitally enriched product-service offerings and value creation systems almost converge due to improved flows of information and materials, which benefits the customer experience and business value alike. However, realising this tight interlinkage of activities and sub-activity systems is subject to an enabling structure – the findings suggest an active flexi-directional interlinkage of cyber and physical activities. This flexi-directional interlinkage is based on the coherence discussed above (Section 5.2.3) of the digital and non-digital entities of an activity, and takes the idea further by interlinking and matching the various physical items, parts, processes and their software-based digital counterparts with one another. Eventually, the possibilities of rapidly linking different activities with each other, increasing the interaction speed, or increasing the depth and quality of linkages, are all bases for swiftly reacting to changing environmental conditions and realising emerging opportunities, whether digital (cyber) or non-digital (physical).

An impression of what can be thought of as a flexi-directional linkage of cyber and physical activities can be gained by two statements from Eta Drive. Eta Drive's director of manufacturing technologies remarked on linking activities to increase flexibility: "*The next big step for us is the MES-MOM project, where we merge the ERP system with all these operational processes and quality data. Today, these are two separate worlds – the classic ERP and another system where we keep and manage our process, quality and recipe data.*" In addition, Eta's COO added, "*Our first and most important step is the 'digital factory', where we are unifying and integrating our heterogeneous IT landscape with the MES-MOM project that includes an Internet of Things platform.*" Eta's MES-MOM project aiming to establish a digital factory sets out to vertically and horizontally interlink nearly all existing processes and entities by introducing this new software platform. Similarly, Zeta Home's sales director commented on their project to reduce delivery time from 42 to 14 days: "*To achieve this, a lot of integration of systems are necessary. If we look at Industry 4.0, there is a lot of communication between the planning system, ERP, and the systems in production – many things to think of.*"

The findings indicate that an active flexi-directional interlinkage of cyber and physical activities is a basis for achieving alignment across the I4.0-driven BMI. This active flexi-directional interlinkage is achieved in three distinct themes: establishing holistic real-time interoperability across software suites (Section 5.3.1); adapting processes actively by balancing standardisation and flexibility (Section 5.3.2); building capable and secure IT and data infrastructure (Section 5.3.3). Figure 12 shows the anchorage of this aggregate dimension in the empirical findings with its underlying second-order themes and first-order concepts.

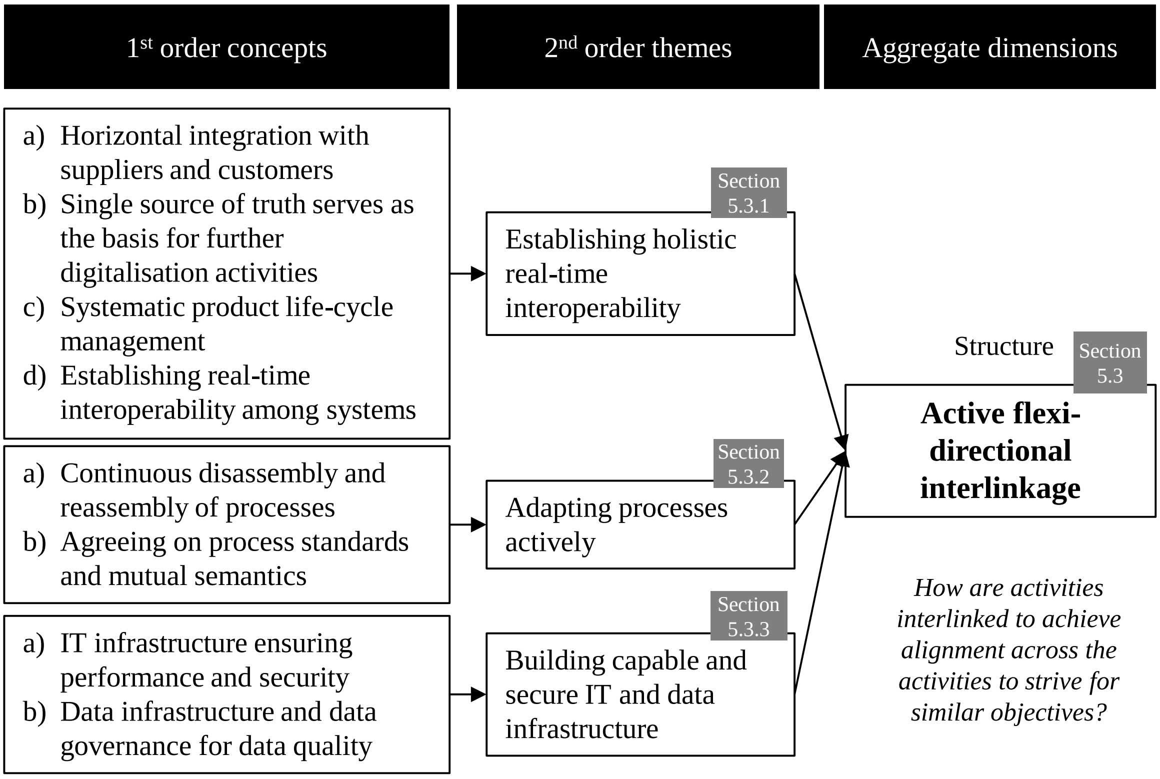

Figure 12. Coding synthesis: factors crucial to achieving dynamic consistency in an I4.0-driven BMI structure view

5.3.1 Establishing Holistic Real-Time Interoperability

The findings indicate that one of the first things manufacturers should consider when innovating their business model is a horizontal linkage perspective with suppliers and customers. This is particularly important with suppliers *and* customers, as the type, speed, sequence, volume, etc. of exchanged information and materials between these actors directly determine how information and material exchanges between the manufacturers should be set up best. The findings suggest two further aspects that enable an appropriate real-time linkage across internal and external activities: a SSOT, in the form of a database non-redundantly[4] incorporating all generated and received data; and a systematic product life-cycle management for weaving together the value-adding functions along a product's life cycle, including design, engineering, production and after-sales. The remainder of this section is organised along these three aspects: a) horizontal integration with suppliers and customers; b) single source of truth; c) systematic product life-cycle management. Moreover, a fourth section provides a detailed account of the importance of interoperability in general: d) establishing real-time interoperability among software suites.

a) Horizontal integration with suppliers and customers

An example of deeply interlinked activities between supplier, manufacturer and customer was observed at Delta Steel, with their "pharmacy of steel" BM. Being able to create and deliver these small batch sizes at Delta is subject to a consequent horizontal integration of suppliers and customers for swiftly exchanging relevant information to act on. Delta's director of sales and production planning described this integration as follows: "*We see our customers really as partners who help us to further develop our business model. The business model [pharmacy of steel], that's something we've developed proactively together with our customers. We also got together in the other direction with our suppliers. […] Moreover, we've interlinked our ERP systems, where our customers can book production slots in our supplier's workshop – that's no show, we work with these open and live data.*"

Delta's example demonstrates the multiplicity of effects that horizontal integration may have for a better alignment of activities across the I4.0-driven BMI. Regular development dialogues intensified and deepened the linkage between Delta Steel, their

[4] "Non-redundantly" refers to every specified datum being entered into the system at only one specific point in time, but multiple data describing the same phenomenon may be included.

customers and their suppliers, which served as the basis for learning and evolving together. Thereon, they developed a BM new to their industry that accelerates the flow of the physical material between Delta, their suppliers and their customers. The new BM is made possible especially by interlinking the ERP systems of all actors, drastically simplifying transactions. Moreover, this interlinkage even changed the structure of the value chain, as every single product is bespoke (Figure 13).

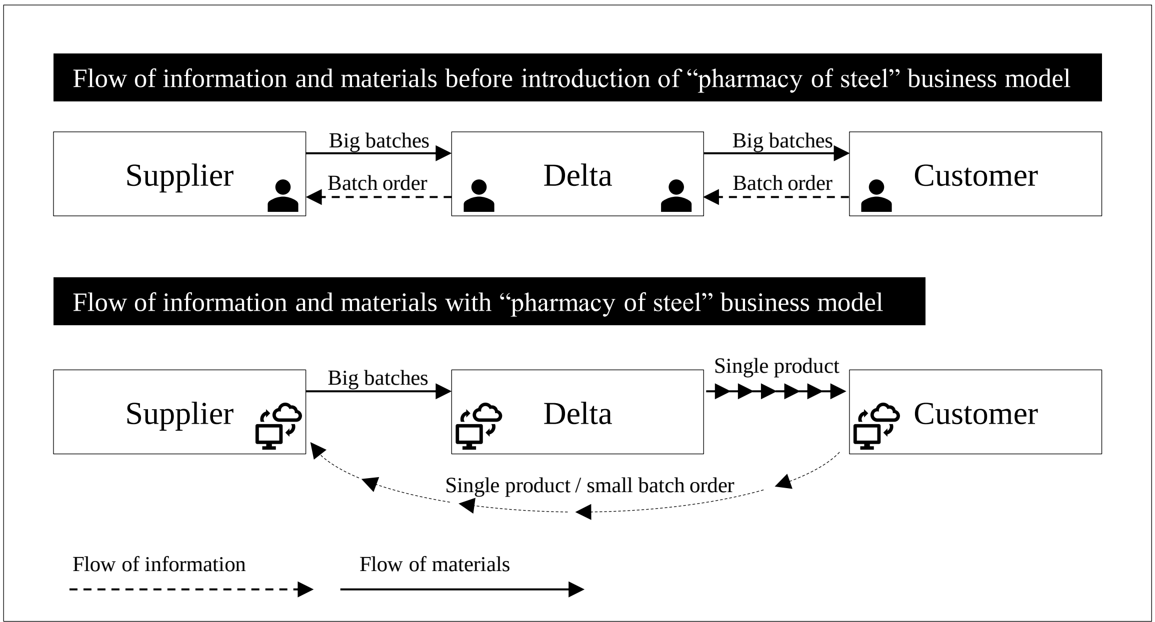

Figure 13. Schematic view of information and material flows between Delta Steel, their suppliers and their customers

Another example demonstrating the importance of horizontal integration for interlinking activities was observed at Zeta Home. Their horizontal integration aimed to improve the flow of information from their customers to their factory, to shorten the lead time and improve customer experience. Zeta now can offer their customers live data "*about when exactly the product could be installed. This includes whether a technician is available at a specific date, whether the factory has sufficient production capacity in the week before the delivery date, and whether the logistic provider can ship the product on time*" (Zeta's director of customer support and logistics). Based on the interlinkage of actors and systems through one IT platform, Zeta's sales partner can sell a bespoke product, individually configured and produced, during their first visit to the customer. There is no longer any need for further visits, sending of paper contracts, or other activities that were required until recently and prolonged the sales process.

As the examples of Delta Steel and Zeta Home for horizontal integration further demonstrate, the changes to the process landscape, digital and non-digital, enable and foster an increased interlinkage of activities – both customer-facing and business-internal. To a certain degree, the distinction between customer-facing and business-internal activities becomes blurred. To set up the appropriate flow of physical goods, a clear understanding is needed of what information needs to be available and when, for each player in the value chain. The business processes to achieve this can be amended to attain a coherence within the activity system.

b) Single source of truth serves as the basis for further digitalisation activities

The findings indicate that a horizontal integration is made possible by creating a SSOT as one of the most central elements for fostering interlinkage between activities in an I4.0-driven BMI. Such a data lake enables multiple types of data to be stored non-redundantly in one central location. All the examined companies highlighted the importance of a SSOT, differing only in the breadth of data sources and types that were included during the time of the case studies.

The examples described above of horizontal integration at Delta Steel and Zeta Home were based on a SSOT. The same applies for the MES system introductions at Iota Electric, Epsilon Racing, Eta Drive and Theta Heating. They are all significant steps for each company to interlink operational and non-operational activities. Supporting the importance of a SSOT, Iota's head of smart factory stated that "*the basic layer of all the other technologies, like big data analytics, is that you need to have the data at one central location.*" This was complemented by Delta's director of controlling and business excellence: "*Most importantly I need a shared, very wide-reaching database – a harmonised database. That is not sexy digitalisation […] but you first need all these data.*" Creating this non-redundant SSOT is vital for data-based improvements of the value creation system and digital enrichments for products and services alike. The findings show SSOTs that incorporate all possibly obtainable data about products, direct processes, and indirect processes such as finance, as well as environmental data including weather and traffic data.

The importance of a SSOT is further supported by an example from Epsilon Racing, describing the challenge of rapidly delivering bespoke and small batch size products. Due to a lack of easily accessible information (and therefore automatable processes), rapid delivery and bespoke products have traditionally been subject to human intervention to transform customer demands into orders, then into manufacturing documents, and finally into production-relevant data. Epsilon's manager of cost engineering described this dilemma: “*Our customers demand more and more variants for their products. […] It increases logistics and complexity costs enormously. And our customers do not understand and are not willing to pay a premium for additional variants. As a consequence, we need to become smarter […].*” Becoming smarter here refers to the simplification and acceleration of processes that are required to create and deliver bespoke customer solutions in small batches, which Epsilon does with their MES as a SSOT.

The findings suggest that a SSOT is one of the most important structures for realising an appropriate flow of information among activities. Most firms started to incorporate operational and business data in the form of MES and ERP data. Incorporating these multiple data types and sources from digital and non-digital processes enabled firms to enhance value creation and delivery, as well as improving value propositions significantly. Thus, the improved flows of information between activities triggered significant improvements to the flow of materials, demonstrated by Zeta Home’s successful 14-day delivery project, as Zeta’s director PLM and digitalisation remarked: “*One important aspect for us was to harmonise our back-end processes with one ERP template only. When every country and sales organisation runs their own system, how do you properly combine data from these systems and make them interoperable to achieve one system?*

c) Systematic product life-cycle management

Building on the SSOT, the findings indicate an increasing weaving together of design, engineering, production and supply-chain functions. Networking technical, administrative and commercial data enables a convergence of various digital and physical entities around a product throughout its life cycle. Such systematic and digital product life-cycle management (PLM) from ideation to end of life contributes significantly to profitably meeting customer demands of small batch sizes and rapid deliveries. Although not yet fully implemented, all examined firms in this study remarked on it, and some have started major projects to implement an end-to-end PLM.

Customers demand customised products in small batch sizes. The increasing scope of product variants is not only difficult to manage with respect to the supply chain but creating the relevant documents for the design and production of each variant is elaborate. Eta Drive, for example, started a project to systematically bring the software solutions of the relevant functions – from design to production and after-sales – to one shared software platform to improve the interlinkage of these activities, as noted by Eta’s director of high-performance manufacturing technology: "*We must have our design data in our PLM software machine-readable. Once all tolerances are machine-readable, I can simply read them with my production machines, without someone typing them into a CNC code. Moreover, once a customer requires changes, I can immediately incorporate them in the system and introduce them into our worldwide production facilities.*" By weaving together all relevant functions on a software basis, the flow of information – and the flow of materials based on it – is improved, to deliver a scalable, high-variant, high-volume value proposition.

An example that further supports the importance of a systematic PLM, and moreover serves as a simple example of the overall theme of real-time interlinkage, was observed in several case study firms. It incorporates many of the underlying aspects of the three discussed linkage mechanisms (horizontal integration, SSOT, PLM): a system to track every product in a mass-production process as part of product traceability, including tracking product quality, identifying the root causes for possible defects in the field. A traceability solution provides great opportunities to improve internal processes by tracking individual products' process parameters along the value chain and comparing them to their specified design measures. These data are further matched with the conditional state of production resources, environmental data, etc., to draw correlations and other influences for improvement opportunities. In addition, these solutions are set up to incorporate input from products in the field or from suppliers' processes by horizontal integration. Today, usually only batches are identified, not single products, as Epsilon Racing's manager of advanced engineering noted: "*In our industry, among all competitors, we will achieve a USP [unique selling point]by tracking every single product throughout the entire supply chain, although we are not producing in a one-piece-flow. We have not found a single competitor's product that can deliver this.*" Achieving this often technically advanced traceability is enabled by SSOT and systematic PLM. This solution offers a diverse range of opportunities for the manufacturing firm to improve internal processes as well as improving the value proposition to customers.

The merit of I4.0 is said to lie in using data from a ubiquitous connectivity of things, processes and value chains. To realise this, the findings show that manufacturers establish a structure of SSOT and systematic PLM that allows these data to flow efficiently and converge. To account for their intermediate position between suppliers and customers, manufacturers horizontally integrate these systems, often as the starting point for changing their BM, as one company's internal value chain is reliant on another company's activities, e.g. in the form of on-time or on-quality delivered supply materials.

d) Establishing real-time interoperability among software suites

As noted earlier, a SSOT can have various levels of scope and complexity. Making any SSOT possible is subject to making software systems communicate with each other. Moreover, achieving fully fledged connectivity of single platforms such as MES, ERP or PLM in a single interoperable SSOT is the grail of interoperability and thereby of Industry 4.0 itself. Almost all interviewees expressed the desirability of this connectivity, yet also remarked how difficult it is to achieve. Increasingly, activities are digitally replicated in software systems, so it is vital to enable the communication between these software systems to enable the linking of activities. Despite some of the examples discussed above, the manufacturing firms reported that most departments and functions run specialist software solutions that are not capable of exchanging information with each other – either much manual work is required for transferring data from one system to the other or, more often, data are kept in these systems only and are (digitally) printed for further use. This leads to a disruption of information flows for a number of reasons. All the examined manufacturing firms reported the huge potential in making these software suites interoperable to improve the flow of information and thereby the interlinkage and alignment of activities. The findings suggest two crucial aspects to discuss: (1) interoperability of software systems; (2) software interfaces as enablers of interoperability.

(1) Although a full interoperability of *all* functionalities is not evident at the examined manufacturers (indeed, to the knowledge of the author, it barely exists), two examples highlight the principle of interoperability and its importance for achieving alignment across the activities of an I4.0-BM.

For realising their "pharmacy of steel" BM, it was inevitable for Delta Steel to make their ERP and MES system interoperable. Only by merging operational data with order and finance data were they able to develop their individualised product offerings, as detailed knowledge about the operational processes is required for offering these individualised products to customers instantly. Moreover, for customers to see in real time whether Delta has a production slot available at short notice, Delta needed to connect their two systems. Another benefit of this interoperability was described by Delta's director of controlling and business excellence, who noted the convergence of value and amount data (i.e. finance vs. operations view) that sensitised the organisation to continuously improving their value-adding activities: "*In technology and operations departments of manufacturing firms, a correct understanding of what monetary values they are operating with is missing. So we've therefore made visible to our workers the amount of gas they've consumed, in Euros per hour, for their specific production line. That means they think, 'Oh look, we used 5000 Euro of gas here, maybe we can do that with 4800'. That visualisation is like the consumption display in your car. Alone, this knowledge and visibility for the worker is extremely important.*"

As with finance and operations topics, information disconnections also frequently occur once production functions interact with other systems, such as design and engineering with PLM systems, or sales with CRM systems. Enabling these software suites to communicate is critical for achieving alignment across activities. Theta Heating, for example, started to develop a new PLM system to merge engineering and finance data and include product-specific measures from production and during their usage phase all into this platform. Theta's director of IT said, "*We are currently running multiple systems for drawings, calculations, revenue and cost planning, production engineering, sales planning, etc. In our new PLM system, we consider the entire process from birth to death, including disposal. Therefore, all these software systems need to be replaced or made interoperable.*"

(2) The findings highlight that the interoperability of these systems, as well as the implementation of individual systems such as PLM or MES, is subject to intensive consideration of software interfaces. On this, Epsilon's director of operations remarked that "*[a] proper definition of interfaces is very important. So by that I really mean data interfaces. That I define my interfaces well, and make sure that everyone interacts in the system, that it is also made open, always tapeable, for example via OPC-UA [an open-source technical software protocol for machine-to-machine communication] or something.*" Epsilon's MES system brings various individual activities within the operations environment to one platform, requiring multiple interfaces to machines and individual software solutions. His remark about open interfaces refers to industry standards such as OPC-UA, which is a standard protocol for plug-and-play connectivity of software suites with machines.

In their process to develop and implement their MES-MOM system, Eta Drive experienced the same as Epsilon Racing, that software interfaces are the cornerstone of the interlinking of activities, which markedly improves the flow of information. Eta's director of high-performance manufacturing technology said about their experience, "*On the technical side, it is important that certain standardisations take place, that the IT systems can communicate with each other and that information can be transferred further on the basis of this, with little effort. In recent years, there have been several changes in terms of standardisation at the industry level to use uniform protocols. And if new devices, machines, etc., support these protocols, then information can be transported, collected, transferred much better. From my point of view, this is already an important component, and can be seen as a move towards Industry 4.0.*"

These quotes about industry standardisation indicate the complexity, but also the importance, of software interfaces for the success of Industry 4.0 in manufacturing firms. Having easily accessible systems on the basis of standardised data exchange protocols is a matter of industry standardisations; easily relates to the ability to communicate with new machinery equipment or new software in a plug-and-play manner that does not require to establish a separate data exchange protocol. In contrast to the widely accepted view that standardisation results in a loss of flexibility, standards for data exchange enable flexibility and speed. With standardised data exchange protocols, software and machinery equipment have a tested and validated interoperability that simplifies the change of information flows. The speed of developing and agreeing on these standards on an industry level is rather slow. The effort to achieve plug-and-play, e.g. known from USB ports on every computer, is highlighted by Epsilon's manager of advanced engineering, who commented on the effort it takes to discuss the interfaces with all machine suppliers and process owners: "*Interoperability is a big task – it goes from IT and data infrastructure in general to every process manager who has to implement the defined interfaces identically with every equipment supplier. And all this then has to be aligned with the different software packages as well.*" As I4.0 is a rather new phenomenon, for some areas, standards have not yet become fully established, requiring additional efforts for manufacturing firms in this early stage of I4.0.

The big advantage of interoperability is the reduction of complexity costs and failure rates by streamlining the flow of information through software systems that exchange data, rather than humans transferring data from one system to another, or not working in a system at all. The approach taken by most manufacturing firms is to establish a SSOT, which the various software solutions take as a shared data basis. Thus, interoperability allows specialist software for specific tasks that is better suited than a “big” software solution trying to capture all tasks. Software interfaces are one of the most important, though not visible, technical means to realise this flexi-directional interlinkage – vertically within a firm and horizontally with suppliers and customers. By improved information flows, the flow of physical goods can also be improved significantly. Accordingly, the findings reveal that all examined manufacturing firms engage in establishing interfaces to improve the flow of information across their BM. They focussed on connecting the operational MES systems with the business-focused ERP system, alongside the design and engineering-focused PLM systems.

Interlinking activities across the internal and external activity system must be complemented by an active management of these interlinkages and processes in general. To actively seize opportunities, manufacturers must take a flexible approach to establishing new or amended existing interlinkages between activities and processes. This active management of processes is discussed next.

5.3.2 Adapting Processes Actively

As described in the previous section, the interlinking of actors and entities follows processes that are, to a large extent, implemented through software suites. The findings suggest that manufacturing firms need to actively manage and adapt their digital and non-digital processes to account for the accelerated speed of developments in the context of Industry 4.0. Adapting their processes adaptively means that firms set standards for their processes but, at the same time, are able to take a process apart to reconfigure it into a new standard that assures improved flows of information or material. This ensures that new or changed flows of materials and information to interlink activities are embedded in transparent and reproducible arrangements. According to the findings, this adaptive process management is a critical success factor for achieving a sustained linkage of actors and entities across the activity system; it comprises two main aspects: a) continuous disassembly and reassembly of processes to swiftly adapt and change them as necessary; b) agreeing on process standards and mutual semantics across the firm.

a) Continuous disassembly and reassembly of processes

A crucial part of active process adaptation is the continuous work on processes, both non-digital and digital, to ensure they are flexible and responsive. This entails the ability to quickly disassemble existing processes, reconfigure them, and reassemble them in reaction to changing environmental conditions or active pursuit of opportunities. Generally, many firms observed the importance of quick process disassembly, however, not all examined firms had implemented specific teams or schemes to do so. Delta Steel, Iota Electric, Eta Drive and Zeta Home all took a dedicated business process management approach; Theta Heating and Epsilon Racing slightly lagged behind here, with operational improvement programs but no specific business process management for amending processes in software suites on a continuous basis.

Zeta Home re-engineered large parts of their process landscape in sales, design, engineering and production, in order to simplify and speed up the flow of information and materials across the activity system to reduce their lead time from more than 40 days to only 14 days. Zeta's director of PLM and digitalisation said, *"We mapped the entire process from end to end – the actual process and then a target process. We really looked at what we needed and what was efficient, and identified all the media discontinuities and derived the requirements for our software system from it.*" This quote predominantly describes Zeta's approach to fundamentally change the flow of information and materials across their entire BM to offer a new value proposition to their customers, improving the customer experience significantly. Besides the initial change of the process, it is important to remain flexible to further changes in the process if required. Due to the rapid speed of developments, new opportunities to further improve the flow of information or materials may arise, requiring disassembly of the process and suitable reassembly. Zeta's director of customer support and logistics highlighted this general notion that continuously adapting processes is important: "*Processes need to be adapted and improved first – that is very important. Otherwise, you're going to digitalise a process that's not working. And then everybody blames the digitalisation, but you should blame the process, which is not good. And that's very, very important.*"

A continuous work on processes to rapidly react to changing conditions, requires a different mindset, as noted by Delta's IT director. He remarked with regard to Delta's wide-reaching change of business processes to implement the "pharmacy of steel" BM, that one needs to "*[t]hink holistically! In processes that may even be beyond our plant.*" The notion of mindset alongside the manager's cognitive abilities will be further elaborated in Section 5.5.

b) Agreeing on process standards and mutual semantics

At the same time as keeping processes up to date, flexible and adaptive, the findings suggest that continuous work to establish standardised processes similar to traditional operational excellence approaches is also necessary; without stable and standardised processes (which, however, are subject to change), manufacturers found it difficult to guarantee reliability and dependability, which are often critical customer requirements. Examples of the importance of standardising processes were observed at Eta Drive, Delta Steel, Zeta Home and Iota Electric.

Iota, for instance, put great emphasis on standardising their processes to reduce human influence on them. Iota's managing director explained why: "*We have very high [staff] fluctuation that requires us to practically make our processes independent from human interference. It should not matter which employee, with what level of education, performs a task – the process needs to have the same stability. That is our ideal target.*"

And as a part of standardisation, the findings indicate a significant need to agree on semantics – the meaning of terms, KPIs, etc. – across the firm. When processes are increasingly standardised and adapted, and activities are interlinked all across the BM, then multiple functions and individuals interact with each other as well and need to work with the same processes. Inevitably, processes and terms will be new to some people, and some functions might need to let go of their traditional way of working or their traditional technical jargon. The findings indicate that this volatility and the need for individuals to swiftly adapt to changing procedures can be supported best by defining and agreeing on the precise meaning of technical terms, and the calculation and definition of KPIs. Delta's director of IT remarked on Delta's discussion about semantics in the course of establishing their "pharmacy of steel" BM. "*Semantics is one of the main challenges for the entire digitalisation process! You need to accept that people have different opinions, but then you must agree on a mutual way forward. And the executives need to be the role models in using and trusting the defined, central database.*" His colleague, the director of controlling and business excellence, added, "*It is important that it is not 'my' or 'his' or 'her' datum, it is our firm's datum, and for each KPI, there can be only one true datum – we just need to agree together how we calculate and name it.*"

Similar thoughts were observed at Epsilon Racing during the introduction of their MES system. Even in the same production department in one manufacturing firm, it is normal to have diverging semantics. This different view on data and KPIs prevents manufacturing firms from reacting swiftly and disrupts the smooth and appropriate flow of information. As a consequence, the flow of materials can be disturbed as well.

The agreement on process standards and mutual semantics is important for an active and flexible management of processes. These standards and mutual semantics must be subject to an active adaptation as well. Since I4.0 requires rapid changes to processes, it is important for the actors working in it to gain a common and shared understanding of the focus of the necessary changes, which is subject to standardised processes and mutual semantics, therefore representing an important factor for rapid changes. While control variables for monitoring process variances may be valuable, KPIs need to be adapted in accordance with the changed processes, as well as accounting for the new focus of the respective processes. Therefore, standardised processes and agreed semantics support the interlinkage between activities, as flows of materials and communication are simplified and streamlined.

At first sight, adaptable and flexible processes and process standardisation seems contradictory. However, to replicate physical processes in a software environment, standardised processes are required; otherwise, different versions of the physical process must be created in the software environment, which absorbs human capacity and increases complexity. Moreover, customer requirements or other environmental requirements may change swiftly, therefore firms must be able to disassemble, reconfigure and reassemble their processes accordingly. While standardisation seems to conflict this flexibility, the quotes above indicate that manufacturing firms find it easier and more reasonable to change a process that is known (i.e. standardised by means of documents, trainings, etc.), than to change and digitalise a chaotic process. From an activity system perspective, active and adaptive process management with process standardisation simplifies the interlinkage of activities, as the *who*, *how* and *what* are clearly defined. Remaining adaptive is vital to ensuring overall flexibility.

5.3.3 Building Capable and Secure IT and Data Infrastructure

Replicating and sensing the physical world and linking it to its digital counterpart is a challenge in itself. To capture physical processes, combinations of comparatively monoskilled sensors are used to copy the range of stimuli humans can consolidate with their multi-skilled sensory systems. The findings indicate that the variety and quantity of data and their transmission requires manufacturers to build an IT and data infrastructure that enables these data to be networked and stored in a structured and replicable way, ensuring performance and reliability. Not all the examined firms gave rigorous consideration to building these infrastructures when they started to change their activity system, but most realised it throughout their projects or understood the importance. This section presents the principle organised into two aspects: a) IT infrastructure ensuring performance and security; b) data infrastructure and data governance for data quality.

a) IT infrastructure ensuring performance and security

Generally, the IT infrastructure incorporates the required devices, networks and technologies that enable large amounts of data transmitting, processing and storing, including antennas, servers, etc., as well as processing power to enable advanced software suites to run smoothly and analyse large bulks of data. Integrating different software suites, using Internet of Things devices such as the HoloLens and having hundreds of salespeople using an online portal remotely requires performant and reliable IT infrastructure, comparable to the road infrastructure for cars. This vivid picture is borrowed from Zeta Home's senior design engineer, who further commented on their project to reduce delivery time to 14 days: *"The [IT] infrastructure has to be in place to read and write information; it's the basics – you need to have that first. There's no point thinking of any other great solution – if you have a very modern measuring device but the infrastructure down the line is very outdated, then there are a lot of bumps in the road. Then you're potentially not fully benefiting from the modern technology you have in front.*" Similarly, the COO of Eta Drive, with their MES-MOM project, remarked, "*We've learnt a lot from others, and the IT architecture is very decisive, as it determines how efficient we'll be in the future.*"

Considering the IT infrastructure as "the basics" or "decisive" gives an indication of how crucial the security of this infrastructure is – an IT infrastructure that does not work disrupts an entire business ecosystem, since activities are interlinked across various activity systems. On the one hand, interviewees clearly see the importance of this topic; on the other, they see that security concerns prevent them from scaling up their solutions. Generally, the topic of security was barely evident in manufacturers' considerations. Where it was, it was mostly seen as a blocking point rather than a crucial point of action, as demonstrated by an example from Iota Electric's head of smart factory, who shared the following issue: “*IT infrastructure – it’s a basic, you can’t even start without it. But we are currently starting pilots with smart glasses and smart watches and we already see a lot of blocking points in our infrastructure in terms of IT security. You can’t log into the Iota wifi with a smart watch, for example – this is a huge blocking point.*”

b) Data infrastructure and data governance for data quality

As the data analysis shows, interlinking activities by means of interoperable software suites requires not only a robust IT infrastructure but also, closely related to this, a data infrastructure and data governance structure that require the involvement of multiple stakeholders. The main principle behind data infrastructure is that a single datum is non-redundant, i.e. every datum only exists once. To ensure that, the stakeholders in the firm need to agree on where (into which system), at what process step, and at what frequencies, quality and granularity etc., each datum shall enter the SSOT. All the case study firms had thoughts about these topics, but processes to handle these issues were scarce.

In the course of their project to reduce time from sales to delivery, Zeta Home interlinked many activities and thereby had to ensure appropriate data infrastructure. Zeta’s senior software interfaces engineer noted representatively for others that “*[y]ou need to have clearly defined business processes and derive a useful data architecture from them, without unnecessary redundancies. […] Data shall only be entered into a system once. You can look them up in many systems and they occur in different systems, but they are entered only once, and that position and the value are correct.*” Moreover, shared, non-redundant data infrastructure requires a rigid data governance process that provides rules of data ownership; i.e., someone responsible for each datum to ensure data quality. Data quality is critical, as an I4.0-driven BMI increasingly builds on data-based decisions, which may be taken wrongly if data are inaccurate. Accordingly, one must have a rigid process to ensure data quality and security.

Data governance regulates what quality each datum shall have, which actor may access which data, and how these data are secured against restricted access. Epsilon Racing’s director of manufacturing process engineering noted regarding data governance, “*For me, security is the basis. Before I think about what other data I want to collect and tap into, I must ensure security against unauthorized access. We might already be one step too far, without proper discussions. Or maybe we deliberately do nothing ….*” His slightly ironic closing remark demonstrates an observation in many firms – interviewees that work in IT or had previous work experience with data security find themselves often alone with their fear about stolen or corrupted data. The following remark from Eta's director of manufacturing technologies supports this: "*Regarding access to data, when I talk to the data security manager, he is paranoid about everything that can happen. […] It is an exciting discussion, this opinion-forming process about which data are relevant and which are not. But it slows down, our transformation process because certain questions must be clarified. […] This is still an unlaid egg to me, what's correct and false. We still need to discuss it.*".

The examples highlight the importance of data infrastructure and governance but also underpin a need for solutions and further consideration of broader management in manufacturing firms. Furthermore, there is an ambivalence among managers as to how data security should be approached in their firms. On the one hand, data security is seen as very important for protecting intellectual property, yet on the other, a certain knowledge and imagination is lacking as to how easy it could be to steal or corrupt data and what consequences this could have for the company.

In summary, capable and secure IT and data infrastructures are critical elements for the interlinkage of activities in an I4.0-driven BMI, serving as the backbone of the I4.0-driven BMI. Corrupt or malfunctioning IT infrastructure disrupts all other activities as both value creation and the value propositions increasingly rely on software systems to control the physical flow of materials and to facilitate the reliable and appropriate flow of information. It only takes a minor corruption or interruption in either infrastructure to unbalance the entire interconnected activity system.

5.4 Governance – Agile Working Ensembles

When either the content or structure of a BM was intended to be innovated as a result of I4.0, the manufacturing firms all chose to place the decision-making authority into the hands of agile working ensembles. An agile working ensemble is a construct orchestrated by manufacturing firms that proactively confers the power of decision-making about arrangements of activities and the interlinkage between activities into the joint hands of different teams.

In all cases, manufacturing firms were facing quick decisions on complex challenges regarding I4.0-related innovation of their BM. As Theta Heating's Industry 4.0 project manager said, "*Only by reacting fast and with strict self-control do we manage not to lose the connection to competitors, hence our I4.0 project team can decide ourselves within the budget [referring to what software or technology solution should be purchased to solve upcoming problems].*" Similarly, Eta Drive's director of high-performance manufacturing technology highlighted that decisions need to be taken much quicker than before due to increasing competition from companies that are rapidly developing I4.0 solutions: "*If you see how flexible, dynamic and fast the Chinese machine suppliers incorporate Industry 4.0 solutions in our machinery in China – although I find it hard to say – then we do not have time to wait for our German and Swiss partners to discuss data protection. We need to move much faster.*" In addition, Epsilon's director of technology and innovation remarked that "*faster means more competitive, and, by using simulations of the physical product and its environment, we reduce our development time.*"

Three aspects for governing the activity system through agile working ensembles were observed in this study: working in hierarchy- and function-spanning teams (Section 5.4.1); approaching challenges entrepreneurially (Section 5.4.2); and value thinking across fences (Section 5.4.3). The data structure for the aggregate dimension, termed agile working ensembles, is presented in Figure 14. For data reporting, key quotes are displayed in the relevant sub-sections.

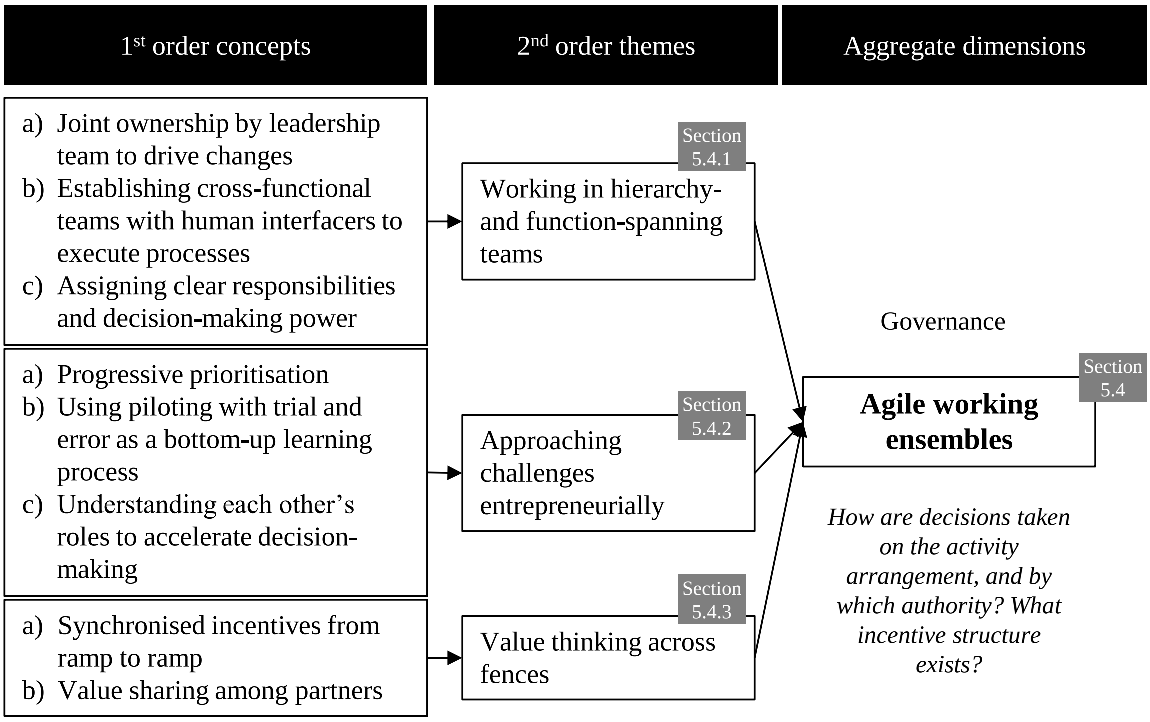

Figure 14. Data structure for the aggregate dimension of agile working ensembles

5.4.1 Working in Hierarchy- and Function-Spanning Teams

The findings suggest "working in hierarchy- and function-spanning teams" as one of the three themes that explain how manufacturing firms should organise their decision-making authority for changes to their I4.0-driven BMI. Hierarchy-spanning refers to the ongoing involvement of top leadership in Industry 4.0 change projects, which is further cascaded down to other levels of management. Function-spanning refers to the involvement of multi-disciplinary actors in taking decisions regarding the selection of activities and their interlinkage, as challenges increasingly demand multi-faceted skills and perspectives to be taken on. According to the findings, working in hierarchy- and function-spanning teams in principle comprises three aspects: a) joint ownership by the leadership team to drive changes; b) establishment of cross-functional teams with human interfacers to execute processes; c) assignment of clear responsibilities and decision-making power.

a) Joint ownership by leadership team to drive changes

Regarding the decision-making authority for changing the organisation and linking of activities, the findings indicate the importance of an authentic personal involvement of the top leadership as the spearhead of taking joint ownership. This is in line with the general notion of dynamic consistency to achieve a coherence among the entire I4.0-driven BMI; only the top leadership has the power to initiate substantial changes to the activity system. Decisions to trigger changes to this system should each be clearly focused on improving the experience of internal or external customers.

Building on top leadership as the initiating decision-maker for changing the activity system, Eta Drive's COO described one of the first and most important decisions he and his board colleagues took with respect to digitalisation: "*Digitalisation is a topic for us as an entire firm. If you want to tackle it holistically, network all data from design and development, production, finance, etc. – to do all these cross-analyses – then at first you need to onboard people from all the different areas, build teams independently from their organisational structure, and make them work for solutions. We therefore have a double leadership in the MES-MOM project, from the technical COO side and from the IT/CFO side, and have staffed it accordingly.*" Moreover, Eta established the same project structure for their PLM project, jointly chaired by one project leader from both the CEO-side and one from the CFO-side. The executives have not purely delegated digitalisation away, but as the COO further remarked, showing his continuous personal commitment for Eta's digitalisation efforts, "*You always have to fly the flag. Every week I have 30–40% of my time in meetings on this subject [digitalisation], so I am in the subject. And as a superior, I must show that it is important to me as a boss. You have to take part in the discussions and then not promote any rifts and borders.*"

The inevitability of joint ownership of the leadership team as the top decision-making authority is further supported by Iota Electric's managing director, who initiated Iota's Industry 4.0 journey about 5 years ago when he started his job as managing director: "*I, as a leader, need to be consequent, provide a direction, and lead them by distributing the mindset and the vision.*" The importance of a specific leadership mindset, also touched on by Eta's COO, was moreover noted by Theta Heating's manager of open innovation, claiming that an executives' main task beyond setting a clear direction is to demand cross-functional working: "*For the past year, we've had a new CTO. He demands cross-functional working. For him it's a must, both internally and externally.*"

Taken together, these quotes demonstrate the importance of joint leader ownership to drive the BM change, by enthroning, empowering and moderating the highly cross-functional teams that take decisions regarding the arrangement and interlinkage of activities in an I4.0-driven BMI. Moreover, a specific leadership mindset has evolved as critical, which shall be further elaborated in Section 5.5. The notion of involving functions across the spectrum in the I4.0-driven BMI shall be discussed next.

b) Establishing cross-functional teams with human interfacers to execute processes

As outlined above, one of the most important decisions to be taken by the leaders in manufacturing firms is to involve all departments and empower cross-functional decision-making; the complexity and speed of developments with their wide range of possible effects requires expert teams to take competent decisions. The increasing convergence of activities of the product-service system with the value creation system requires multiple functions in a manufacturing firm to align their work tightly to ensure appropriate flows of information and materials between activities, actors and entities. The importance of setting up cross-functional teams, empowered to take decisions in the I4.0 journey, is noted by most examined firms, although not all firms act accordingly yet.

Commenting on their MES-MOM development and introduction process, Eta Drive's digital factory project manager and head of performance management noted that "*involving all the necessary players and working together efficiently has been a long process, but it is one of the biggest assets that we have created in recent years, [the ability] to bring it together and be able to look at cross-functional problems and solve them.*" Eta's COO supported this, saying, "*We aligned the project in the following way: people who describe the functionality, and people who bring the technical solutions – always orientated towards customer focus, even if they are internal customers. [...] This also requires people to contribute and show a willingness to build architectures, data models, etc., so that this is possible.*" His remark highlights a crucial aspect for achieving a sustainable cross-functional involvement – a clear objective with a delegation of responsibility alongside a reasonably described distribution of roles, which allows a clear allocation of tasks. Moreover, requiring people to actively contribute indicates the need to allocate required resources. His view is supported by Epsilon Racing's director of technology and innovation, who spoke about their MES introduction: "*It is important to pick up as many areas and departments as possible and convince them of the advantages of digitalisation.*" Epsilon's MES development project manager agreed: "*If not all functions and departments* *are involved and contribute, then you really have a hard time achieving any acceptance for a new software solution.*"

Having established the sense of urgency to work in cross-functional teams with leaders remaining involved, the findings suggest that the decision-making authority is conferred to these cross-functional project teams whose members remain formally based in their original domain function. The latter is crucial, as the convergence of software, electronics and mechanics requires in-depth skills that should be concentrated in specific functions, and at the same time requires these specialists with their very different knowledge bases to work closely together. To best utilise the profound knowledge of these different "worlds", the findings suggest using "human interfacers" that can be thought of as mediators between two or more functions. The case studies indicate a wide range of examples of human interfacers, with an emphasis on brokering between traditional domain experts, and data and software experts. Retaining profound and in-depth domain expertise and becoming more collaborative is a ridge hike for manufacturing firms.

This balancing act is described by Eta's manager of innovation and technology, who reported on Eta Drive's product development process where software made superfluous essential mechanical components with the aid of additional sensors and communication capabilities and turned it into a smart, connected product. The way this product was developed accounts for part of its success: "*[W]e have multiple organisational areas involved in this project with many different superiors – mechatronic, software, operations and the business side. It's a big effort to align them, to synchronise everyone, as it means not everyone does what their organisational function demands, but contributes to the same objective of this project. It takes many discussions across these different locations and organisational areas, but it pays off.*"

If one takes a closer view on the decision-making process of these cross-functional teams, the findings indicate the necessity to have human interfacers. Iota's head of smart factory, for example, reported about this in the course of analysing operational data from the company's rich data lake: "*We have data from the last 15 years from every process. I could give it to someone, but it would not be effective. You need a process expert or an intermediate to guide them [referring to experts in data analyses].*" Moreover, Zeta Home and Theta Heating described similar situations; they both introduced key-users to broker between software developer teams and operations people, being familiar with the domain expertise and relevant topics on the software and IT side, as noted by Zeta's senior software interfaces engineer: "*[T]he software key-users are interfaces between normal users and software developers – they receive intensive training.*" The must-have capabilities of a human interfacer were nicely described by Eta's head of advanced manufacturing: "*[Human interfacers] need to be very good communicators and generally good with people. They must be able to speak to very different people in their languages and at eye level.*" This capability description matches with the researcher's own observations at Theta, Epsilon and Eta. Eta's head of advanced manufacturing who had these capabilities can be considered a human interfacer at the management level. He held various senior positions in production and product development before he was appointed to lead Eta's advanced manufacturing efforts, which include, among others, advanced robotics, cobotics and machine learning. His experience in operations alongside his eagerness to learn about new technologies, complemented by good communications skills to moderate exchanges between tech-savvy and operations-savvy staff, can be regarded as crucial for his success. He managed to persistently overcome obstacles to advanced manufacturing in the organisation, an approach that has now created a pull effect for solutions across the firm, from operative departments to his advanced manufacturing team.

c) Assigning clear responsibilities and decision-making power

For making the most of this cross-functional set-up, the findings suggest assigning clear responsibilities and decision-making power to these cross-functional teams.

For example, Zeta Home, Eta Drive and, in part, Theta Heating chose to assign clear responsibilities and decision-making power to their teams by using the scrum methodology: "*We have a dedicated product owner team – the voice of the customer, market and technology – and they provide [biweekly] targets for what should be achieved by the software team. And the teams themselves then decide how they can best achieve and break down these targets within the next two weeks*" (Eta's innovation and technology manager). This touched-on distinction of clear responsibilities is important for a cross-functional team, as it contributes to efficient progress. "*For every requirement we developed for the MES-MOM project, we named a responsible individual who had to sign for this requirement. […] And that was very important – they had to sign for what was written in the document*" (Eta's digital factory project manager and head of performance management).

Taking an approach of shared decision-making in teams is an important step towards supporting a rapid and continuous alignment of activities. By having process experts and responsible persons taking accountability for their decisions and actions, manufacturing firms can establish a governance that allows the flow of information and materials to change as it is best in the view of the stakeholders involved. Moreover, superiors cannot be involved in that many topics, and mostly they do not have enough expertise to take profound decisions on every topic. Eta's digital factory project manager and head of performance management, however, remarked that this approach does "*not work in a culture of fear – you need to be empowered to sometimes make a mistake as well*," but mistakes must be learned from. This notion of trial and error as a learning process shall be further discussed in Section 5.5.

As challenges are increasingly too complex and manifold to have one person taking a decision alone, working hierarchy- and function-spanning teams is crucial, but difficult to employ. Experts in cross-functional teams need to be organised and empowered to take decisions about what activity arrangements are required to ensure an appropriate flow of information and materials, and how these activities are best interlinked to achieve this. However, achieving performant teams is hard work, as noted by Eta's head of advanced manufacturing: "*There is an imbalance. Many people think you just buy three or four additional data scientists and they can do something with data. However, we have found out, over the last three years, how difficult it is to bring the domain of the data scientist together with the domain of the process engineers and product engineers. […] That is really the hard work.*" These cross-functional teams not only span hierarchies due to the need for authentic leadership, but they must also be established at different levels within the hierarchy, as demonstrated by (1) Eta's management board, who cross-functionally and continuously rearrange their overall activity system, (2) Delta's directors who have daily informal lunch sessions in which they update each other, discuss critical topics and take rapid decisions, and (3) Iota's approach to joining the forces of data scientists and process engineers.

Further aspects to empower these teams to take decisions shall be discussed next.

5.4.2 Approaching Challenges Entrepreneurially

The previous section indicated that the formal organisation of decision-making authority in teams is subject to a specific mode of working in these teams that only enables this form of decision-making. The findings suggest a mode of working that approaches challenges entrepreneurially, which governs how manufacturing firms and their hierarchy- and function-spanning teams should organise their work to come to decisions for changes to their I4.0-driven BMI. When the examined manufacturing firms approached Industry 4.0, they reported a mode of working that differed from their traditional mode of working and comprised, in principle, the following three aspects that are in the style of start-up firms that have not yet developed rigorous routine procedures for many tasks: a) progressive prioritisation; b) using pilots with trial and error as a bottom-up learning process; c) understanding each other's roles to accelerate decision-making.

a) Progressive prioritisation

The findings indicate that working in cross-functional teams, as discussed above, is a pre-requisite for – and, at the same time, a consequence of – taking one decision after the other and prioritising progressively. Acknowledging and being able to take decisions in sequence, rather than upfront as in traditional waterfall project plans, was reported as a success factor by several of the examined manufacturing firms who have implemented changes to their I4.0-driven BMI. It shall not be claimed that manufacturing firms found it easy when they took on this way of decision-making; however, when customer experts work together with design engineers, business process engineers, IT architecture experts and software developers, then it is very difficult, if not impossible, to fully foresee all decisions to be taken.

To achieve their ambitious 14-day delivery goal, the management board of Zeta Homes set up a cross-functional project team with free rein to take decisions to accomplish this goal; this proved to be vital due to the complexity of tasks involving a broad set of internal functions and external experts, including service, design, engineering, production, IT and software development. Zeta's head of digitalisation and PLM described their approach to decision-making as follows: "*You need to learn to prioritise. All the time, re-prioritising, live testing, writing test scripts, thinking in user stories and writing them down. You need to […] be able to make concession decisions. What's more important at this specific moment – shall I focus on this specific product feature and leave others out? The main thing is that a minimal viable product is put out on the streets to be tested for feedback.*"

An upfront determined sequence of tasks, as in traditional project management methods, does not meet the requirement of fast-paced developments in an I4.0 environment that involve multiple customers and value creators. Rather, the next steps are prioritised and determined by the cross-functional teams that have first-hand data insights into the progress and requirements at every point in time. This approach of progressive prioritisation is supported by Eta's director of high-performance manufacturing technology and CEO of a product business unit, who elaborated on Eta's management team's prioritisation: "*In my executive role, we always need to prioritise in the holistic interests of the firm. If we consider, for example, advanced product simulation, we know that it could benefit us immensely. However, our priority is still on growth and stabilising our processes. […] Accordingly, MES-MOM is our primary objective.*" Besides the need for continuous (re-) prioritisation and taking decisions one after the other, his quote also highlights the abovementioned importance of a continuous involvement of leadership in digitalisation projects. Only by being closely involved and getting to know the complexity of such projects will leaders sharpen their perception of what type and scope of projects can be handled by their organisation.

b) Using piloting with trial and error as a bottom-up learning process

Every case study firm reported on several I4.0-projects that were unprecedented in their firm and presumably within their industry. A common approach observed for these new projects was an early piloting of ideas that incorporated a learning process based on trial and error. Piloting here refers to testing a new software, product or service in a small area of the firm, or with a small group of customers, to learn which feature or supporting aspects might need improvement.

When Zeta Home developed the software solution for shortening their delivery time, Zeta's sales director found that "*[i]f you look at the project, it was very important that we did a lot of pilots and a lot of testing. We started with a few salespeople using the system in Country A, then a few others in Country B. It was a very controlled environment, with many checks whether it works or not.*" His colleague, a senior software interface engineer, added, "*We had pilots and that really was a good thing. We told all the users that it's a pilot only and that they should give their feedback. We told them that it's not perfect yet, but that we want to learn from it. […] We found many areas for improvement – it really was a success.*"

This approach to pilot a solution before rolling it out has multiple effects. As the quotes demonstrate, by contributing to the solution development process, the end users have the chance to co-develop the solution to accommodate their needs, as they often know best whether a solution suits day-to-day operation. Accordingly, it is much easier for a cross-functional team to take rapid decisions when they know that they have a chance to pilot a solution and get first-hand feedback for learning and improving, before the solution will be set in stone. This approach is particularly important for changes to the activity system, as projects and solutions are often unprecedented. This freedom to try and learn, and take situationally appropriate decisions, contributes to a faster adjustment of solutions to the current environment. Iota's head of smart factory supports this view. He described some of Iota's approaches to piloting I4.0 solutions for enhancing their own factories: "*A success factor for Industry 4.0 is to do pilots, and then see the results. Then people decide, based on that, whether it's worth it or not. Currently, we're doing a pilot project for augmented reality, to see whether it's something useful for us.*"

Through their input into the development process, people who contribute develop "ownership" and are more willing to accept change to a new solution. Moreover, using pilots to try and learn fast is one aspect of rapidly changing flows of information and materials, as decisions about changes can be taken swiftly. This form of trial-and-error learning in small, delimited, but real, areas – mostly bottom-up from engineering level – is especially important for the dynamic consistency of an activity system, as people executing processes take ownership of learning and improving.

c) Understanding each other's roles to accelerate decision-making

Trying and learning fast, and especially changing rapidly, is subject to gaining an understanding of each other people's roles, which is shown to accelerate decision-making. It was stressed several times by interviewees that decisions for changes to the activity arrangement or the interlinkage of activities in an I4.0-driven BMI must sometimes be taken rapidly but still under the consideration of multiple aspects. For being able to take rapid decisions in a team, and empowering teams to take decisions, it was found important for different people on these teams to continuously exchange information to achieve a basic knowledge of each other's roles. This was found to be an effective approach to generating and implementing decisions rapidly. Few case study firms had followed distinct procedures to gain a mutual understanding, but rather relied on individuals' drive to do so.

Eta's director of high-performance manufacturing technology touched on both of these aspects when he described Eta's approach to purchasing new production machines and lines that are using advanced Industry 4.0 solutions: "*We can purchase better and cheaper machines if we get to know each other much better. You build a relationship and* *through that you get to know what the other party wants or needs. But, moreover, it's the entire improvement; we need this mutual understanding and agreement that one cannot stop moving forward, especially with respect to Industry 4.0, which has really been hyped up, but eventually there is much to think about*." In his opinion, it is important that Eta and its machine suppliers frequently exchange information and expectations in order to develop a mutual understanding and superior machines. His quote indicates that decisions can be taken much quicker once the actors involved know each other well and know what to expect from each other. The same holds true for more than the process of preparing a decision. The findings show many examples of interviewees stressing the importance of supporting decisions already taken by continuously exchanging information with the users of a solution, either to support or to persuade them. Zeta's HoloLens project manager explained this process for their introduction of the Microsoft HoloLens as a measuring device in service operations: "*Key to the successful roll-out was supporting the users. They need to be keen to use it, and since we [as a firm] rely on them using the system, we need to support them accordingly, making sure that they don't face any drawbacks of it in their work; at best, they should benefit from it as well.*"

Moreover, having a knowledge of, and a feeling for, each other's roles also proved important at the operational level, as not every decision is taken unanimously due to different personalities and different perspectives, and therefore might cause conflicts. Iota Electric's managing director remarked, about the implementation process of I4.0 projects on the shop floor, that "*There is no standard recipe. You need to communicate about the project: why do we have a certain vision, what are we aiming to achieve, and why is it important? And, in particular, why the specific decision for this solution contributes to the long-term sustainability of our plant*." As he aptly stated, knowledge of each other's roles makes it easier to understand the other side and to understand why and how a decision is made, especially since the two different worlds of product-service offerings and the value-added system continue to grow together in such closely interlinked development activities.

Generally, the findings suggest that manufacturing firms should approach the manifold challenges entrepreneurially to arrange their activities and improve the flow of information and materials between these activities. By accepting to prioritise progressively, cross-functional teams can react swiftly to changing environmental conditions or changing customer demands. To rapidly determine whether an anticipated solution to a challenge is appropriate, early pilots support firms in taking decisions to continuously optimise the flow of information and materials as needed. The findings indicate, that taking entrepreneurial decisions in hierarchy- and function-spanning teams is strongly related to the way the incentives for decision-makers are structured to work towards similar goals. This aspect will be discussed next.

5.4.3 Value Thinking Across Fences

Working in hierarchy- and function-spanning teams in an entrepreneurial mode is new to most manufacturing firms. Traditionally, they have worked in functions, and incentives for individuals have been laid out accordingly. The findings indicate that manufacturing firms need to adapt their incentive system to account for this different way of working, as individuals might otherwise take decisions not for optimising the overall system or achieving a common objective, but for optimising their own incentivised target. In the third of the three themes of agile working ensembles, the findings suggest a "value thinking across fences". This refers to how manufacturing firms should organise their incentive system for ensuring that decisions to their I4.0-driven BMI are taken in sight of common objectives. In principle, value thinking across fences comprises two aspects: a) synchronising incentives from ramp to ramp; b) value sharing among partners.

a) Synchronised incentives from ramp to ramp

It emerged from the case studies that cross-functional collaboration works as expected when manufacturing firms manage to incentivise individuals to work in teams, and to incentivise teams to strive towards shared objectives. In this respect, the data analysis revealed a common principle across the examined firms: incentives should be synchronised for supporting the achievement of similar goals of teams and reflecting individual contributions to these goals.

Making Delta Steel's "pharmacy of steel" BM work as it does today required the integration of customer-facing activities with value-creating activities and accordingly the close collaboration of cross-functional teams across the business on a constant basis. Delta's director of finance and controlling illustrated how important the establishment of shared, influenceable goals is for people: "*The more people have the same goal that they are able to influence, the better. You can always say that they are all reasonable people and everyone should always think for everyone, but when it comes to their own wallet […].*

We then came to the conclusion that, for example, the production staff are assigned the same goals as the quality engineers, *and the quality engineers are assigned the same goals as the production staff; ideally, these will be the same goals, which the teams can influence together, and work together to achieve them.*" He further explained that Delta have aligned their KPIs for direct and indirect areas by pragmatically merging amounts and values, traditionally used separately in operative and administrative areas, respectively. His colleague, Delta's Director production and technology, agreed: "*We have broken down our business targets for each department and then made sure that individual people can influence these targets. […] Take a production supervisor – he's less interested in sales volume, but he wants to see things that he can influence. We've set up our business intelligence system accordingly, so people can see the data and KPIs they can influence. […] Workers, for example, get a notification when their process is too slow, and if the time loss is too high, they need to type a reason into the system. We as superiors now have an indication how our workers take decisions in specific situations, but can also see whether machine problems are coming up.*" Moreover, they aimed to infuse this thinking beyond boundaries into the entire organisation with an organisational change program, as Delta's director of IT explained: "*We needed to make sure that we have our employees with us, and that means thinking holistically. Each department usually just wants to do what's necessary. But we actually need to think in processes that may even go beyond our own factory. Intrinsically, every human wants stability, but we want to allow customers to change their orders just before we start our physical production, as this is our USP. To get everyone on board, to move away from this silo mentality, is one of the core tasks.*"

Another example was observed at Zeta Home, who started to change towards ramp-to-ramp thinking in the course of their project to link service, design, engineering and production for a shortened delivery time. During of this change, Zeta adapted parts of their incentive structure. Before the incentive structure was changed, Zeta's senior project leader for 14-day delivery reported, "*[…] the managing directors were only looking at their own units. No wonder, if you're rewarded like that […]. They had the wrong incentives. And if we could screw each other over, we would do that in the past. Nowadays, we have people in these positions who look at the total process and make it transparent, and also introduce incentives that are related to our strategy*." Zeta now is organisationally structured in a different way; however, the core message of this quote is that it is individual leaders who need to trigger the change, implicating that cognitive aspects play a role. This is further supported by two of his colleagues noting that Zeta still has some room for improvement regarding end-to-end thinking as incentives are not yet fully aligned: Zeta's factories that are located in central Europe receive their order through Zeta's country sales organisations, which are self-sustaining in every country worldwide. Zeta's senior design engineer explained that these "*country sales organisations pay for the transport from the factory to the customer's home. Accordingly, [the sales organisations] try to optimise the transport costs from the factory to the customer,*" by accumulating multiple customer orders and having them shipped together in one truck-load, instead of to each customer order individually, as requested for rapid delivery. In addition, Zeta's director of PLM and digitalisation commented: "*We have to consider what we value more, but no one has ever looked at something like this before. It's okay if the transport to a specific country is 50 Euro more expensive because we ship every product individually, but we will generally deliver our products faster everywhere in the world.*"

The importance of shared objectives and incentives is further supported by a negative example from Theta Heating. Theta has a new chief strategy officer who is, at the same time, one of the successors of the business owners who are advocating for open innovation. However, her vision has not been picked up, as Theta's director of digital transformation noted: "*Our chief strategy officer […] started a value process for new corporate values, working and organising the firm differently, getting out of the silos. But sales and earnings, that's how we're managed, nothing else.*" A positive example where a mutual vision is supported by incentives for individuals was observed at Iota Electric. Iota's mission is "You can count on us", implicating that customers can rely on high-quality products, delivered in the condition it was ordered and complemented by an excellent service. Iota's managing director explained that this claim, among others, is subject to 24/7 availability of engineers: "*This reliability, this customer commitment, is supported by incentives. So all the engineers, for instance, have a standby contract. If something happens outside of working hours, they get an extra 20 percent for being on standby. And then, of course, more if they even have to intervene in the company. I can't say "You can count on us" and then send people home at 4 p.m.*"

The examples demonstrate that an appropriate flow of information and physical action is subject to a ramp-to-ramp synchronisation of incentives towards shared objectives. They show how decisions that are made due to sub-optimal incentive systems may disrupt an optimal flow of materials, or cause critical information not to flow appropriately between departments, e.g. during out-of-work hours. This ramp-to-ramp thinking with an appropriate incentive structure has not yet reached its full potential in manufacturing firms, but the findings indicate its importance.

b) Value sharing among partners

Thinking ramp-to-ramp is closely related to sharing value with partners. The notion of sharing additional value generated by data emerged as a critical topic for manufacturing firms as activities may span beyond their own factory walls, e.g. in the form of data that are received by suppliers or provided to customers. The additional value that the data provided by the manufacturer generates for its customers is often not easily quantifiable *a priori*; accordingly, discussions about value sharing arise.

One of the core pillars of Delta's "pharmacy of steel" BM is a very close integration of Delta with their suppliers and customers, who all together increasingly benefit from sharing data among each other. In particular, Delta provides production data to pilot customers that enable them to further manufacture Delta's product more efficiently, as Delta's director of IT reported: "*[We] are currently patenting a process to provide technical data to our customers' customer so that they can improve their production processes as well. So, if we provide data, they shall not claim more failures, but control their processes according to the data. And the patent is about the value-add for us through their process improvements.*" His colleague, Delta's director of controlling and business excellence, added: "*We help ourselves if we help our customers. Our business model is to give the customer a package, where he has the impression that he's buying a good product from us. And ideally – and this works out quite well – he also pays a corresponding price that we can live with quite well. [...] Consider the data exchange with customers or suppliers – it's a topic that can bring our firm very far forward, because it helps to know what the customer does with our products, or what we do with our suppliers' products.*"

Another example of thinking about value sharing was received from Eta Drive with regard to their partnerships with machine suppliers. As Eta has been very strong on industrialising complex products, they are reliant on innovative manufacturing equipment. Eta's director of high-performance manufacturing technology reported that machine suppliers' power of innovation has slowed down, which is why Eta thinks about value partnerships to change this lack of innovation: "*It is very costly and laborious if the management of the machine supplier is not prepared to take a step regarding digitalisation innovation. What might be understandable [...], as the air is relatively thin, is to do extra things in innovation. But it is important, and I believe this is a great challenge for us. We* *must split efforts into the classic machine equipment business and, at the same time, we also have to establish strategic partnerships to incorporate new innovation, new possibilities and thereby take a step forward. In the next machinery generation, the new ideas then become reality.*"

The findings indicate value sharing among partners as an important aspect in facilitating more intensive collaboration internally and with other firms. This is especially required owing to the increasing speed of developments and the complexity of converging value-adding activities and product-service offerings. The increasing interlinkage leads to the partners being increasingly dependent on each other, with the drawback that the share of some successes cannot be determined exactly. Due to the speed of development, however, companies are dependent on working out solutions quickly, for which they usually need partners who are also prepared to act quickly and take a share of the risks involved.

5.5 Cognitive Foundation – Proactive Mindset with Integrity

The previous sections have operationalised the notion of dynamic consistency of an I4.0-driven BMI along the lines of the three design themes of an activity system: content, structure and governance. However, the empirical findings indicate that there might be more to the operationalisation of dynamic consistency in the context of I4.0 that goes beyond thinking of I4.0-driven BMI as an activity system. Rather, the findings suggest a cognitive aspect that serves as an intangible frame, supporting the tangible arrangements of an I4.0-driven BMI described earlier. This cognitive foundation characterises specific mental modes, including behaviours, believes and habits, that are imperative for arranging and running a dynamically consistent I4.0-driven BMI. The cognitive basis is as indispensable as a cell nucleus, for the (re-) organisation of activities to ensure optimal material and information flows through appropriate linkage structures and as an ordering scheme for regulating these arrangements and linkages. Furthermore, the cognitive foundation accounts for and operationalises the different perspectives that a system, its activities and their relationships can be perceived from, giving them different meanings at different times, as described in the systems theory literature that translates to BMI (Velu, 2017).

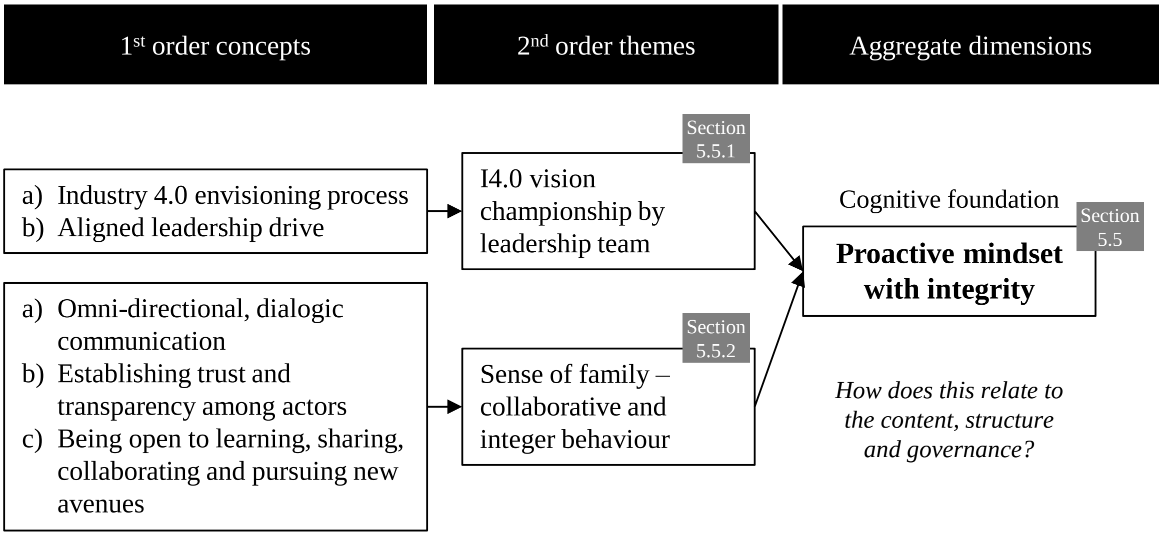

Figure 15. Coding synthesis: factors crucial to achieving dynamic consistency in an I4.0-driven BMI, cognitive foundation

Across the examined manufacturing firms, interviewees highlighted cognitive aspects that in their view were either superordinate or the basis for initiating appropriate changes to the organisation of activities. The complexity and superiority of these cognitive aspects is nicely reflected in a statement from Delta's chief information officer: "*Getting [everyone] to think holistically, away from this silo mentality, is the core [of digitalisation]. How do I communicate and how do I manage that so employees do not see changes in technology as a threat?*" Moreover, Eta's COO noted that "*you need this organisational change process for digitalisation – to really take all your staff from different areas with you on this journey of digitalisation.*" These thoughts are complemented by Iota's managing director: "*Working towards a goal or vision should actually not just be accomplished by 'getting people there' and motivating them, but it must be part of the philosophy. And there is no patent remedy. You need to communicate a lot about this – why do we have our mission, what did we imagine with it, why is it important? How is it related to the long-term sustainability of our location, as it could be relocated somewhere within a year? It's in our common interest to get so good that nobody can think of it. Within [Iota], we are not the in cheapest location, so we have to have another argument why [Iota] is producing here…. Only next to that is technical competence.*" As these quotes indicate, the superordinate frame for the alignment of the activity system is something rather intangible – something of a philosophy or a mindset.

Two themes that provide a better understanding of the cognitive foundation underpinning a dynamic consistency of an I4.0-driven BMI in manufacturing firms emerged from the findings: 1) vision championship by the leadership team; 2) a sense of family, with collaborative and integer behaviour. The data structure for the aggregate dimension, termed proactive mindset with integrity, is presented in Figure 15. For data reporting, key quotes are displayed in the relevant sub-sections.

5.5.1 Industry 4.0 Vision Championship by Leadership Team

Across the entire sample of examined manufacturing firms, interviewees highlighted the utmost importance of an Industry 4.0 vision that is clearly championed by the executive leadership team. When projects and activities need multiple experts with very different occupations to closely collaborate, a vision that serves as a common goal is crucial to provide a focus and enable actors to prioritise and compromise. Moreover, the omni-directional interlinkage and collaboration makes it crucial to have the entire leadership team on the same page. The findings indicate two themes in particular for achieving this: a) an Industry 4.0 envisioning process leading to a clearly stated business vision that encompasses Industry 4.0, and b) an aligned leadership drive, where leaders drive projects and changes based on an agreed roadmap.

a) Industry 4.0 envisioning process

Considering the entire sample of examined manufacturing firms, four of these six firms have undertaken distinct processes to innovate their BM based on I4.0. The findings indicate a common principle followed by these firms. Whether the company was motivated by a customer problem a (as Zeta Home and Delta Steel were) or by a technology problem (Eta Drive and Iota Electric), the findings suggest an iterative process encompassing four steps. First, as none of the leadership teams had a clear idea of what digitalisation is or what power it has, they embarked on leadership learning journeys about digitalisation to see examples in and from other firms and industries. Second, with their newly gained knowledge, they intensively discussed internally how and what digitalisation holds for their firm, and how the business vision should change. Third, based on this, the leadership developed an agreed Industry 4.0 vision with a plan to achieve this vision. Fourth, they explored the digital technologies that could support them in achieving the vision. The following two examples of (1) Zeta Home and (2) Eta Drive are representative for others:

(1) Zeta did intensive customer research to learn more about their customers and their interaction with their product as well as the initiation of the purchase, as Zeta's director of PLM and digitalisation explained: "*In 2014, we started a big customer survey, and have also asked our own sales force what aspects were Zeta's USP in the market and what customers need from us. After the number one topic, trust in our product reliability, the speed of delivery was the most important aspect for our customers. So we deduced that we could speed up certain processes and really provide a value-add for our customer by delivering our products faster.*" His colleague, Zeta's senior design engineer, described the process subsequent to this customer insight: "*We followed blue-sky thinking – where we want to end up in an ideal world. And in an ideal world, our salesperson would go to a customer's house […], put on a HoloLens to measure the environment, sit down with the customer and an iPad to configure the product, and know for sure that this configuration is manufacturable.*" This blue-sky thinking provoked discussions that ultimately manifested as Zeta's vision of cutting delivery time from more than 40 days down to 14 days. Zeta's chief service officer agreed: "Often in my career I would see nice technologies and try to find a problem so we could use them. *But this time we did it the other way around – based on this problem, we looked for technological solutions, integrating all of our software systems and using the HoloLens. […] Digitalisation should be an enabler; it should not be the goal itself. It should make you smarter, or make things quicker, better etc., but not only because it's fancy and nice.*"

(2) Already being the technology leader in their industry segment, Eta Drive has developed revolutionary product solutions that serve autonomous vehicles. With their traditional product and this new product solution, their vision was explained by Eta's head of advanced manufacturing as follows: *"[To become the] worldwide number two or three in terms of volume in our segments, but you can only achieve this by cost leadership. Therefore, we need to grow to achieve scale effects*" (as explained by Eta's head of advanced manufacturing). Triggered by media coverage of digitalisation, Industry 4.0 and similar topics, Eta's COO started an examination of what Industry 4.0 is and how it could help them reach their vision. Eta embarked on learning about examples and opportunities provided by digitalisation for manufacturing, as Eta's COO explained: "*We invited*

specialists from Accenture, SAP and others who have done digitalisation projects before to our factories [to inspire] a vision in our people and to teach us. With their help, we discussed with our people in the factories what ideal processes could look like. So, we have listened carefully to what all the other firms did and have taken this as a basis to develop our own Industry 4.0 strategy. The important parts are a) what the IT architecture is, as it determines your efficiency downstream, and b) what process standards do we want, and which processes should be digital." Only from this learning process was Eta able to internally discuss what benefit they may gain from digitalisation, resulting in their MES-MOM and PLM projects and a refined business vision to establish a global digital factory by 2025, as Eta's head of advanced manufacturing described: *"The whole idea of connecting MES and ERP and making this system Internet of Things-ready has evolved over time. It became sharper after we dealt with it intensively, because now there is an understanding among the broad range of decision-makers in the firm that I can increase efficiency through digitalisation. [...] And this really is the crux, to establish a mutual understanding and common objective at the board level. You need to bring all these different perspectives on a topic – everyone's pain points and use cases – into harmony and then break it down into chunks and functions.*"

Mutual learning journeys are important for establishing a suitable Industry 4.0 vision for a manufacturer. By drawing analogies with other firms and industries, in combination with conceptual ideas that combine technologies and processes, a clearly defined vision underpinned by strategic forward-thinking can be developed. As possible activity arrangements in an I4.0 BM are almost infinite, the cognitive process for leadership teams requires drawing analogies, combining technologies and procedures, developing concepts and engaging in logical reasoning to decipher ways to create a sustainable vision with a clear strategic pathway. This requires the highest cognitive abilities of managers for sensing the need and embarking on a (personal) learning journey: sensing opportunities provided by I4.0 to rearrange activities within a manufacturing value chain and using what they learn to innovate their own BM. The final agreement on appropriate activity arrangements, interlinking structures and governance schemes that are suitable for the firm and its environment provides the guardrails for their teams. Within these guardrails, their teams are empowered to choose and agree on specific solutions that holistically provide the best contribution to achieving this vision.

b) Aligned leadership drive

What becomes evident by examining the examples of clearly defined visions and stringently executed strategies is how central an aligned leadership drive is. Aligned leadership drive refers to the ability of a leadership team to align their own interests and then to follow a mutual vision and strategy, driving it forward together. Several firms accomplished this by clearly defining projects to reorganise the activity system, and executing these projects with a very strong leadership drive and support. Firms that reported explicit I4.0 envisioning procedures, including Iota Electric, Eta Drive and Delta Steel, also said that their executive board is driving the I4.0-BMI process.

Iota's head of smart factory, who participated in Iota's change program over the last few years, commented on the importance of leadership and alignment: "*For I4.0 you need to convince people that they would like to do things and they would like to learn things, to move out of their comfort zone. Leaders are responsible for promoting the topics and pushing a new mindset through the organisation. […] This is one major challenge for the management team in achieving the Industry 4.0 targets. And you need to speak the same language.*" This view was supported by his colleague, Iota's director of IT: "*Sometimes [you] have to introduce something that does not make the worker's life easier. Then they particularly need to understand what the overall benefit is, why it's necessary to change their working habit.*"

Most of Delta Steel's directors were interview partners for this study and all commented similarly on the importance of leadership, indicating a significant coherence among them: Delta's director of controlling and business excellence commented that "*for digitalisation, the executive board needs to clarify and ensure that everyone understands the way forward. If you have diverging views, then you don't have a chance.*" This was complemented by Delta's director of IT: "*The board must set an example for the firm, for example by only accepting data from our data lake.*" Delta's director of technology and production added that "*you've got to want digitalisation. It's that simple. And you have to keep at it to get it done.*" For Eta, the COO remarked on this alignment, with little need to comment further on it: "*I need to coordinate with my executive colleagues if there is any indication of borders or rifts – as a board, we need to demonstrate unity. We are interested in the results. We have to provide the framework conditions that people can work in.*" Diverging views and the resulting discussions are important for setting the right vision and directions. However, once agreed, the leadership team needs to stay united in pushing forward – problems should be discussed behind closed doors and then solved together.

Closely considering these examples of unity, alignment and the effort to demonstrate good leadership can be refined into individual behaviours, beliefs and habits of the top executives that are imperative for any of these sustainable attempts. Several interviewees pointed out the need for a "mindset change" and a "change management process". Iota's head of industrial engineering, for example, reported on Iota's journey from a rather underperforming firm to an up-to-date production facility that received a prestigious Industry 4.0 "Factory of the Year" award in 2018: "*If you do not manage to step back and realise that you need to stop certain behaviours, like fixing issues in production with duct tape, but start to coach your staff to a different mindset, then neither Six Sigma nor digitalisation will work. We started discussing this complete mindset change four to five years ago. […] Now after [these] years I can see that we have really built up a different culture in our firm.*" Similarly, Delta's director of IT reported on their process to establish the "pharmacy of steel" BM that "*an entire change process takes time – lots of these things go under the hood, you cannot see them.*" In addition, Eta's head of advanced manufacturing commented, "*We do have a strategy and that is essentially important. But it's the mindset level which is probably even more important – anchoring this strategy and making it credible. I believe the most important part, really, is the credibility.*"

The last note about "credibility" highlights once again the cognitive notion involved in leading the change of a manufacturer's BM in the context of I4.0. The findings show the importance of an I4.0 vision, which can only be implemented successfully by the joint and aligned effort of manufacturing firms' leadership teams. When the leadership teams agree on a vision of how to rearrange the I4.0-BM, appropriate flows of materials and information, with the same objectives, can be established; without aligned leadership drive, individual (sub-) activities would be directed towards different objectives, hampering an overall system alignment.

5.5.2 Sense of Family – Collaborative and Integer Behaviour

Interviewees across the entire sample of examined manufacturing firms highlighted the importance of a different kind of communication, cooperation and general co-existence that was required for making appropriate changes to their firm's activity system in the complex context of I4.0. The findings indicate a sense of family as an appropriate circumscription for an open collaboration and an acting with integrity, that is pursued by manufacturing firms for making sustainable changes to their BM with I4.0 principles. A sense of family in principle unfolds in three aspects: a) omni-directional, dialogic communication; b) establishing trust and transparency between actors; c) being open to learning, sharing, collaborating, and willing to pursue new avenues.

a) Omni-directional, dialogic communication

Explaining ideas and background information, discussing the why, the what, the how of new activity arrangements and interlinkages – in short, a dialogic communication – was identified as a crucial aspect by almost all interviewees. Hence, the notion of intensive discussions among leaders to establish an aligned vision does not end with "publishing" the vision, but it must be continued once this vision is being rolled out and executed. Concerns of employees have to be taken seriously and leadership should be open to adjust decisions based on this employee feedback. The previous sub-sections of this chapter on the findings from the present study have indicated the "fundamentality" of changes that I4.0 entails for manufacturing firms' BMs. As discussed above, the nature of activities and the nature of many employees' jobs fundamentally changes correspondingly. These changes require firms to discuss such deep cuts in people's working lives with them – to moderate anxiety but also to prime them for the need to pursue different ways of working alongside continuous learning.

The need for such discussions is supported by Zeta Home's project manager of the HoloLens introduction for the sales technicians. She elaborated on how difficult it was for their staff to embrace the fundamentally different way of working with the newly introduced digital solution: "*[M]any of our service technicians now need to work with a HoloLens and an iPad – it's obvious to them that they will be fully immersed in the digital world. And I think we have to pay attention to that – of course, digitalisation makes many things easier, but they are still people who might make a mistake. […] Communication and change management are crucial here, and we are therefore closely communicating with them and supporting them a lot.*" Similar concerns about a dialogic communication were raised by Eta's COO, who worries that one might underestimate the effort to get people on board on the I4.0 journey: "*I think one of the main risks is to impose a solution on our people. It required intensive discussions over months with plant managers to develop our own pathways. The effort for implementation, the time to get people to get that up and running, that will be crucial.*" His digital factory project manager and head of performance management added a concrete example: *"We [Eta's management team] found it difficult to communicate the overall vision we had for Industry 4.0. […] For many it was, for example, not obvious why they had to let go of their individual software solutions that were working very well. But to take the next step for digitalisation, we need to break up these silo-solutions and bring it all to one platform. It requires tremendous discussions with people to persuade them – in fact, it was sort of a cross-functional learning experience.*" The notion of persuading and discussing with their own employees, explaining to them why it is important to integrate software solutions or why cobots contribute to a location's future, but also listen to their views and concerns, is a common pattern across all the case study firms. Delta Steel, Theta Heating and Epsilon Racing reported similar examples.

Beyond communication among their own staff, communication with customers received extra attention in the reports of Delta and Eta. Delta's director of sales and production planning noted that "*many of these [digitalisation] projects are just possible by intensively talking with the customer. We have long-standing relationships with individual customers based on trust through constant communication,*" referring to the success of Delta's horizontal integration with their customers, where the customers, for example, have real-time information about Delta's production process.

A third target group for communication about I4.0-driven BMI are shareholders. Eta Drive, Zeta Home and in parts Epsilon Racing took similar approaches, by describing user stories to persuade shareholders about the benefit and necessity of investing in specific I4.0 projects, although the benefit might be hardly quantifiable in advance. Eta's digital factory project manager and head of performance management explained their approach to persuading their shareholders to invest in their MES-MOM and PLM project as follows: "*We have use cases and change stories, where we described in 100 slides different activities and processes of today and how they will look within our future MES-MOM or PLM system. […] We also had to persuade our sponsors, as in the end everything is about the business case. Because it is usually hard to calculate such projects. Everyone who has ever calculated a PLM system will soon realise that it's barely possible to estimate.*"

Case studies show that a dialogic communication, i.e. communication as a conversation and not information, with and among very different stakeholders is crucial for sharing mutual demands and needs as well as objectives and goals. Against the background that activities may be fundamentally rearranged, and actors and activities that were not collaborating before get interlinked, communication was found to be extraordinarily important in achieving alignment across the entire activity system. Moreover, based on an extensive communication, where both interlocutors can pose their ideas and opinions and discuss their viewpoints, innovative ideas can flourish. Furthermore, communication is a basis for creating trust and transparency – this aspect shall be discussed next.

b) Establishing trust and transparency among actors

Trust is created by taking the concerns of the other side seriously and developing an understanding of the needs and problems of others. In the course of an increasing focus on data, trust is crucial in several regards. Manufacturing firms aim to improve the flow of information and materials by leveraging data and software systems to omni-directionally link these activities internally and with partner firms. This results in an increasing transparency, from physical flows of goods and flows of information to individual capabilities and performances. The findings indicate that transparency, however, is a double-edged sword – without trust in the good faith of collaborators, individuals and entire firms will find it difficult to collaborate, as, for example, shared information may be misused. The same applies to providing data and information to software systems. Hence, gaining transparency holds enormous potential to improve the flow of information and materials in a manufacturer's BM; however, transparency does not come without trust – and trust likely not without transparency.

For example, when Delta Steel re-engineered their internal business processes to realise their "pharmacy of steel" BM, they introduced new, and interlinked existing, software systems to establish transparency through a SSOT of data, including detailed data about operational processes. Delta's director of IT put himself in the shoes of their workers, who were largely affected: "*Creating transparency is great. However, for someone who is working on such a transparent workplace, it is not. The human, and the culture, is something you need to take care of. If one makes a mistake, which now is often immediately obvious thanks to the single source of truth, then he must be able to say that! Failures and inconsistencies must be pointed out in order to improve ourselves. Managers need to understand that.*" Moreover, Delta Steel's BM change, which is reliant on real-time data providing transparency, requires trust between actors of the value chain, most notably between Delta and their suppliers and customers, as Delta's director of IT reported: "*This holistic concept of our pharmacy of steel with a holistic value chain required that our customers also change some processes and invest in specific assets or changes. That requires trust in each other and really a good relationship before anyone would do that.*"

His colleague, Delta's director of controlling and business excellence, added, "*you need to be confident in your own processes and data, as you literally drop your trousers and your customers can see if you have problems in your production. […] Therefore, it's vital to have a trusting relationship with your customer.*" This example of Delta with their close customer collaboration that is required for their BM nicely demonstrates the reciprocity of trust, and the benefits that are enabled by such trust. The reciprocity of trust and transparency was also noted by Iota's director of supply chain management and planning who elaborated on their problems with non-transparent flows of information of a specific supplier: "*For me, that comes down to a lack of openness from the supplier. I always have the feeling that they want to conceal something or want to hold back information, although this information would really help us to balance our production. The entire production system would work much better and our staff would not be so demotivated.*"

Despite the reciprocity of trust and transparency between actors, the findings are not unambiguous about whether trust or transparency is first – the two seem to represent a chicken-and-egg conundrum that requires leaderships' cognitive integrity to resolve. However, trust and transparency have been found vital for a successful re-arrangement of activities within an I4.0-driven BMI or the linkage between systems and actors. Trust and transparency are the soil for an openness to share data and information, and fruitfully collaborate.

c) Being open to learning, sharing, collaborating and willing to pursue new avenues

The findings indicate a set of mindsets favouring a purposeful interlinkage, arrangement and governance of activities in the context of I4.0-driven BMI. The data analysis shows that the development speed and growing complexity due to I4.0 makes it important to (1) be open to learning from others, and to share knowledge or data with others; and (2) possess a willingness to pursue new avenues. These characteristics are necessary both across functions within the firm, but also within the value network, as capabilities to appropriately take a certain decision or to carry out specific activities may not exist in a team or even firm-wide.

First, many leadership teams seem to experience contrasting views regarding an openness to learn and share among themselves. Some leaders have an open mindset, believing intrinsically in the openness to learn new things and work with others, while others have a more protectionist attitude and might rely on extrinsic incentives. The importance of being open to learning and, at the same time, sharing one's own insights with others was highlighted by Delta's director of sales and production planning, who described the initial starting point on Delta's path towards their "pharmacy of steel" BM: "*One must also force oneself to create free space for new things (although one cannot immediately tell the benefit) – both temporal and mental free space. We, as a management team, did that sometimes with IBM – taking a workshop at theirs and then inviting them to us, to just think freely and be open to what's possible, without knowing how we want to do it, how we want to implement it. Just brainstorming how we could enhance our business model with digitalisation. You really take your time and leave space for it.*" Moreover, Delta Steel shows great openness to share real-time operational data with their customers and suppliers. Openness is one of the cornerstones for the successful reconfiguration of their activity systems towards the "pharmacy of steel" BM.

In addition, Theta Heating's director of digital transformation talked about the difficulty of being open. He remarked about the open innovation approach of their executive board, stating that the new chief strategy officer has open innovation "*as a matter of her heart, but we are controlled and managed by revenue and profit. The new CTO also pushes it with the new open innovation lab at the university. However, the general pressure to pursue an open innovation approach is sadly very weak and subject to individual executives.*"

Being open to learning from others and sharing one's own knowledge or data is at the heart of I4.0, as challenges are too complex and opportunities too manifold to handle alone. The findings suggest this openness to learning and sharing is a crucial cognitive aspect of top leaders and employees alike in starting and retaining a firm's BMI journey in the context of Industry 4.0.

Second, the findings indicate a willingness to do new activities and to pursue new avenues as a crucial mindset aspect. This relates to the novelty of I4.0 solutions for many manufacturers. New technologies and new ways of working that yield benefit for manufacturing firms regarding changes to their I4.0-BM are often unprecedented in their firm or industry. Eta's CEO of a product business unit, who also serves as Eta's director of high-performance manufacturing technology, summarised Eta's approach to digitalisation as a "*doer's way, and not always saying 'no, we don't want that' or 'we definitely don't do this'. We have developed this culture over the past few years – not discussing the issue for* *too long, but simply doing things […] However, for digitalisation we need more creative people that are driving this entrepreneurial thinking into our organisation.*” This entrepreneurial attitude at Eta Drive is underpinned by setting up an “advanced manufacturing” team to explore new ways to current processes by means of advanced analytics and cobotics with a specific focus on finding improvement opportunities and realising potentials. Eta’s head of advanced manufacturing commented on the importance of pursuing these new avenues: “*We need more people who have the experience and affinity to tackle new digital topics. You need them to drive projects.*”

It becomes evident from the notions of “openness”, “willingness”, or “a doer’s way” that this is subject to cognitive attitudes and habits of individuals, but more importantly of top leaders, as they are further driving the establishment of a respective culture and atmosphere within the firm and its ecosystem. These findings demonstrate that sensing and seizing changes in a complex activity system, such as an I4.0-driven BMI, and reconfiguring the activity system appropriately for achieving dynamic consistency, is conditional on the cognitive capabilities of managers.

5.6 Chapter Summary

This chapter provided the findings elaborated from the six case studies by identifying common patterns resulting from the coding analysis, conducted on the data gathered in personal interviews. In doing so, the findings aimed to answer the research question:

What are the microfoundations of dynamic consistency in I4.0-driven BMI?

The previous sections (5.2, 5.3, 5.4) present evidence for the operationalisation of dynamic consistency in an I4.0-driven BMI along the lines of the three design themes of a BM as an activity system: content, structure and governance. The following three aggregate dimensions were found to operationalise large aspects of dynamic consistency: 1) content – organising the I4.0-driven BMI with a value focus on data and software as a catalyst that ensures appropriate exchanges of materials and information to granularly segment customer needs and responsively fulfil these demands with individualised solutions; 2) structure – achieve alignment across the activities through an active flexi-directional interlinkage of cyber and physical activities on the basis of interoperable software systems;

3) governance – decisions about changes to the activity system are taken by agile working ensembles who are incentivised to collaborate within and beyond the firm and take decisions as a team. Moreover, the analysis showed that these three aspects that follow the BM as an activity system cannot sufficiently operationalise the notion of dynamic consistency. In addition, a cognitive foundation complements these aspects; this aggregate dimension proactive mindset with integrity is elaborated in Section 5.5.

The next chapter will discuss these findings with respect to the existing literature.

6. Discussion and Conclusion

This chapter first provides a collective synopsis and discussion of the key findings in Section 6.1, then highlights their contribution to theory in Section 6.2, before briefly discussing implications for practitioners in Section 6.3. Limitations of this research and recommendations for future research are given in Section 6.4. Section 6.5 concludes this thesis.

6.1 Collective Synopsis and Discussion of Findings

Despite noting the importance of considering the interdependencies of BM components and the dynamics involved, the BMI literature to date has not yet provided sufficient insights into what factors and mechanisms operationalise this notion of dynamic consistency as introduced by Demil and Lecocq (2010). Accordingly, this thesis has addressed the following research question: *What are the microfoundations of dynamic consistency in an Industry 4.0-driven BMI?* This section discusses the key findings on the microfoundations of dynamic consistency of I4.0-driven BMI in manufacturing firms, obtained from the data analysis in the Chapter 5.

Along the ordering scheme of the BMI as an activity system and the thereto relating design themes by Amit and Zott (2001), and Zott and Amit (2010), the findings provide a detailed picture of the concrete arrangements and facilitating mechanisms that support manufacturing firms in achieving dynamic consistency in the realm of the Fourth Industrial Revolution. Based on in-depth case studies with semi-structured expert interviews in two manufacturing industries, the findings presented in Chapter 5 revealed four aggregate dimensions that answer the following questions regarding the notion of dynamic consistency in I4.0-driven BMI:

(1) Content – what are the activity arrangements to ensure appropriate exchanges of material and information? What capabilities ensure this? A *value focus on data and software as a catalyst* to improve customer experience with digitally enhanced product and service offerings. By using data and software to complement existing domain expertise, to obtain granular information about customer needs, and to fulfil these needs rapidly, on time and on quality.

(2) Structure – how are activities interlinked to achieve alignment across activities to strive for similar objectives? *Active flexi-directional interlinkage* of activities through real-time interoperable software suites and the proactive adaptation of processes through disassembly and reassembly to improve the flows of information and materials.

(3) Governance – how are decisions on the activity arrangement and their interlinkages taken, by which authority, and what incentive structure exists? *Agile working ensembles* empowered to take decisions and to approach challenges entrepreneurially, incentivised by sharing value across function and firm boundaries.

(4) Unexpectedly, the findings indicate that the common view of BMI as an activity system does not enable a sufficient explanation of the notion of dynamic consistency. But the cognitive view of BMI significantly contributes to the understanding and achievement of dynamic consistency. These two perspectives pay tribute to the characteristics of complex systems, that can be perceived from different perspectives, giving them different meanings at different times (Velu, 2017). The findings highlight the importance of specific cognitive foundations, i.e. individual mindsets and collective behaviours that enable the changes discussed above to the activity system in the first place: *Proactive mindset with integrity*, where leaders take championship for a mutual I4.0 vision and create a sense of family, referring to an open, collaborative and trustful behaviour across the firm, enabling a holistic journey of I4.0-driven BMI execution.

Accordingly, the findings of this research project provide valuable insights into how manufacturing firms can organise their I4.0-driven BMI holistically, reducing synergy losses through isolated, redundant or misaligned approaches to utilising I4.0. Figure 16 presents a graphical summary of the microfoundations of dynamic consistency in an I4.0-driven BMI. In the following sections, the four main aggregate dimensions synthesised from the data analysis shall be discussed in more detailed.

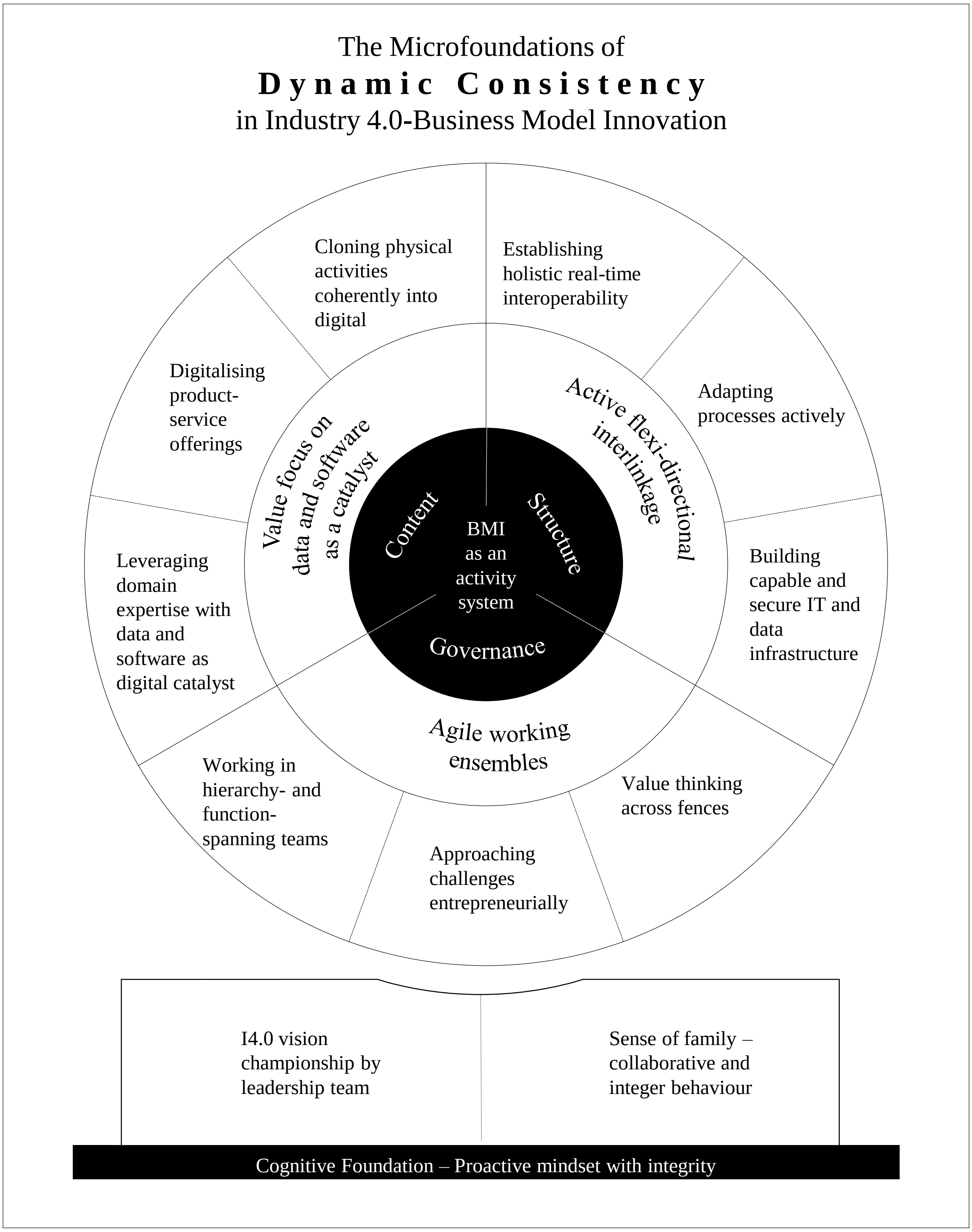

Figure 16. Explicated microfoundations of dynamic consistency in an I4.0-driven BMI

6.1.1 Content

Content: *What activity arrangements ensure appropriate exchanges of material and information? What capabilities enable this?*

When organising the content of their I4.0-driven BMI, manufacturing firms have to consider what activity arrangements ensure appropriate exchanges of materials and information, and what resources and capabilities enable this (Amit and Zott, 2001; Zott and Amit, 2010). Whereas current literature has highlighted individual effects of digitalisation on individual content elements of a manufacturing firm’s BMI (cf. Porter and Heppelmann, 2015; Burmeister, Lüttgens and Piller, 2016; Kiel, Arnold and Voigt, 2017), it has, to the best knowledge of the author, largely remained silent on what mechanisms drive manufacturing firms’ activity selection to ensure an appropriate exchange of information and materials across their I4.0-driven BMI.

The findings suggest placing a value focus on data and software as a catalyst. This means to use data and software to granularly segment customer needs and fulfil these needs flexibly and responsively with individualised product and service offerings. Central to this value focus is leveraging existing domain expertise with data and software as a digital catalyst. Data and software as a digital catalyst allows manufacturing firms to complement or support their traditional strengths by retaining their domain expertise and leveraging it with data and software, to (1) granularly segment customer needs, (2) meet these needs with individual digitalised product-service offerings and (3) fulfil these individualised solutions by cloning physical activities coherently into digital to flexibly and responsively act on changing customer demands. Figure 11 in Section 5.2.1 shows a graphical schema of these three mechanisms.

(1) Exploring customers’ jobs to be done (cf. Christensen *et al.*, 2016) in order to identify their needs is essential to then granularly segment customer demands and ultimately provide targeted, individual solutions to them. By using data and software to consolidate and analyse information about customers, in combination with digitalised products and services that provide individual real-time data, manufacturing firms can finely segment their customers, positioning them so as to individually enhance their experience. To be more precise, the findings show, in line with the literature, a general tendency towards shortened product development cycles, short and flexible delivery times alongside increasing variants and volumes, and individual solutions that become very important for

customers of the examined manufacturing firms (Kagermann *et al.*, 2013a; Brettel *et al.*, 2014).

(2) Manufacturers can only fulfil this demand of individual solutions by again using digital technologies as a catalyst to create *digitalised product-service offerings*; connectivity, data and software allow product and service offerings to be customised through after-sales individualisation, over-the-air updates or advanced services such as individual data analytics for preventive maintenance. For supporting granular customer segmentation and the individualisation of the value proposition, the findings indicate digitalised products and services as the central element. As expected, prior literature, especially Porter and Heppelmann (2014), has already extensively discussed smart, connected products as one of the main impacts of I4.0 to manufacturing firms' BMs: the connectivity of products and services as an instrument for interacting more intensively with individual customers beyond the point of sale to retrieve data about customer usage and insight into improvements of design or production; and the possibility for after-sales modification and individualisation based on software (Arnold *et al.*, 2016; Kiel *et al.*, 2017). However, with regard to a dynamic consistency as the continuous alignment of activities in a BMI, the literature has fallen short of explicating the importance of connected, digitalised products and services.

(3) As these solutions are increasingly individual to customers, manufacturing firms need to increase their *responsiveness and flexibility* to create and deliver them. The findings indicate that manufacturers do this by creating a coherence between cyber and physical activities through "digital cloning". This refers to, and is mainly achieved by, a software-based replication of the physical activity system, often realised through the use of CPSs, which have been extensively discussed as a core aspect of I4.0, often in the context of digital twins (Kagermann *et al.*, 2013a; Industrial Internet Consortium, 2017). This digital cloning enables quick reactions based on transparent, real-time, digital data-based information (Brynjolfsson and McAfee, 2016). The digital replication of physical activities for a software system-based facilitation of information exchanges, and the pooling of available information, positions manufacturing firms to significantly improve the exchange of information and materials across their BM. It thereby increases flexibility and responsiveness.

Moreover, the findings suggest facilitating tacit knowledge in software systems. They show that the digital cloning of these activities is, however, subject to a data selection puzzle. Due to the physical nature of manufacturing processes, it is not feasible to simply "gather all data", as in practice it is not possible to determine all the potential influencing factors *a priori*. Accordingly, the findings suggest accounting for this data selection puzzle by building software environments in a way that allows data to be included later on, when they are considered relevant, but starting with data that are considered relevant by process experts in the beginning.

Given the focus on data and software, alongside the importance of responsiveness and flexibility, manufacturing firms must rely on certain in-house capabilities in data computing and software development to react swiftly to rapidly changing customer demands. This is generally in line with other scholars' work (Porter and Heppelmann, 2014; Arnold *et al.*, 2016), although these capabilities have not been discussed as important for the speed of responsiveness to change flows of information and materials in an I4.0-driven BMI process (Müller *et al.*, 2018; Müller, 2019), or in the context of activity alignment, i.e. achieving dynamic consistency.

The role of leveraging data and software as a digital catalyst is, in comparison to non-hardware-driven businesses, a critical aspect for manufacturing firms: the analogy of a catalyst is drawn from chemical processes; according to the Cambridge Dictionary, a catalyst is a substance that triggers or accelerates a reaction, without being used up itself. Using data and software as a catalyst in the context of dynamic consistency in an I4.0-driven BMI refers to the role of data and software to leverage existing domain expertise. In comparison to industries where products, services and value-creating activities can be completely digitalised (such as media content), manufacturing firms are based on their know-how in their existing domain, which may, for example, reside in engineering or production. Production machines can be supported and enhanced by the use of digital solutions; however, a large part of manufacturing is the physical making of products. As discussed, by using data and software as a catalyst, manufacturing firms reflect on their strengths and further expand them by better understanding customers and enabling the flexible and responsive fulfilment of the targeted needs. The inherited interplay and increasing interdependence of product-service offerings and value-adding activities, in particular, has been barely discussed or empirically underpinned in (I4.0-) BMI literature, only being discussed to a certain extent under the term "mass customisation" (Fogliatto *et al.*, 2012).

6.1.2 Structure

Structure: *How are activities interlinked to achieve alignment across them when striving for similar objectives*

Given these selection and organisation mechanisms for I4.0-driven BMI and the notion of dynamic consistency, the digitalisation of product-service offerings and the coherence of cyber and physical activities is especially enabled and achieved through a structure that allows effective information and material exchange; the findings therefore indicate an active flexi-directional interlinkage of activities to achieve this in I4.0-driven BMI. Active flexi-directional interlinkage is particularly subject to a comprehensive and omni-directional interoperability of various software systems that enables a convergence of multiple sources of data from the product life cycle, the value chain and business data into one SSOT. A granular segmentation of customers, and the flexible and responsive fulfilment of their needs with individualised solutions, is only possible once all the specialised software suites in a manufacturing firm – sales, product design, production engineering, manufacturing management and warehouse, as well as customer relationship management and the overarching enterprise resource planning – are made interoperable to share one single source of data truth. Based on the internal integration of these systems, a horizontal integration with customers and suppliers or other partners can be set up, although the findings indicate that, from a strategic stance, horizontal integration serves rather as a trigger for BMI, since the BM of a manufacturing firm is reliant on other firms' activities upstream and downstream. Nevertheless, horizontal integration can only be implemented once a certain degree of internal integration has been achieved. Related to this increased integration, interviewees stressed the importance of a capable and secure IT and data infrastructure, as they provide the backbone of information and material exchanges.

Generally, regarding the importance of an omni-directional linkage of activities, the findings are congruent with those of (Kagermann *et al.* (2013a), Brettel *et al.* (2014), and VDI and ZVEI (2015). Thereby, the findings draw on the increasing coherence of cyber and physical activities, discussed in Section 5.2.3. The coherence of cyber and physical as well as the sharing of information across functions is, among other aspects, especially enabled by a SSOT as a data aggregation instrument. SSOT crystallised as the most important single aspect for any further digitalisation activities, denoted by almost every interviewee in the study. A focus on a SSOT is important as it facilitates the interoperability of diverse software suites, enabling the combination of all available data for analyses and other uses that may not have been thought of beforehand. At the same time, the SSOT is the backbone for greater responsiveness and flexibility, as information for redirected flows of information and materials are available in one central location, and thereby significantly contribute to a tighter alignment of customer data, value-adding activities or product-service offerings. While from a technical point of view, the particular importance of a SSOT is most commonly consensus, for BMI and alignment of activities in a I4.0-driven BMI, this finding is unprecedented.

An increasing interoperability requires standardised processes and interfaces, and the findings match with the literature here (e.g. Xu, Xu and Li, 2018). In addition, findings indicate the need for flexible processes, which also is mentioned in the literature on both I4.0 and BMI (Doz and Kosonen, 2010; Achtenhagen *et al.*, 2013; Brettel *et al.*, 2014). According to the findings, manufacturing firms seem to face a conundrum here which has not received much attention in either I4.0 or BMI literature – to standardise processes for enabling interoperability but still keep the processes flexible. To solve this conundrum, the findings indicate an active adaptation of processes, referring to the ability to disassemble standardised processes into their parts to reconfigure and reassemble them for a better flow of information or materials. This active process adaptation is vital for a continuous flexibility and responsiveness to create and deliver individualised solutions. A closer examination reveals that this is not contradictory – the findings clearly suggest that firms need to be able to continuously disassemble, reconfigure and reassemble their processes in response to changing customer needs in order to meet the increasingly required demands of flexibility and responsiveness. This reconfiguration also builds on the value focus on data and software discussed in Section 5.2. The digital cloning of physical activities and their software-based facilitation in a SSOT positions manufacturing firms to better assess their current flows of information and materials. Based on the greater availability and granularity of real-time data about physical processes, this enables them to rapidly determine improved flows of information and materials.

However, as manufacturing firms still rely on hardware production, they need to ensure the reproducibility and reliability of their processes, which is why process standardisation still receives considerable attention from practitioners. The findings suggest that standardised processes and agreed semantics among actors in the BM provide a fruitful basis for disassembling and reassembling processes, as standardised processes can be analysed and taken apart more logically than non-standard processes.

Finally, data and IT infrastructure has only received limited attention in I4.0-driven BMI so far, but mostly in the context of skills needed for Industry 4.0 (Kiel *et al.*, 2016; Müller, Buliga, *et al.*, 2018). Moreover Xu *et al.* (2018) claim that a further integration of activities may be limited due to a lack of sophistication of the relevant technologies or a lack of techniques. These aspects cannot be empirically supported by the present work's findings – rather, the findings suggest a lack of understanding and discussion in the literature about the important role of trust and personal relationships between actors. In this respect, the limiting factors for many integration approaches is trust, not so much the pure technical features. Moreover, solid and rigid data governance processes that ensure data quality at all times were seen as crucial by many practitioners but have not received much attention in the I4.0-driven BMI literature. The importance of data and IT infrastructure for I4.0-driven BMI is especially logical once considered against the intensification of linking actors and entities across the activity system in real time, as discussed in Section 5.3.1. Data are increasingly the basis for (autonomous) decisions; firms want to be sure that data that enter their SSOT have a specified quality. In addition, real-time linkage is of utmost importance for dynamic consistency, so it is clear that a performant IT and data infrastructure – the backbone of real-time linkage – needs particular consideration for manufacturing firms. While the general importance of solid data governance approaches has been shared in information systems literature (e.g. Khatri and Brown, 2010), it has not received much attention in the BMI literature (MIT Sloan Management Review, 2016).

6.1.3 Governance

Governance: *How are decisions on activity arrangements and their interlinkages taken? By which authority? What incentive structure exists?*

The ability to actively adapt standardised processes by disassembling and reassembling them, to manufacture individual product-service offerings responsively, requires parts of the manufacturing organisation to work in "agile working ensembles". Agile working ensembles are characterised by a hierarchy- and function-spanning team that jointly executes processes. Based on a joint ownership by the leadership team to drive the change, teams and their experts are empowered with clear responsibilities to act entrepreneurially. The teams' empowerment encompasses to prioritise their tasks and next steps as appropriate, to change the activity selection and the flow of information and materials between activities. This is especially important against the background that development speed accelerates continuously due to the exponential development of digital technologies. Owing to this speed of change, firms also have limited time and resources to build expertise internally in all fields that are required to be changed in order to stay ahead of competitors (cf. Section 5.2 on content and Section 5.3 on structure – product-service offerings and value-adding activities must often change simultaneously), requiring collaboration with suppliers, customers and other partners. To account for this increasing cross-functional collaboration within the firm and across the ecosystem, the findings suggest incentive structures that support this collaborative working and rapid decision-making by sharing value across traditional departments or firm boundaries.

While cross-functional teamwork is congruent with the existing literature (Fjeldstad and Snow, 2018), the findings highlight that teams should not only span cross-functionally but also cross-hierarchically, with management involvement accounting for the exposed importance of I4.0-driven BMI for the entire organisation. Moreover, the findings show that these hierarchy- and function-spanning teams can only work successfully when they approach their challenges entrepreneurially. The latter refers to a progressive prioritisation that is based on a bottom-up learning mechanism that uses piloting of solutions very early and rapidly to test and validate or discard ideas, and based on these solutions the team prioritises the next steps. While Sosna *et al.* (2010) similarly discuss trial-and-error learning, their notion is a mechanism to kick-start the invention of a new BM, i.e. the front end of BMI as a top-down approach. In contrast, the findings suggest a testing of solutions with pilots to refine and continuously improve a solution to increase users' and customers' satisfaction, denoting a "bottom-up" or empirical learning mechanism during the process of innovating an existing BM. The findings can be seen as complementary to the approach taken by Sosna *et al. (2009).*; bottom-up/empirical learning during the BMI process serves I4.0 well, as speed is crucial for increasing responsiveness and appropriately interlinking activities. To a certain extent, bottom-up/empirical learning is similar to the experiential learning described by Berends *et al.* (2016), where action is the source of learning, which further argues for the complementary use of cognitive search and experiential learning to deal with the configurational complexity of BMs.

Explicit studies on I4.0-driven BMI also generally claim that an entrepreneurial mindset with a focus on risk taking and openness is a key foundation for driving BMI (Burmeister, Lüttgens and Piller, 2016), which at first sight seems largely congruent with the findings. However, while the literature to date predominantly focuses on decision-making while searching and initiating new BMs, this work's findings emphasise insights into how a fast responsiveness and flexi-directional interlinkage will affect the structure of governance and incentives with respect to who holds decision-making authority during the process of BMI. While this fast responsiveness is technically enabled by a flexi-directional interlinkage of activities, it must also be accompanied by changed principles of who can make tactical decisions during the I4.0-driven BMI. Highlighted by the need for speed in various dimensions, it becomes clear that decisions cannot solely be taken high in the hierarchies of organisations anymore, but that various types of decisions must be taken by the cross-functional and cross-hierarchy teams that are close to the point of action, i.e. where processes are disassembled and reassembled to enable flexibility and responsiveness. In a certain sense, governance structure changes from being political (i.e. an appointed authority is assigned to decide due to its hierarchical positioning) to being technocratic (i.e. the decision is taken by the expert or team that is closest to the point of decision and best equipped with information about the decision). The types of decisions that should be taken by decentralised teams of experts particularly concern improvements in the exchange of information and materials within the activity system to generally optimise serving customer demands. In contrast, decisions related to the choice of (key) activities shall still be taken by the management team. These decisions are based on sensed customer needs and hence determine the competitive core of the firm; accordingly, these decisions require a holistic overview of the activity system and set the tone for realising synergetic effects.

Given their empowerment to take decisions, these teams can prioritise their work content progressively, instead of *a priori* as in traditional waterfall projects. They can focus on the most important aspects that are required to serve customer needs responsively. This aspect of entrepreneurial working and decision-making, which is generally extensively discussed, has not been highlighted in the (I4.0-) BMI context for the actual process of BMI, but has mostly been limited to the front end of generating ideas for new BMs (Velu, 2017).

In support of this changing governance structure, with teams that increasingly span functions and also firm boundaries, the findings indicate that incentive schemes are needed that share the appropriated values among the partners and contributors, and thereby account for the technocratic decision-making that is required for rapid responsiveness and an active flexi-directional interlinkage. These schemes must cross-incentivise functions in order to foster collaborative working and mutual technocratic decision-making with (external) partners to design, manufacture or sell their products and services. The findings suggest structures that synchronise incentives among collaborators and towards being open to sharing value among partners, both within the firm and across the wider ecosystem, as rapid decision-making by these teams is not possible if incentives diverge. The comparison to orchestral or theatre ensembles highlights how important it is to harmonise the incentives of functions and individuals across the team in view of a shared objective, encouraging teams to rapidly take appropriate decisions that support the shared goals.

While appropriate governance is mentioned in the literature as a possible success factor for I4.0-driven BMI (Burmeister *et al.*, 2016), value thinking across fences and the relation to rapid, technocratic decision-making has received little recognition in I4.0-driven BMI and BMI as an activity system, despite digital technologies allowing much more granular and individual incentive structures.

6.1.4 Cognitive Foundation – Proactive Mindset with Integrity

In addition to the explicated microfoundations based on the notion of I4.0-driven BMI as an activity system, the findings clearly revealed that the formerly discussed aspects organised around the design themes of content, structure and governance cannot sufficiently operationalise the notion of dynamic consistency. Instead, they indicate the need for a cognitive foundation fostering a "proactive mindset with integrity" that complements the activity system view, providing the foundation of dynamic consistency of an I4.0-driven BMI. As the findings suggest, a "proactive mindset with integrity" can be further distinguished as two-phased – phase one concerns the initial ideation and start of the I4.0-driven BMI with a focus on the leadership's mental processes, whereas phase two concerns the ongoing process of dynamic consistency during the I4.0-driven BMI. In phase one, open-mindedness is crucial in the form of an I4.0 vision championship by the leadership team that is required to generate new cognitive models of the future BM to provide a strategic pathway for the organisation. Phase one is very much like the prevalent notion of BMI as a cognitive schema, as discussed by Martins *et al.* (2015).

In phase two, once the innovation of a BM towards the generated vision is underway, the findings indicate the importance of a sense of family that supports collaborative and integer behaviour. This notion reflects the view taken in studies such as Hock *et al.* (2016), which focus on cultural aspects that favour BMI. A sense of family denotes a freedom for and willingness of people to learn, share and collaborate internally and beyond. Moreover, the findings suggest an omni-directional, dialogic communication as crucial. Dialogic communication is important to encourage people to speak up, generate ideas and provide constructive feedback. This, in turn, is subject to solving the identified trust and transparency conundrum – as data and information are increasingly shared and stored in a SSOT, people must be assured that these data are not misused in any way, otherwise transparency cannot be achieved. At the same time, the findings show that the rapid responses required by manufacturers' customers are subject to trusting the data as well as colleagues – in particular, once manufacturers want to respond swiftly to changing requirements, interviewees clearly show that trust is an elemental enabler of speed. However, as the findings show, trust only develops through transparency, and transparency increases the quality and the speed of information and material exchanges between linked parties. Solving this organisational conundrum is a key task for organisations in the course of a successful I4.0-driven BMI.

Given that a (two-phased) cognitive notion of BMI is vital for understanding dynamic consistency that has, to date, been purely based on BMI as an activity system, one has to examine more closely what is offered by the BMI view as a cognitive schema to further understand the notion of dynamic consistency. The two cognitive phases indicated by the findings can be related to the characterisation of the cognitive BM as a frame for individual minds as well as the collective discourse within the organisation, shaping and sharpening the opportunity recognition and leading to a shared view of the BM across the organisation Massa *et al.* (2017).

The predominant discourse in the BMI literature discussed the first part of this idea, BM as a "frame for individual minds", focusing on the upfront development of new business ideas or ideas for how the existing BM could be changed. This view is similar to phase one, identified in the findings as *I4.0 vision championship by the leadership team.* Some scholars, for example, perceive cognitive schemas as a general framework for ideating new BMs, which is bound to the absence of exogenous change (Martins *et al.*, 2015). Other scholars more generically perceive a BM as a cognitive model for managers to make decisions regarding their actions (Baden-Fuller and Morgan, 2010). Broadly following this definition of a cognitive BM, Velu (2017) advocates for cognitive discretion as a mechanism for an upfront triggering of BMI. Moreover, Doz and Kosonen (2010) advocate for strategic agility. In their view, strategic agility consists of leadership unity and resource fluidity as well as strategic sensitivity. The finding *I4.0 vision championship by the leadership team* supports their concept of strategic sensitivity, regarded as the sharpness of perception and awareness to strategic developments, informing the front-end process of (I4.0-) BMI. Leadership unity and resource fluidity present related ideas to phase two of the cognitive phase, discussed below. However, despite viewing BMI as a cognitive concept providing firms with fruitful insights into the challenges facing technology shifts such as I4.0 (Tongur and Engwall, 2014), incumbent manufacturing firms still face cognitive challenges in identifying new BMs. One aspect may be the prevalence of the dominant design of the previous BM that made these firms successful (Doz and Kosonen, 2010; Kiel *et al.*, 2017; Schneider, 2018). Prioritising and utilising a suitable I4.0 pillar and pathway for a promising BMI is therefore a matter of BM decision driven by the firm's strategic vision (Casadesus-Masanell and Ricart, 2010; Köbnick *et al.*, 2020) that is based on the managers' cognitive envisioning (Tongur and Engwall, 2014).

The findings empirically build on these claims by highlighting the need for leadership teams in manufacturing firms to embark on a joint envisioning process. This incorporates learning about the opportunities and challenges related to I4.0, as well as iterative discussions among the leadership team to generate shared cognitive maps for their BMs. Particularly given the increasing flexibility and responsiveness required of manufacturing firms to serve individual customer demands, it is vital that leadership teams critically examine and discuss suitable approaches. As large parts of the firms' process landscapes may need to be disassembled and reassembled to improve flows of information and materials, it is vital that the leadership teams reach a mutual understanding of their cognitive maps in order to jointly champion the required changes. Joint championship is imperative due to the holistic changes required, and the scope of interoperability that interlinks activities and actors across the firm. Moreover, only a joint vision and championship that incorporates an active involvement of the leadership teams enables an agile governance structure where cross-functional teams are empowered to take decisions, and generated values are shared across fences.

The second cognitive phase identified as crucial for informing the notion of dynamic consistency relates to an organisation's culture, incorporating an integrity of behaviour based on trust and transparency alongside an openness to learn, share and collaborate; this second phase embraces the perception of "collective discourse within the organisation", as

Massa *et al.* (2017) further characterise cognitive BM. The perception of collective discourse has received limited attention in the BMI literature; only a few studies have examined specific aspects of the collective discourse notion that relate to these findings. Achtenhagen *et al.* (2013), for example, propose critical capabilities that foster a strong culture alongside active and clear leadership; this includes developing and sharing clear values, exerting a visible and credible leadership style and focusing on communicating the value-creating strategy across the company. In general terms, they argue that strategizing actions, capabilities and activities are complementary when fostering BM change, which can be seen as supportive of the findings in Section 5.5. Moreover, Hock *et al.* (2016) propose that novelty-orientated cultural values such as flexibility and open communication foster strategic sensitivity, collective commitment and resource fluidity, which are said to be in favour of BMI. A sense of family can be regarded similar to what Doz and Kosonen (2010) labelled “leadership unity”, focusing on top-team unity in making bold and fast decisions, without win-or-lose politics. In addition to this top-team unity, the present work’s findings indicate the importance of spreading this unity into the organisation. Hence, the main focus of a proactive mindset shifts from the leadership team into the organisation, which needs to be proactive to embrace change and to be open to new ideas. While Doz and Kosonen (2010) similarly propose “resource fluidity” as the ability to reconfigure capabilities and redeploy resources swiftly, the findings of this thesis are rather concerned with the underlying organisational behaviour to achieve a fluidity of resources. Doz and Kosonen’s concepts generally support the findings of this thesis, but their discussions and other discussions in the literature remain on an abstract, conceptual level, whereas the present findings provide more concrete and empirical insights.

The role of trust in (I4.0-) BMI was found to be crucial but has received very little consideration to date. One study that lightly touched on the role of trust was that by Santos *et al.* (2009), who theorised that the intention to change a BM will be hampered if the social dimension of activity interlinkages is ignored. The findings clearly support this claim and, furthermore, expand this notion by highlighting a triangular relationship between trust, people and data/information. They show that trust is especially relevant for running an I4.0-driven BMI, as the required speed of change to achieve flexibility and responsiveness is subject to rapid decision-making that relies on trustful data and trustful information exchanges between (social) actors.

While these few studies that have been discussing the notion of cognition as a collective discourse remain rather abstract and superficial, the present findings provide evidence of how a sense of family facilitates and puts into practice a fruitful collective discourse in the course of achieving dynamic consistency. The mechanisms discussed in the Sections 6.1.1 to 6.1.3 enable a granular segmentation of customers and the responsive fulfilment of their individual needs. They require manufacturers not only to collaborate in cross-functional teams within their own firm, but increasingly with partners across the ecosystem. Since the response to changing customer needs often requires speed of action, for developing product-service offerings as well as for the swift adaptation of value-adding processes (by disassembling and reassembling them), it is important for manufacturing firms to have a shared mindset in place that operationalises the collective discourse into actionable mechanisms. By building a mindset that relies on dialogic communication, firms establish an environment of trust that fosters the information transparency. Importantly, the latter is needed for the rapid exchange of information as a basis to appropriately exchange materials across the activity system to serve changing customer needs. Moreover, trust and transparency are important assets for working in cross-functional and hierarchy-spanning teams that are empowered to take far-reaching decisions. Moreover, the sharing of appropriated value among partners within and beyond their own firm largely relies on trust and transparency, as individual contributions to goals are often hardly quantifiable.

The cognitive perception of a BM that needs to be modified in the face of external discontinuities and disruptions (Teece, 2010), can be compared to scientific hypotheses that may need to be changed or rejected after confronting data (Saebi *et al.*, 2017). This thinking can be translated to the notion of dynamic consistency. While dynamic consistency requires vision and leadership based on cognitive processes, these generated cognitive maps need adjustment over time. In response to external discontinuities such as I4.0, these adjustments need to be made rapidly and changes in one BM component may trigger negative feedback loops in another, or enable positive feedback loops (i.e. synergetic effects) that need to be resolved to achieve alignment across the activity system. Such a continuous (re-) organisation of activities ensures appropriate flows of information and materials – known as dynamic consistency.

6.1.5 Connecting the Dots

Together, the four aggregate dimensions – a value focus on data and software as a catalyst, active flexi-directional interlinkages, agile working ensembles, and a proactive mindset with integrity – explicate the microfoundations of dynamic consistency as the alignment of activities across an I4.0-driven BMI with the aim of improving exchanges of information and materials.

Considered together, these mechanisms suggest a new conceptual thread for thinking about I4.0 and BMI. The academic discourse on I4.0 has predominantly suggested technical solutions for individual problems in manufacturing processes to improve efficiency or productivity. In addition, those manufacturing firms that use BM frameworks envision static BMI in the form of a one-off generation of new BMs, often following the static BM canvas approach. However, these frameworks do not consider the dynamic, ongoing changes in the interdependencies of activities in a BM, particularly between value-adding activities and the changing product and service offerings. The latter also applies to another part of the academic discourse that discusses the shift from output- to outcome-orientated BMs where customers pay for specific solutions to a problem (Baines *et al.*, 2007; Martinez *et al.*, 2017). However, these discussions are mostly limited to an innovation of the product-service offerings, i.e. to the value proposition as only one of four BM elements (Lorenz *et al.*, 2019). This narrow focus might be causative for manufacturing firms still following the traditional “make-and-sell” type of BM, where standardised products and services are sold to customers.

However, due to rapid technological developments, the traditional make–sell BM seems less appropriate in times of I4.0. I4.0 drives an increasing ubiquity of available real-time data that, for example, enable more granular information about customer needs and flows of materials; eventually, the flow of information can also be improved significantly. The findings and their discussion suggest that this centrality of information is a BM that can be circumscribed as “sense-and-act”, as opposed to “make-and-sell”. Furthermore, the findings provide evidence for the mechanisms that manufacturing firms must use to actively innovate their make-and-sell BM on an ongoing basis to eventually achieve such a sense-and-act BM.

In a sense–act BM, manufacturing firms use I4.0 to granularly *sense* real customer needs. Firms can then proactively *act* on individual information about the customer to fulfil these needs. This BM archetype accounts for the shift towards individualised solutions that enable enhanced customer experiences and thus yield higher productivity and profits. "Sense" thereby indicates the necessity and capability to closely understand either existing or potential customers with their individual needs based on granular information about their applications, current and expected usage patterns and the like, mostly obtained through CPSs in smart, connected products. Based on this information, customer needs can be granularly segmented into fulfillable demands. "Act" refers to the manufacturer's ability to take advantage of these individual customer demands proactively. Flexibility thereby plays a vital role: first, as the capability to understand the required changes to the manufacturer's products and services in order to enable customers of existing and new products to better serve their customers' wishes. Second, flexibility denotes the ability to develop and produce these individualised products and services rapidly, and deliver them on time and on quality. Flexibility is significantly subject to effective access to data and transparent flows of information to appropriately organise the flows of materials. Both these requirements are made possible by the strategic use of I4.0 to obtain valuable information and take the required actions in their respective value-adding activities.

This research shows what mechanisms manufacturing firms have to deploy to actively innovate their existing make-and-sell BMs on an ongoing basis towards sense-and-act BMs. This includes not only the digitalisation of product and service offerings, and the cloning of physical activities into digital, but also, more importantly, the active management of interdependencies of a closer integration and interoperability of the product-service offerings and the value-adding activity system; in short, the dynamic consistency. This continuous form of BMI is key to the successful implementation of I4.0, as the increasing interoperability and integration of systems in an I4.0 environment undoubtedly leads to an increasing interdependence of the impact of activities in the firm that are subject to constant technological and customer-driven change. The following paragraphs discuss the microfoundations that were found to operationalise the notion of dynamic consistency.

The speed of developments – both the speed of change and the speed required to change flexibly – generally becomes a new norm for manufacturers during the era of I4.0. The microfoundations of dynamic consistency indicate technological, organisational and cognitive mechanisms that firms are advised to follow in order to manage the transformation towards a "sense-and-act" BM that allows granular fulfilment of customer-specific needs. *Cognitive mechanisms* were found to be both the basis and the penetrating arrowhead for technological and organisational changes that are described by the firm’s activity system. While the imperative of rapid and flexible change must at first be recognised and embraced by the leadership team, they must then champion and communicate a coherent I4.0 vision for the firm, to gather the organisation behind a shared goal and to provide reasoning for resource allocations.

Technologically, the use of data and software as a catalyst to enhance the existing domain expertise lays the groundwork for granularly sensing customer needs. Through digitalising products and services and by achieving a coherence of cyber and physical activities alongside an omni-directional interoperability of software suites, manufacturing firms can swiftly and proactively seek opportunities arising from this granular understanding of individual customer needs. Swift and proactive action for manufacturing firms is, moreover, subject to processes that allow reliable outputs in the form of expected quantities, qualities and timeliness. The findings indicate that to achieve this, an active process adaptation is needed to disassemble existing processes, reconfigure them as required and reassemble them into a new process. *Organisationally*, flexibility and speed of action need agile working ensembles that not only approach these challenges entrepreneurially in cross-functional teams but are also, importantly, empowered to take decisions. This change from hierarchical decision-making towards taking decisions at the point of action is reflective of the speed and complexity of the decisions to be taken. For example, when product and service development processes converge with manufacturing engineering, the complexity of decisions through the interdependencies of activities is so high that decisions are best taken by these cross-functional expert teams that are also incentivised for such mutual decision-making.

While the championship of a cognitive vision by the leadership team must trigger the BM transformation towards a sense–act BM, the required far-reaching organisational changes are subject to *another cognitive mechanism*: a collective mindset of collaboration and integrity across the organisation that favours learning, omni-directional and dialogic communication, and trust and transparency. The latter are particularly crucial, as their absence hinders speed, for example in terms of non-transparent information or distrust among team members due to diverging incentives.

As the interplay of these microfoundations shows, a holistic approach to I4.0 requires viewing the BM from different perspectives. Taken together, the activity system view and the cognitive schema view provide sufficient insights to explain how the flows of information and materials should be designed, structured and governed. In view of establishing a sense–act BM, the alignment of activities is subject to granularly identifying customer needs and flexibly reconfiguring and reassembling the value-adding activities. To date, though, BMI literature has largely discussed the two angles separately: BMI as an activity system describing the core logic of how an organisation achieves its goals (Zott and Amit, 2010), and BMI as a cognitive schema that serves as an instrument to more efficiently organise decision-making in conditions of imperfect information and complex cognition (Massa *et al.* 2017).

While the literature review on I4.0, BMI and I4.0-driven BMI indicated that the activity system view holds great potential to inform the notion of dynamic consistency in an I4.0-driven BMI, the cognitive aspect of BMI played a somewhat subordinate role. The analysis of the case studies showed that the activity system view can sufficiently describe significant aspects of the notion of dynamic consistency. These rather tangible aspects include, among others, the need for manufacturing firms to place a "value focus on data and software as a digital catalyst" to ensure that they manage to granularly segment their customer needs, and organise themselves for increased flexibility to ensure a responsive fulfilment of these individual customer needs. Moreover, an active flexi-directional interlinkage provides the structure ensuring an appropriate flow of information and materials between activities. However, this shift from the traditional "make-and-sell" BM that has been characteristic of manufacturing firms for many decades, towards a BM that finely senses and acts on rapidly changing customer demands, cannot be accomplished by purely setting up tangible measures. As this new type of BM relies heavily on humans and information as a trigger for response and action, it is vital to view this process from a perspective that provides insights into how information is being processed by humans, who are still the main decision-makers in these systems.

Acknowledging that information is, to a certain extent, subjective (as illustrated by the modest relativistic philosophical stance of this research), one needs to consider the cognitive aspect that is involved in the changes to a BM. Not only do different people in an organisation have different cognitive maps of the firm's existing BM, but they likely also have different cognitive maps of the need to change specific aspects of this BM, and of the threads and opportunities held by I4.0 for their firm, both biased by their personal experiences and professional stance within the firm. Accordingly, these cognitive aspects must be acknowledged and actively managed if a firm is to achieve dynamic consistency throughout their BMI. Moreover, an activity is assembled from a mix of human, physical and capital resources (Figure 7, Section 2.5.1), and I4.0 denotes the ubiquitous interconnectivity of processes, things and humans. Both definitions are central to the present study, emphasising the significance of humans and thus providing further support for considering human cognition in activity alignment. To align activities, the flows of materials and information need to be appropriate, and these mechanisms of information and material exchange are established by humans who hold the power to change their flow.

Accordingly, the findings consolidated as a “proactive mindset with integrity” provide the cognitive foundation for the more tangible measures that enable the BM to become more responsive to granularly segmented customer needs. The cognitive foundation can be seen as the soil for the tangible activity system measures; and the continuous work to establish a shared cognitive map and further improve it is the fertiliser that enables the tangible mechanisms to unfold their potential for rapidly creating and delivering individualised product and service offerings.

Only a few studies have discussed the combination of the activity system view and the cognitive view as fruitful for understanding the BMI process. For example, Velu (2017, p. 613), in his study about perceiving BMI as a complex system, highlights the need to draw information and analyses about the individual sub-systems/BM components, as well as the firm’s environment, from multiple sources. This approach enables a “more effective changing of the BM components while understanding the complex interdependencies to keep the system integrated with a view to keeping the revenue and cost architecture in continuous alignment”, which implicitly denotes a sense of combining cognitive thinking with the view of BMI as an activity system. With respect to the general notion of combining the activity system and cognitive view of a BMI, the present work’s findings expand the view of Berends *et al.* (2016), who argue that a BM should not be reduced to either organisational actions or cognitive representations, but should be understood as a duality of these two dimensions; this duality makes BMs inherently dynamic and generative. While their study highlights the need of duality, it does not provide details or guidelines about the mechanisms of either of the two views. Accordingly, the findings of this study not only underpin the call for a two-sided view, but expand it by presenting empirical evidence of how these two perspectives converge and work in concert in an I4.0 context. In this I4.0 context, the joint view of both perspectives enables dynamic consistency. The speed of technological change that triggers swift changes in customer needs requires manufacturing firms to frequently adjust their activity system, which is subject to leaders using the sensed information to adjust their individual and collective cognitive schemas of their BM.

By considering the activity system perspective as well as the cognitive schema perspective of a BMI, dynamic consistency in an I4.0-driven BMI recognises that I4.0 is a socio-technical development that requires a holistic approach to innovation, as opposed to tactical measures only. Although exponential technological developments are the root cause for I4.0 having a revolutionary impact, especially revolutionary for manufacturing firms is the changing way of thinking and subsequent action. For decades, make–sell BMs have been prevalent, with incremental technological changes triggering customer demands. I4.0-driven BMI now paves the way for manufacturing firms to enter an era of individualisation, where customers demand solutions for their individual problems and require manufacturing firms to sense their needs, segment them granularly, and proactively fulfil these individual customer needs responsively.

6.2 Contribution to Theory

This study examined the research question of what the microfoundations of dynamic consistency are in an I4.0-driven BMI. Based on empirical evidence, the study set out to answer this question by explicating the microfoundations of dynamic consistency. These insights advance the understanding of current state of knowledge in three ways.

Advancing the understanding of dynamic consistency

The notion of dynamic consistency was initially introduced in 2010 by Demil and Lecocq, who postulated the need for continuous work on the alignment of the different components of a BM. This principle idea of achieving dynamic consistency was repeatedly explicated in various studies over the past few years (Ritter and Lettl, 2017; Foss and Saebi, 2018), and more recently in the context of I4.0-driven BMI (Kiel *et al.*, 2016; Ritter and Lettl, 2017; Foss and Saebi, 2018; Müller, *et al.*, 2018). However, a more detailed understanding of what mechanisms apply has not been presented to date. The present study adds to the body of knowledge by unravelling the mechanisms required to appropriately align activities across an I4.0-driven BMI. By doing so, this study explicates the microfoundations of dynamic consistency, supported by empirical evidence. The depicted microfoundations of dynamic consistency advance the understanding of the mechanisms that underlie the dynamics involved in the BMI process.

By embedding the empirical findings to the three design themes of a BM as proposed by Amit and Zott (2001), and Zott and Amit (2010), this study relates the evidence underlying the microfoundations of dynamic consistency to the topical discussion of BMI as an activity system. By considering an I4.0-driven BMI as a system of interdependent activities, the following tangible mechanisms enable manufacturing firms to continuously align their activities across their I4.0-driven BMI: the activity (re-) organisation follows a value focus on leveraging data and software as a catalyst to enhance existing domain expertise – for digitalised product-service solutions and a coherent cloning of physical activities into digital. The interlinkage of activities is facilitated mainly by a flexi-directional interlinkage of software suites enabled by a holistic interoperability. Moreover, activity linkage is subject to the ability to constantly disassemble, reconfigure and reassemble existing processes in order to ensure optimal exchanges of information and materials. Decisions about changes to the activity organisation and interlinkage mechanisms are made by agile working ensembles that are empowered to take decisions and incentivised to share value across function and firm boundaries. Moreover, these tangible mechanisms must be enabled and supported by a rather intangible cognitive foundation: a proactive mindset with integrity. This denotes two principle aspects: a) individual cognitive maps of the role of I4.0 for the BMI that must be synchronised and championed by the leadership team, and b) a collective sense of family that provides the basis for a collaborative and integer organisational behaviour.

Integrated view of BMI from both an activity system and a cognitive schema perspective

The thorough examination of the current state of knowledge about BMI has shown that the BMI is, with few exceptions, mainly discussed and viewed from two separate perspectives: either as an activity system, describing the core logic by which an organisation achieves its goals (Zott and Amit, 2010), or as a cognitive schema, serving as a tool to efficiently organise decision-making in conditions of imperfect information and complex cognition (Massa *et al.*, 2017). Building on the rather conceptual ideas presented in the few studies that propose an integrated view (Doz and Kosonen, 2010; Berends *et al.*, 2016); Velu, 2017), this study, supported by empirical evidence from the context of I4.0, argues that both perspectives should be applied simultaneously. Although the concept of dynamic consistency is based on the view of the BMI view as an activity system, the analysis of the empirical evidence showed that mechanisms relating to the three design themes of an activity system (content, structure, governance) fall short of sufficiently explaining the interdependence of activities in a complex activity system, i.e. an I4.0-driven BMI. This is especially due to the rapid speed of technological developments that requires manufacturing firms to frequently revisit the cognitive maps of their BMs.

Having identified that both perspectives are useful for understanding the mechanics of continuous alignment in an I4.0-driven BMI, this thesis expands and further strengthens the conceptual notion of a BMI as a complex system through empirical evidence. Velu (2017) conceptually argued, that BMI follows the four characteristics of a complex system: distinctions, sub-systems, relationships and perspectives. While the first three characteristics have been well covered by discussions about BMI as an activity system, “perspectives” has not received much attention so far, specifically not through empirical evidence or in the context of achieving dynamic consistency. This study provides empirical evidence that BMI, like a complex system, must be viewed from different perspectives to be holistically understood. In particular, it proposes viewing a BMI from both perspectives at the same time. By showing how the activity system and cognitive schema views of a BMI unfold at the same time in practice, this study contributes significantly to a better understanding of the BMI construct as a whole.

Approaching I4.0 holistically by transforming make–sell BMs into sense–act BMs

This thesis argues that a continuous BMI process is key to capitalising holistically on I4.0. It enables manufacturing firms to transform their traditional make-and-sell BMs into sense-and-act BMs that yield higher profitability and profit margins.

Contrarily to this argument, the examination of the current state of knowledge has shown a concentration of I4.0 literature on technological aspects underpinning the Fourth Industrial Revolution. Technologies and technological frameworks, their application, possible benefits and the like have been discussed extensively so far. However, studies have predominantly presented tactical changes to individual problems in manufacturing processes, improving the efficiency of firms’ existing BMs (Arnold *et al.*, 2016; Kiel *et al.*, 2017). These studies advanced the understanding of technological impacts of I4.0 on individual BM components. Generally, the discourse about the I4.0-driven innovation of the BM is only in its infancy. Most manufacturing firms use BM frameworks that envision static BMI in the form of a one-off generation of new BMs, but these frameworks do not consider the dynamic, ongoing changes in the interdependencies of activities in a BM, in particular between value-adding activities and the changing product and service offerings. However, due to rapid technological developments, it is not enough for manufacturing firms to “simply” develop new BMs based on smart, connected products or to further optimise manufacturing operations as the end objective in itself. The literature to date lacks an understanding of how manufacturing firms may approach I4.0 holistically. This study advanced this understanding of the dynamics involved in manufacturing firms’ implementation of I4.0.

In particular, this study proposes a BMI framework – the first of its kind, to the best knowledge of the author – that holistically utilises I4.0 principles to enable manufacturing firms to transform their traditional make-and-sell BMs into sense-and-act BMs. This framework focuses firms’ efforts to organise their value-adding activities both more efficiently and more flexibly, and thereby facilitate greater responsiveness towards changing customer needs. At the same time, tighter integration with customers and suppliers through software interoperability and smart, connected products and services enables a firm to improve customer experience through a more granular segmentation of changing customer needs – basic information input for responsive operations. I4.0 facilitates these innovation efforts through deeper collaboration with network partners to create and capture value from the increasing integration and interoperability of activities across the BM; these are largely interdependent, where changes in one activity or process affect (the relationship with) another activity or process (Velu, 2017). The increasing collaboration with network partners in the context of I4.0 further underpins Mason and Spring’s (2011) notion that the BM is dependent on interactions with others in a market-place.

This dependency shows that manufacturing firms must take an active process approach to innovate their existing make-and-sell BMs on an ongoing basis towards sense-and-act BMs. Crucially, the interdependencies of the product-service offerings, the value capture mechanisms, the value-adding activities and the value network must be actively managed. This continuous form of BMI is key to the successful implementation of I4.0, as the increasing interoperability and integration of systems in an I4.0 environment undoubtedly lead to an increasing interdependence of activities in the firm that are subject to constant technological and customer-driven change.

6.3 Practical Implications

Beyond the contribution to theory, this study has three principal implications for practitioners in manufacturing firms. First, to take advantage of I4.0 developments, management teams of manufacturing firms are advised to synchronise and develop a mutual understanding of I4.0 across their team at the management board level that especially recognises the need for a holistic approach to I4.0; i.e. recognising that I4.0 impacts all aspects of a BM. In doing so, management teams should carefully consider the impact that the accelerating speed of technological developments inevitably has in the form of changing customer demands at the operational level and customer needs at the strategic level.

Second, based on these considerations, managers are advised to develop a shared strategy for how their firm can utilise data and software as catalysts to enhance their existing domain expertise for improving customer experience. The emphasis should lie on obtaining granular insights about individual current and prospective customer needs in order to granularly segment customer demands, through digitalising products and services collaborating more closely with customers. At the same time, emphasis must also be placed on increasing the flexibility and responsiveness of the value-adding activities to fulfil these granularly segmented customer needs swiftly. Flexibility and responsiveness refer to the ability to rapidly change the design of the products and services that fulfil customers' needs. Thus, the findings indicate the coherent cloning of physical activities into digital and making software suites interoperable as important measures to increase flexibility. By sensing individual customer needs and acting on them swiftly, manufacturing firms can transform their traditional make–sell BM into a sense–act BM that yields higher profitability and profit margins.

Third, to embark on the transformation of their traditional make–sell BM into a sense–act BM, manufacturing firms must enable a collective behaviour that is based on integrity and collaboration. Given the speed of developments, experts across functions, and even across firm boundaries, need to collaborate to swiftly create and deliver products and services that serve the changing customer needs. While a culture of integrity and collaboration fosters entrepreneurial working with transparency and trust among actors, firms must amend their organisational governance processes accordingly – decision-making needs to be largely handed over from superiors to the cross-functional teams to enable rapid decisions to be made by authorities who have the best knowledge and information.

Moreover, the workshops conducted to present the findings of each case study indicated that the results of this research could be used as a management guideline. This may support manufacturing organisations in their continuous engagement to innovate their BMs, aiming to take a holistic approach to sustainable value creation and appropriation from I4.0 developments. Several of the examined manufacturing firms independently followed up on their case study and adopted both the outcomes from the workshop and the workshop concept itself into their routine management cycles. As an alternative for these workshops, Table 13 of guiding questions may stimulate managers' cognition when they consider innovating their BM. In particular, these sets of questions may serve as a guideline for managers in assessing the degree of dynamic consistency across their firm.

Table 13. Guiding questions for practitioners for embracing I4.0-driven BMI

Content: Understand how (key) activities should be selected and organised in your firm	I4.0 enables manufacturing firms to transform from a make-and-sell BM to a sense-and-act BM, yielding higher productivity and profits. • What mechanisms do you use to obtain and granularly segment individual customer needs? • What information can be remotely gained from products during their usage that enable better segmentation of customer needs? • What features have you incorporated into the products that allow customer-specific services, possibly even remotely after sales? • What information needs to be collected to improve key activities that enable better understanding of changing customer requirements? • How is the information used to improve the responsiveness of activities to changing customer requirements? • Which processes need to be digitalised to improve the ability to sense and act? • What capabilities can be enhanced or built by using data and software to react swiftly to identified customer needs?
Structure: Plan information and material exchange, and its flexibility	The required responsiveness and flexibility of manufacturing firms is linked to the need to swiftly reorganise the interdependent exchange of information and materials. • How do you manage the redesign of processes to meet changing customer requirements? • How do you manage the bi-directional exchange of information between the different phases of the product life cycle? • How do you enable the interoperability of different software systems that facilitates the interlinked exchange of information and materials? • How is a single source of truth of all data across the firm ensured? • What are your firm's organisational processes to ensure secure and fit-for-purpose IT and data infrastructure to remotely processes large amounts of data from various sources in real-time with limited latency?
Governance: Revise decision-making regimes and incentive structures	More rapidly changing customer needs, market environments and technological capabilities require rapid but profound decision-making. • How has your leadership team defined decisions to be taken by management and cross-functional teams of experts respectively? • What are the clearly formulated goals that you have set for your teams to develop sensing and acting capabilities? • To what degree are your teams empowered to prioritise their work among themselves to increase the speed of action? • How do you enable empowerment of employees to continuously learn and make improvements from pilot projects? • How do you incentivise individuals and cross-functional teams to work together towards shared objectives?
Cognitive foundation: Generate a plan and create a culture for innovating your BM in the light of Industry 4.0	I4.0 is an ongoing process that affects the base of an organisation and requires initiation and cognition from the top leadership. • What are emerging trends in I4.0 and beyond that may become a risk or an opportunity in transforming to a sense-act BM? • What are your processes for learning and adopting I4.0-driven BMs from other industries and sectors? • What approach do you take to achieve agreement and rapid action among the leadership team for the transformation from make-sell to sense-act BM? • How do you allocate resources with an appropriate reconfiguration of capabilities to reflect the increasing role of data and software? • What mechanisms are deployed to encourage open dialogue and communication across hierarchies and functions? • What is your approach to encourage individuals to share information, being open to learn from others, and pursue new avenues?

6.4 Limitations and Future Research Recommendations

The strength of this research lies in the large amount and depth of empirical evidence compared to other studies in the reviewed literature. More than 86 hours of formal interviews with 72 representatives of nine firms were included in this research. In addition, five firms with more than 30 practitioners contributed indirectly to this thesis through discussions and focus groups. Nevertheless, owing to the nature of an inductive approach using multiple case studies, the research design has its methodological limitations and other shortcomings, some of which might be the starting point for promising future research studies.

First, nine manufacturing firms were examined, six of them in detail. Due to this small number of case studies, there could be room for further improvement in the transferability and generalisability of the results. Despite Eisenhardt (1989) and Easterby-Smith who attribute generalisability to the chosen approach of case study research, transferability of some of the findings might be a more suitable interest. To increase the transferability of the findings, future studies could broaden the context to other manufacturing industries, industry sectors, or manufacturing firms of different sizes and types, for example small and medium-sized enterprises.

Second, the selection of interviewees as informants was mostly carried out in dialogue with the contact person at the respective case study firm. There could be some selections bias, although to prevent this, a triangulation from different sources of data was used: interviews of multiple individuals per firm, internal firm documents, and publicly available documents including press, webpages and technology reports.

Third, while the total period of gathering empirical evidence took about two years, the interviews, factory visits and workshops took place over a period of three to four months at each case study firm. As I4.0-driven BMI is a (continuous) process that usually lasts many years, interviewees had to report details such as the events and shortcomings of their firm's BMI process in hindsight. This form of retrospective reporting might result in bias from the interviewees due to missing details or a concentration on specific events. For this study, data triangulation and multiple informants for each BM were used to moderate this caveat. Future studies could therefore take a longitudinal approach offering fruitful, real-time insights by closely accompanying firms' I4.0-driven BMI processes over time.

Fourth, this study was intentionally not designed to examine the cognitive aspects of firms' BM, but rather to examine the BM from an activity system perspective. However, as the analysis showed, viewing the BM from both perspectives yields particularly valuable insights. Accordingly, this study may be a starting point for further research designs that examine the interplay of the activity system and cognitive schema views using systems theory.

Fifth, as demonstrated in the findings, most firms have close collaboration with suppliers, customers or technology vendors. However, this study looks only at the focal firm, relying on narratives obtained from the firm about its partnerships. Future studies could examine in-depth the dynamic consistency of the value network of a focal firm that may include customers, suppliers, distributors, shareholders, or even competitors. Moreover, the consistency among multiple BMs in a multinational enterprise might yield interesting insights as well.

It is hoped that future studies might use this research as an introduction to activity interdependence and alignment in the field of (I4.0-) BMI, and as a starting point for further work on the understanding of systems thinking in the context of I4.0-driven BMI.

6.5 Summary and Conclusion

The progressive digitalisation of manufacturing firms is subject to an increasing body of research under the term Industry 4.0. While the notion of I4.0 indicates an increasing integration and interoperability of activities in a manufacturing value chain, discussions in this field have predominantly focused on technologies and their application in tactically improving the efficiency of existing manufacturing processes. As a result, scholars increasingly call for a better understanding of how manufacturing firms can use the opportunities and approach the challenges of I4.0 holistically; to do so, many propose taking a BMI perspective. This thesis showed that, due to the rapid technological developments that go along with swiftly changing consumer demands, a better understanding is needed of the dynamics that underlie BMI processes; in particular, the active management of an increasing interdependency of activities in a BMI process. The notion of a continuous management of activity alignments in a BMI was first introduced by Demil and Lecocq (2010) as “dynamic consistency”. However, despite a growing interest in the phenomenon of activity alignment, in particular against the progressive digitalisation in manufacturing firms, research elaborating on the mechanisms involved in achieving dynamic consistency has been scarce. This research project therefore examined the question "*What are the microfoundations of dynamic consistency in an Industry 4.0-driven BMI?*" using an inductive research design. Nine European manufacturing firms were examined, and data were obtained mainly through 72 semi-structured interviews with executives, directors and senior managers from different functions across the firm.

Based on a qualitative content analysis through open coding, the findings explicate several mechanisms, described below, that are vital for achieving alignment across activities in an I4.0-driven BMI and aimed at improving the flow of information and materials across the BM.

(1) To ensure an appropriate exchange of information and material across their I4.0-driven BMI, manufacturing firms shall take a *value focus on data and software as a catalyst* to enhance customer experience through granular segmentation, flexibility and individual responsiveness. (2) An *active flexi-directional interlinkage* of activities through interoperable software suites across the entire I4.0-driven BMI, while the ability to rapidly disassemble, reconfigure and reassemble processes provides a means for a responsive value creation, enabling stakeholders to strive for similar objectives. (3) *Agile working ensembles* that approach challenges entrepreneurially, incentivised by shared value across functions and firm boundaries, govern the change processes of activity selection and organisation. Moreover, the findings unexpectedly indicate that the common view of BMI as an activity system does not sufficiently explain the notion of dynamic consistency, and that the cognitive view of BMI significantly contributes to the understanding of this notion. The findings highlight the importance of a specific cognitive foundation that enables the changes to the activity system in the first place, as discussed above: (4) An *open-minded integrity of behaviour*, where leaders champion an I4.0 vision alongside creating a sense of family, referring to open, collaborative and trustful behaviour for the journey of transformation. This study contends that, taken together, these mechanisms enable manufacturing firms to transform their traditional make–sell BM to a sense–act BM that takes advantage of changing customer demands, yielding higher profitability and profits.

With these findings, this study contributes to the existing knowledge in three specific ways. First, the mechanisms explicated in the findings section denote the microfoundations of dynamic consistency. The explication of microfoundations for dynamic consistency advances the understanding of firms' management of interdependencies throughout the process of innovating their BM.

Second, while the current literature on BMI studies it from the two separate prominent perspectives – BMI as an activity system and BMI as a cognitive schema – this present study demonstrates how the convergence of both perspectives enables a holistic view and management of a BMI in the context of I4.0.

Third, whereas I4.0 literature predominantly focuses on technological discussions, this study presents a BMI framework to approach I4.0 holistically and continuously. In particular, this framework enables manufacturing firms to transform their existing make-and-sell BM to a sense-and-act BM.

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Appendix A – Overview of Interviewees

Case study firm		Position of interview partner	Length of interview [min]
Delta Steel	1	director IT	120
Delta Steel	2	director sales and production planning	59
Delta Steel	3	director technology and production	60
Delta Steel	4	director controlling and business excellence	87
Delta Steel	5	head of production planning	60
Epsilon Racing	6	director operations	65
Epsilon Racing	7	director manufacturing process engineering	76
Epsilon Racing	8	manager digital transformation	90
Epsilon Racing	9	project manager MES development	75
Epsilon Racing	10	director technology and innovation	60
Epsilon Racing	11	senior engineer supply chain management	54
Epsilon Racing	12	manager advanced engineering	47
Epsilon Racing	13	project manager MES implementation	78
Epsilon Racing	14	manager digital transformation	40
Epsilon Racing	15	manager cost engineering	55
Zeta Home	16	director customer support and logistics	76
Zeta Home	17	senior design engineer	84
Zeta Home	18	product manager	64
Zeta Home	19	senior project manager 14 days delivery	101
Zeta Home	20	director sales	66
Zeta Home	21	sales manager	30
Zeta Home	22	project manager HoloLens	76
Zeta Home	23	senior engineer software interfaces	60
Zeta Home	24	director PLM and digitalisation	72
Eta Drive	25	head of performance management & digital factory	107
Eta Drive	26	COO Eta-group	52
Eta Drive	27	director manufacturing technologies	40
Eta Drive	28	director high performance manufacturing technology	65
Eta Drive	29	head of advanced manufacturing	61
Eta Drive	30	manager innovation and technology	79
Theta Heating	31	director supply chain management & production	70
Theta Heating	32	head of production	90
Theta Heating	33	manager open innovation	77
Theta Heating	34	director digital transformation	90
Theta Heating	35	project leader Industry 4.0	73
Theta Heating	36	director IT	60

Case study firm		Position of interview partner	Length of interview [min]
Iota Electric	37	head of smart factory	68
Iota Electric	38	head of industrial engineering	76
Iota Electric	39	head of front-end production	90
Iota Electric	40	director finance and controlling	62
Iota Electric	41	director IT	103
Iota Electric	42	managing director	59
Iota Electric	43	head of back-end production	60
Iota Electric	44	director supply chain management and planning	90

Appendix B – Data Display

1st order concepts	2nd order themes	Aggregate dimensions
▪ Granular segmentation of customer needs ▪ End-to-end thinking to leverage data and software for enhancing existing domain expertise ▪ Developing capabilities in data computing and software development	Leveraging domain expertise with data and software as a catalyst	Value focus on data and software as a catalyst
▪ Connectivity of products and services for intensified interaction and granular segmentation ▪ Incorporating intelligence by means of software for individualisation	Digitalising product-service offerings	
▪ Software-system-built picture of the firm's physical activity system ▪ Bringing tacit knowledge into software systems ▪ Accounting for data selection puzzle	Cloning physical activities coherently into digital	
▪ Horizontal integration with suppliers and customers ▪ Single source of truth serves as the basis for further digitalisation activities ▪ Systematic product life-cycle management ▪ Establishing real-time interoperability among systems	Establishing holistic real-time interoperability	Active flexi-directional interlinkage
▪ Continuous disassembly and reassembly of processes ▪ Agreeing on process standards and mutual semantics	Adapting processes actively	
▪ IT infrastructure ensuring performance and security ▪ Data infrastructure and data governance for data quality	Building capable and secure IT and data infrastructure	
▪ Joint ownership by leadership team to drive changes ▪ Establishing cross-functional teams with human interfacers to execute processes ▪ Assigning clear responsibilities and decision-making power	Working in hierarchy- and function-spanning teams	Agile working ensembles
▪ Progressive prioritisation ▪ Using piloting with trial and error as a bottom-up learning process ▪ Understanding each other's roles to accelerate decision-making	Approaching challenges entrepreneurially	
▪ Synchronised incentives from ramp to ramp ▪ Value sharing among partners	Value thinking across fences	
▪ Industry 4.0 envisioning process ▪ Aligned leadership drive	I4.0 vision championship by leadership team	Proactive mindset with integrity
▪ Omni-directional, dialogic communication ▪ Establishing trust and transparency among actors ▪ Being open to learning, sharing, collaborating and pursuing new avenues	Sense of family – collaborative and integer behaviour	

Appendix C – Data Supporting Dynamic Consistency Mechanisms

Theme	Representative Quotations
	Value focus on data and software as a catalyst
Leveraging domain expertise with data and software as a catalyst	• *"not a single person has more know-how about our processes than our people. It is a long and intensive process, also costly, but we need to develop this awareness about digitalisation in general and data specifically by continuously discussing the importance of data and digitalisation among ourselves and with our employees. That is how we did it many years ago with our production system as well*" (Eta's COO). • *"looking at our plants – we do have really a good set-up. But we need to enable our people to do something with all these data. Having data is the one thing but using them is another story. It does not always need to directly be big data analytics …"* (Epsilon's director operations)
Digitalising product-service offerings	• *"the biggest lever is to question what else the customer needs. Where can digital services and digital supplements generate further value in the future? We believe that this must be questioned very critically as to how we can generate added value as a result."* (Theta's manager open innovation) • *"what we see is that the loyalty of our customers increases extremely and ultimately we are the preferred partner. There are many reasons for this and one of them is indeed digitalisation. Because it also requires a basis of trust to exchange data. And to exchange data is an extreme proof of trust."* (Delta's director sales and production planning) • "*A new remote service for our customers will be a huge benefit. Most of our customers are elderly people who do not communicate that well. They report a problem with their product which mostly is not a technical problem but a wrong way of using the product. So once we have the opportunity to solve these problems remotely instead of simply listening what people tell us – big opportunity"* (Zeta's director sales). • *"We are developing digital twins for our products. The aim is to deliver digital prototypes to our customers only. We are replicating all product features, down to single components, inclusive the dynamic function and behaviour."* (Epsilon's director technology and innovation)
Cloning physical activities coherently into digital	• *"crucial for digitalisation is to have a good picture of the processes in the factory with operational data and machine data to predict quality. Moreover, real-time data for transparency is super important. And we need to make things easily accessible for our staff"* (Epsilon's project manager MES development). • *"All the things in production are connected and then we have a million tons of data about physical production. Which are only waiting to be analysed and used for improvement changes, which we want to do or to stop doing certain things which are harming. So in the production, we might do some processes, which we are not aware that they cause us certain problems in quality or whatever. And this can just help us to identify those."* (Iota's director finance and controlling) • *"We have a lot of implicit knowledge available, of course we try to write down a lot of our technical planning in technical documents and*

	specifications, but a document is only as good as it is read. That's exactly the gap we find in reality." (Eta's head of advanced manufacturing) • *"We have a CAD and CAM system, that if you want to configure the production relevant documents in the system, you just have to select the part from the CAD system, copy and paste and it will automatically extract the relevant data. But we don't do it. I think we have a big cut between CAD drawing and production."* (Epsilon's project manager MES implementation)
Active flexi-directional interlinkage	
Establishing holistic real-time interoperability	• *"among all technologies, data connectivity is the most important. Having available the correct data quality, everywhere from everyone, is the biggest and most important aspect for digitalisation. Everything else is subordinate!"* (Theta's project manager Industry 4.0) • *"We have started to provide our customers with product relevant data that we are generating within our manufacturing process. Customers who receive our data are now in the position to control and fine-tune their machinery for every individual product based on these data. If our customers were to change us in favour of another supplier – I would ask him whether that supplier firstly delivers data and whether he has trust in that supplier for delivering the corresponding quality. In our opinion, providing these data has massive potential to increase customer loyalty. And I think, that is really important. Making customers' life to change suppliers as difficult as possible."* (Delta's director controlling and business excellence) • *"One important aspect for us was to harmonise our back-end processes with one ERP template only. If every country or organisation runs their own system, how do you properly want to combine data from these systems and want to make them interoperable to achieve one system."* (Zeta's director PLM and digitalisation) • *"By a consequent usage of end-to-end engineering, sending our design data automatically to our production machines, we reduce interfaces, conversions etc. So, we do not only save time, but also resources, make less failures and we can use this very same design model and provide it to our customers for further usage. For made-to-order this is a huge potential, less for our made-to-stock products."* (Theta's director IT) • *"[i]n principle, it is the interfaces that are exciting. The subject of data collection is all very well, but how do I set the interfaces, how do I always have open systems, and how do I make it soo good that all my colleagues can access them, the data they use, and that they are all on the way in a digitalised form."* (Epsilon's director operations)
Adapting processes actively	• *"We need to consider the overall process. And the next steps must be to optimise further aspects of the process. You can always find reasons as to why to do a process as it is, but you need to keep on optimising them."* (Zeta's director PLM and digitalisation) • *"[P]rocesses need to be adapted and improved first, that is very important. Otherwise you are going to digitalise a process that's not working. And then everybody blames the digitalisation, but you should blame the process, which is not good. And that's very, very important"* (Zeta's director customer support and logistics).
Building capable and secure IT and data infrastructure	• *"[i]nfrastructure standards like network stability etc. is a must, but I would assume it as given."* (Epsilon's project manager MES development) • "*And there are also the learnings that we had in the last months and years in the [...] project, what kind of data do we need at field level, i.e. in a very high granularity, so we also considered how we had to structure these and where we could get them from, and derived a global shop floor*

	master data concept from this, with many different players in the company." (Eta's project manager digital factory and head of performance management) • "*semantics is one of the main challenges for the entire digitalisation process! You need to accept that people have different opinions, but then you must agree on a mutual way forward. And the executives need to be the role model in using and trusting the defined, central data basis."* (Delta's director IT) • "*[t]he functions had to be convinced that the central data pool is useful for them. They did not trust the system and had 3-5 manual notes for their KPI and they mostly did not match with the system. The crucial turning point was when the plant manager demanded to only look and believe into the system data and that his team needs to work to bring the correct data into the system."* (Epsilon's project manager MES development)
	Agile working ensembles
Working in hierarchy- and function-spanning teams	• *"We then built it up in such a way that production, the test field and the engineers, they are the customers who get the digitalisation solutions. Further we aligned the project in the following way: what people describe the functionality, and what people bring the technical solutions – always oriented towards customer focus, even if they are internal customers. […] This also requires that people contribute and show willingness to build architectures, data models etc. so that this is possible."* (Eta's COO *)* • "*Digitalisation is a topic for us as an entire firm. If you want to tackle it holistically, network all data from design and development, production, finance, etc. – to do all these cross-analyses – then at first you need to onboard people from all the different areas, build teams independently from their organisational structure, and make them work for solutions. We therefore have a double leadership in the MES-MOM project, from the technical COO side and from the IT/CFO side, and have staffed it accordingly.*" (Eta's COO) • "*It is important to pick up as many areas and departments as possible and convince them of the advantages of digitalisation.*" (Epsilon Racing's director of technology and innovation) • "*[W]e have multiple organisational areas involved in this project with many different superiors – mechatronic, software, operations and the business side. It's a big effort to align them, to synchronise everyone, as it means not everyone does what their organisational function demands, but contributes to the same objective of this project. It takes many discussions across these different locations and organisational areas, but it pays off.*" (Eta's manager of innovation and technology)
Approaching challenges entrepreneurially	• *"Prioritising and concentrating on the important topics is important in the context of Industry 4.0."* (Theta's director IT) • *"Something that is important for your own department, might not be important for the while firm at this given point in time. You need to consider this holistically and if necessary, this is also prioritised down for the overall importance of the company."* (Epsilon's director manufacturing process engineering) • *"With our advanced robotics team, we started off with a very small project, a handling task. That developed so fast, that we were allowed to build this small lab, where we really have the chance to try new processes and evaluate them in an agile manner. And use the feedback from our tests to feed back into the development of new production concepts and machines."* (Eta's head of advanced manufacturing) • *"To achieve this pull effect of ideas from the direct areas, you need to show them with different pilots that the solutions works wand what benefit*

	they may have. Then they can easily decide whether they want it or not." (Eta's head of advanced manufacturing) • *"[I]t is important to have proof of concepts. You just learn what works and what might not work. Instead of blindly developing something that is killed straight after, you should proof whether the technology is suitable and your desired benefit comes true."* (Zeta's director PLM and digitalisation)
Value thinking across fences	• *"We could provide the OEM with digital data sets from production so that he can make his own production chain more efficient, and the customer who is willing to do the same will also benefit"* (Eta's head of advanced manufacturing) • "*We help ourselves if we help our customers. Our business model is to give the customer a package, where he has the impression that he's buying a good product from us. And ideally – and this works out quite well – he also pays a corresponding price that we can live with quite well. […] Consider the data exchange with customers or suppliers – it's a topic that can bring our firm very far forward, because it helps to know what the customer does with our products, or what we do with our suppliers' products.*" (Delta's director of controlling and business excellence) • *"[…] the managing directors were only looking at their own units. No wonder, if you're rewarded like that […]. They had the wrong incentives. And if we could screw each other over, we would do that in the past. Nowadays, we have people in these positions who look at the total process and make it transparent, and also introduce incentives that are related to our strategy*." (Zeta's senior project leader for 14-day delivery)
	Proactive mindset with integrity
I4.0 vision championship by leadership team	• *"The board must set an example for the firm, for example by only accepting data from our data lake.*" (Delta's director of IT) • "Y*ou've got to want digitalisation. It's that simple. And you have to keep at it to get it done.*" (Delta's director of technology and production) • *Eventually we established our vision – delivery within 14 days from order to delivery*." (Zeta's project manager HoloLens) • *"Within our leadership team, we are lacking a mutual vision and a mutual roadmap. It is only 'my business area and my roadmap', everything else does not really matter. Due to this silo thinking, we very often hinder ourselves."* (Theta's director digital transformation)
Sense of family – collaborative and integer behaviour	• "*We do have a strategy and that is essentially important. But it's the mindset level which is probably even more important – anchoring this strategy and making it credible. I believe the most important part, really, is the credibility.*" (Eta's head of advanced manufacturing) • "*I need to coordinate with my executive colleagues if there is any indication of borders or rifts – as a board, we need to demonstrate unity. We are interested in the results. We have to provide the framework conditions that people can work in.*" (Eta's COO) • *"[f]or me, a crucial success factor for digitalisation is the freedom to act. We need a mode in which we can and must try new things. A positive culture towards failures."* (Theta's director digital transformation)

Appendix D – Example of internal firm documentation Eta Drive

Critical Success Factors – Digital Transformation Project

Establish the Vision	Share the vision with others in a way that inspires and motivates them. Let your stakeholders participate in shaping the vision. Find fellow campaigners who support your vision and act as multipliers in the organisation.
Executive Leadership and Commitment	Sponsor, Steering Committee and Project Management share the same vision and strategy and act accordingly. Support your team and be a servant leader (“no micro management”). “Walk the talk”: Set targets and incentives, break up “silo thinking”, allow for mind-set change, show importance, etc.
Project Organisation	Nominate and maintain a capable project team, delegate responsibility and allow for entrepreneurial thinking and acting. Provide, free or allocate required resources. Adjust/transform organisational setup to support the vision/project. Create framework and platform to allow cross functional exchange and collaboration.
Partner Selection and Collaboration	Make sure vendor has required capabilities. Thorough vendor selection and decision must be supported by all stakeholders to achieve buy-in/commitment. Involve partners (incl. C-levels) into the project. Strive for real partnerships: Let everybody have skin in the game. Establish long-term trusted and strategic relationship with partners.
Project Approach	Set realistic scope and timeline which support the vision. Create early results to keep stakeholders motivated. Gather feedback and reflect regularly against the vision. Be brave enough to change the approach (e.g. waterfall vs. agile) as needed. Be pragmatic (pareto principle) and avoid “playing 100% by the book”.
Stakeholder Management	Communicate to all relevant stakeholders, keep them informed and generate pull effect. Find balance between amount of communication and information needs. Perform regular expectation management and keep everybody on track and focused. Communicate target group specific. Encourage and consider feedback.
Capabilities and Enablement	Trust in people’s ability to develop their skills in new domains. Specifically, in digitalisation projects with lots of new technologies and topics people have to be encouraged to try new things, take risk and learn as they go. Early identification of training needs and timely execution to ensure delivery quality and skilled end users.
Corporate Constraints	Proactively manage and do not underestimate PM efforts for the following: Cost allocation concept, business/value case, approval processes, budgeting/controlling, contracting, compliance (GDPR, data security, etc.), alignment with major initiatives, etc.