Smartifying manufacturing companies: Understanding, developing, and implementing smart service systems

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“*Be the change that you wish to see in the world*.”

Mahatma Gandhi

I wish to thank my family and friends for your continuous support throughout this journey. You gave me the strength and support to pursue my passion.

Further, I would like to express my sincere gratitude to my supervisors, Maximilian and Björn. You gave me the tools, guidance, and freedom to reach my goals.

Abstract

Driven by the emergence and rapid adoption of digital technologies, an influential development associated with organizations' digital transformation is the "smartification" of physical products. In the context of the Internet of Things (IoT), it is possible to equip traditional products with digital technologies (e.g., for sensing and communication). These digital technologies enable new forms of intelligence and turn traditional products into smart things that can offer customers smart services. With smart things as their core and smart services as their value proposition, smart service systems have received significant attention. As self-organizing and self-optimizing product systems, they enable more efficient and flexible processes as well as new value propositions. Smart service systems are expected to profoundly influence manufacturers' competitiveness and affect productivity, economic growth, and working profiles. Despite their growing importance, smart service systems remain poorly understood, which is mainly due to their interdisciplinary nature and complexity by combining different technologies. This hampers scientific progress and practical application. Against this backdrop, this dissertation elaborates on the fundamental understanding of smart service systems and provides guidance on their development and implementation.

To complement the understanding of smart service systems, two different perspectives are taken. Research article #1 investigates the term "smart" and how it manifests by taking an information systems (IS) perspective. Based on a structured review of domain-specific literature, the research article sheds light on how smartness manifests in the context of digital technologies. It defines smartness and proposes the concept of a "smart action." This concept structures and describes the components and patterns involved in creating smartness and can be interpreted as the nucleus of smart service systems. Supplementing this understanding, research article #2 embeds the topic of smart service systems into the context of digital transformation. Due to its importance and progress in research and practice, the article builds upon the understanding in academic literature and includes a broad interview and workshop series with domain experts. As a result, research article #2 develops a framework with six fields of action that are required for digital transformation. The framework sheds light on topics related to using and integrating digital technologies effectively, which are highly connected to and interdependent of smart things and services.

Due to the interdisciplinary nature of smart service systems, their development is often challenged by a lack of shared understanding and collaboration tools among experts in different domains. As a result, development projects are often drawn-out and expensive. To address this challenge, research article #3 develops a domain-specific modeling language for smart service systems. The modeling language provides researchers and practitioners with a visual and easily understandable representation of smart services and smart service systems. It supplies a common terminology as well as a tool to analyze existing and future smart service systems.

To implement and offer smart service systems, manufacturers are also challenged when they have to identify and develop the required capabilities. While the “why” of transforming is usually straightforward, the “how” remains unclear and challenging. To contribute to closing this gap, two perspectives are taken. First, research article #4 develops a framework of the capabilities required to implement smart service systems in manufacturing by taking an IS perspective. The framework includes technical as well as strategical, operational, and cultural capabilities. Research article #5 takes a business model perspective and summarizes the capabilities required for the business model transition. As smart services lead to an increased role for services in manufacturers’ business models, several changes are needed. Research article #5 develops a maturity model that maps capabilities to distinct business models. The maturity model provides descriptive knowledge by structuring relevant capabilities and builds the foundation for developing transition strategies and making long-term decisions.

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I. Introduction[1]

Driven by the emergence and rapid adoption of digital technologies, an influential development associated with organizations' digital transformation is the "smartification" of physical products (Porter and Heppelmann 2014; Scharfe and Wiener 2020). In the context of the Internet of Things (IoT), advancements have led to disruptive changes and have accelerated this development. By equipping physical products with sensors, actuators, computing logic, and communication technology, the IoT enables integrating digital capabilities into a wide range of traditional products (Oberländer et al. 2018; Sisinni et al. 2018). In various industries, manufacturers are in the process of making their products smart (Recker et al. 2021; Scharfe and Wiener 2020). Examples range from smart cars and smart refrigerators to smart sprinkler systems and smart toothbrushes. Such products are equipped with sensors to capture their environment, are connected to the Internet, communicate with other products, and analyze data to improve their capabilities. In the literature, traditional products equipped with digital capabilities are usually referred to as "smart things," a new class of digital technologies (Huber et al. 2019).

Smart things have changed the role and use of products in daily life. They are not only physically usable tools but also active and self-dependent actors due to their advanced digital capabilities (Beverungen et al. 2019; Oberländer et al. 2018). Smart things can decide and act within a predefined degree of freedom – sometimes without any human intervention. For example, compared to cars produced a decade ago, today's smart cars support drivers by keeping in lanes and maintaining the distance between vehicles. As boundary objects between the product provider and service consumer, smart things enable the co-creation of smart services, which are data-based services with some form of intelligence (Beverungen et al. 2019; Huber et al. 2019). Following the smart car example, drivers can use voice control for smart parking and navigation services. Beyond providing smart services, smart things also form (new) smart service systems (Beverungen et al. 2019; Lim and Maglio 2018). For example, Tesla intends to use the data gathered from its cars, such as GPS information and video recordings, to develop even more accurate street maps (Buczkowski 2015; Iqtidar 2020).

With smart things at their core and smart services as their value proposition, smart service systems can be defined as service systems capable of learning, dynamic adaptation, and decision-making based on extensive data use (Beverungen et al. 2019; Lim and Maglio 2018). Smart service systems incorporate capabilities of digital technologies and require smart things as a constituent component. These systems also involve interactions and data sharing among people, organizations, and smart things themselves (Huber et al. 2019; Lim and Maglio 2018). Smart service systems are therefore characterized by their ability to communicate and act in real time, to make decisions autonomously, and to steer themselves based on the obtained data (Pereira and Romero 2017; Huber et al. 2019).

[1] This section partly comprises content from the dissertation's research articles. To improve the readability of the text, I omit the citations' standard labeling.

In manufacturing, the mass incorporation of smart things in highly reconfigurable and connected smart service systems is expected to fundamentally change how products and services are invented, created, and delivered (Hofmann and Rüsch 2017; Stock and Seliger 2016). In the literature, this fundamental shift implied by the realization of digital technologies is often referred to as the fourth industrial revolution or simply Industry 4.0 (Lasi et al. 2014). The transformation to Industry 4.0 holds enormous potential for manufacturers wanting to sustain a competitive advantage and seize new opportunities (Weking et al. 2020). On the one hand, manufacturers can revolutionize internal processes, for example, through using different data sources (e.g., sensor data) and extensive data analytics approaches through which production machines' maintenance issues can be anticipated and proactively solved (Baptista et al. 2018). On the other hand, Industry 4.0 offers opportunities to extend a manufacturer's value proposition and develop new business models (Culot et al. 2019; Zhong et al. 2017).

Offering service bundles with products signifies a fundamental shift in manufacturers' business models. Services are then no longer seen as by-products but are at the heart of the business model. This means that the manufacturers' business models are transitioning from being solely product-focused to integrating services as an essential component (Weking et al. 2020). This brings several possibilities and includes use cases such as predictive maintenance (Baptista et al. 2018) and smart process planning (Trstenjak and Cosic 2017). Such service offerings can be found in all types of product segments and provide a competitive advantage to manufacturers, which can individualize their value propositions and improve customer contact (Weking et al. 2020; Zhang et al. 2021). However, to offer smart service systems, existing corporate functions, processes, and routines need to be adapted. For instance, to provide smart planning services for a manufacturing machine, delivery processes (e.g., technical service support), sale structures (e.g., incentivization for service sales), and pricing and revenue models (e.g., pay-per-use/result) must be modified, compared to traditional one-time product sales.

Because of the opportunities linked to realizing smart service systems in the context of Industry 4.0, academics and practitioners expect this technology-driven transformation to become more prominent (Bauer et al. 2015; Weking et al. 2020). For example, the German Federal Ministry of Economic Affairs and Energy (2021) financially supported a broad variety of Industry 4.0 use cases to introduce smart service systems in manufacturing. A survey conducted in 2020 estimated that manufacturers would invest more than €40 billion by 2020 (German Federal Ministry of Economic Affairs and Energy 2021). Major consulting companies, such as McKinsey (2019) and the Boston Consulting Group (2021), which have close ties to management and a good understanding of future top priorities, attest to the potential of Industry 4.0. They confirm Industry 4.0's benefits in improving productivity and performance management, increasing asset utilization, and creating opportunities through new business models.

However, introducing smart service systems is also accompanied by challenges that may hamper progress. Research has found that only a minority of manufacturers have already successfully implemented smart service systems (Moeuf et al. 2020; Olsen and Tomlin 2020). Small and medium-sized manufacturers, which are the bedrock of most economies, are especially challenged when integrating smart things and offering smart service systems (Issa et al. 2017; Scharfe and Wiener 2020). According to a survey of the German industry association Bitkom, 40% of manufacturers still do not use any Industry 4.0 technologies and applications. In comparison, 94% of them agreed that Industry 4.0 will be key in ensuring their competitive advantage (bitkom 2020). Challenges associated with incorporating smart service systems can be grouped in three categories (Figure 1): Understanding, development and implementation (Olsen and Tomlin 2020; Zhang et al. 2021). Understanding smart service systems forms the foundation of effectively develop and successfully implement them. The major challenges of each category are discussed below.

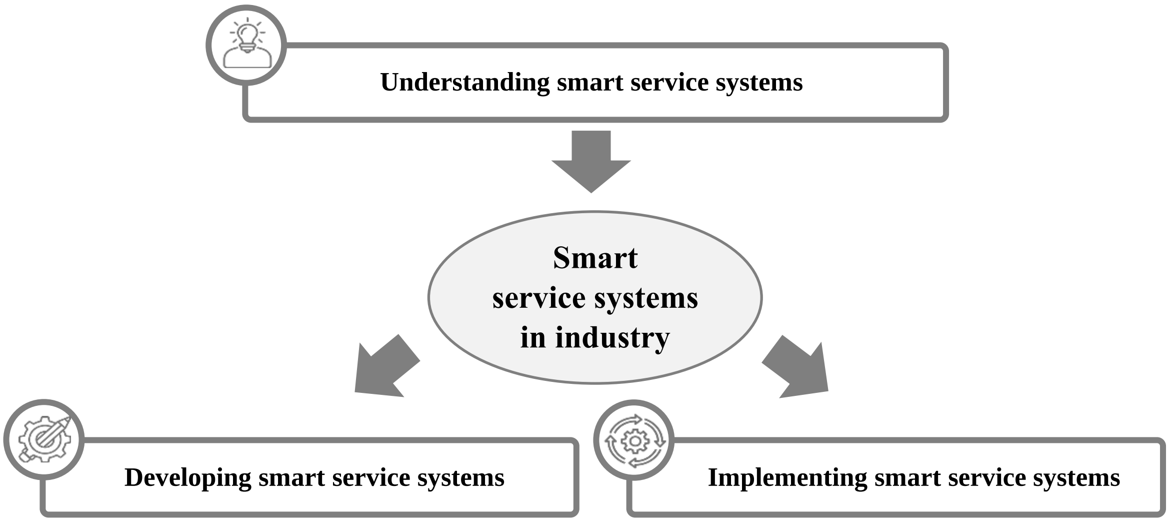

Figure 1: Categorization of problems in the context of smart service systems

Challenges stem from a lack of shared understanding of smart service systems (Alter 2020) and of the interdependencies with other technical and management topics (Larson 2016). As the term “smartness” is nowadays used in broader contexts, understanding what smart means often remains unclear (Alter 2020). In publications or with product offerings, researchers and practitioners often do not explain in detail what renders a thing or service smart. This hampers a common understanding, which is key to effective communication and the systematic development of smart service systems. The understanding of how smart service systems relate to other topics in the context of digital transformation also influences long-term managerial decisions. Not considering interdependencies with topics such as data management or the required digital mindset makes it difficult for practitioners to successfully develop smart service systems and make the right decisions along.

Concerning development, besides roadblocks such as lack of resources (e.g., budget and workforce) and expertise (McKinsey 2019), challenges arise through the multi-disciplinarity of smart service systems. Developing smart service systems requires the collaboration of experts with different domain backgrounds (Huber et al. 2019; Zheng et al. 2018). For example, mechanical, electrical, and software engineers within the product design team need to collaborate effectively when designing smart things (Zheng et al. 2018). Accordingly, methods and tools to reduce the complexity and enhance the collaboration of domain experts are needed to ease the development of smart service systems.

To implement smart service systems successfully, manufacturers often lack an overview and understanding of the required organizational changes. For manufacturers, the complexity stems from supplementing their strengths in manufacturing-related core capabilities by novel abilities to use digital technologies (Bustinza et al. 2017; Ghobakhloo 2018). For example, while mechanical engineering firms are likely to be skilled and experienced in equipping machines with sensor technologies, they are less likely to have the required expertise in areas such as information technology (IT) infrastructure or data analytics (Scharfe and Wiener 2020; Schuh et al. 2020). In addition to lacking capabilities regarding the technical realization, expertise related to the shift in manufacturers' business models may also be needed (Lund and Karlsen 2020; Moeuf et al. 2020). Knowledge of the required capabilities is essential to determine the appropriate strategy and make long-term decisions, such as which capabilities need to be developed internally and which can be outsourced.

To contribute to the challenges outlined above, this dissertation applies different theoretical lenses to develop descriptive and prescriptive theories and models that support researchers and practitioners. It lays the foundation for an in-depth understanding of smart service systems and provides guidance to develop and implement these. The dissertation is cumulative and consists of five research articles. Figure 2 shows how the research articles build on the holistic conceptualization of smart service systems. The articles are structured into the categorization introduced above: understanding, developing, and implementing smart services systems. These topics also form the structure of Section II.

As smart service systems are the focal point of this dissertation, an in-depth understanding lays the foundation for effective development and implementation (Section II.1, comprising research articles #1 and #2). Research article #1 investigates smartness from an IS perspective. It defines smartness and develops a literature-based concept to structure and describe the relevant components and relationships. Research article #2 complements this understanding by investigating smart service systems in the context of digital transformation. By building on academic work and an extensive interview study with domain experts in practice, six fields of action for digital transformation are developed. It positions the topics of smart things and smart services into the broader context of digital transformation.

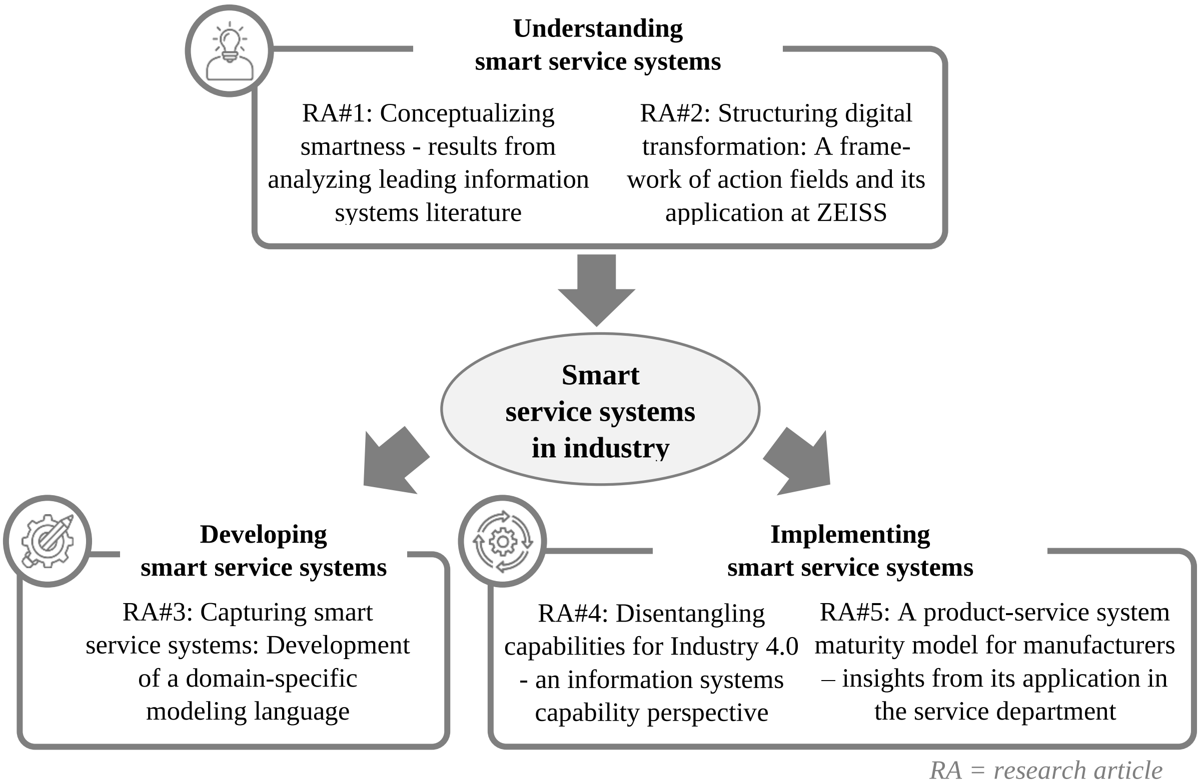

Figure 2: Assignment of the research articles to the topics structuring this dissertation

Based on the understanding of smart service systems, research article #3 (Section II.2) supports their development. It addresses the need for shared understanding and effective collaboration among different domain experts involved in the development process. To address these needs, research article #3 develops a domain-specific modeling language for smart service systems. The modeling language equips researchers and practitioners with the required nomenclature on central concepts and a visual and easily understandable representation for smart service systems. It also enables the analysis of existing and future smart service systems.

To address the hurdles connected to implementing smart service systems, research articles #4 and #5 (Section II.3) identify and structure the capabilities manufacturers require. Research article #4 sheds light on the IS capabilities needed to implement smart service systems in manufacturing. It distinguishes between technical and organizational capabilities. Research article #5 complements the understanding of the required capabilities by taking a business model perspective. With the increasing focus on service as a central part of manufacturers' business models, the research article maps distinct capabilities to different business models. By arranging business models in a maturing manner according to their service focus, manufacturers are guided in their transformation.

Section III concludes this dissertation with a summary and an outlook on future research. Section IV contains the bibliography, while the appendices in Section V include further information on all research articles, my corresponding individual contributions, and the research articles themselves.

II. Overview and context of the research articles[2]

1 Understanding smart service systems

In recent years, the adjective "smart" has been used widely in research and daily life. Its growth stemmed from being used in various IoT contexts, such as smart homes and smart factories (Wiener et al. 2020). However, given rapid technological developments and the broad application of the term, a shared understanding of smartness has not yet been established. While it is recognized that smartness encompasses more than using impressive IT applications, a unified conceptualization of what it is and how it is created remains elusive (Alter 2020). Taking the term "smart things" as an example, Beverungen et al. (2019) define them as boundary objects for the interaction of service consumers and service providers. Oberländer et al. (2018) define smart things as physical objects equipped with their own agency and human-like cognitive characteristics. Neither of them elaborates on what renders the physical things smart. While IS research is rich in explorations of smart things, smart services, and their application domains, it offers no clear understanding of the concept of smartness (Alter 2020).

To address this gap, research paper #1 aims to understand the term "smartness" and how it is created. To build upon existing knowledge about smartness in the IS literature, a structured literature review was conducted. This enabled a clear understanding of how smartness is perceived and laid the foundation for developing a well-grounded concept to explain how smartness manifests. To derive methodologically sound insights, research paper #1 followed the approach Wolfswinkel et al. (2013) proposed. It builds upon the approach of Webster and Watson (2002) by systematically searching for relevant literature and combines grounded theory techniques to analyze the publications. By applying grounded theory techniques to scientific literature, researchers can develop a theory-based and concept-centric understanding, thereby attaining a high degree of accuracy (Wolfswinkel et al. 2013).

In their approach, Wolfswinkel et al. (2013) propose five steps: Define, search, select, analyze, and present. In the define step, the inclusion and exclusion criteria for the literature search are defined. Next, the relevant research domains and search terms must be specified. The search step involves applying the search term along with the inclusion and exclusion criteria to different databases for literature sources. After carrying out these steps and reviewing a random sample of publications for this study, it was clear that only some of them were relevant. The next step, selection, involves identifying relevant articles. To operationalize this step, all titles and abstracts were screened and rated based on their relevance to the topic of interest. This filtering process enabled the selection of only relevant articles. The analysis step includes the in-depth screening of relevant articles and consists of three coding phases: open, axial, and selective coding. As a result, 16 subconcepts were identified and summarized into three higher-order

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concepts, resulting in the representation of how smartness manifests. The last step – present – involves structuring the content and article for its publication in the community (Wolfswinkel et al. 2013).

When screening the literature, it became clear that smartness is not a static characteristic but manifests through reproducible combinations of actors (individuals or smart things) and components (physical objects or technologies). Through these components' (inter-)actions, such as an individual driving a car or a smart car driving an individual, smartness becomes perceivable. The nucleus – the concept of the inner nature of smartness – was developed and coined as a "smart action." Similar patterns consisting of the entities above and combinations of smart actions can be found in publications relating to smart technologies (Porter and Heppelmann 2014; Warkentin et al. 2017), smart service systems (Busquets 2010; Lim and Maglio 2018), and systems of (smart service) systems (Corbett and Mellouli 2017; Porter and Heppelmann 2014). Figure 3 presents the concept and illustrates how the corresponding entities lead to smart actions. In the following section, an overview of the concept of a smart action is provided and its sub-concepts are explained in detail.

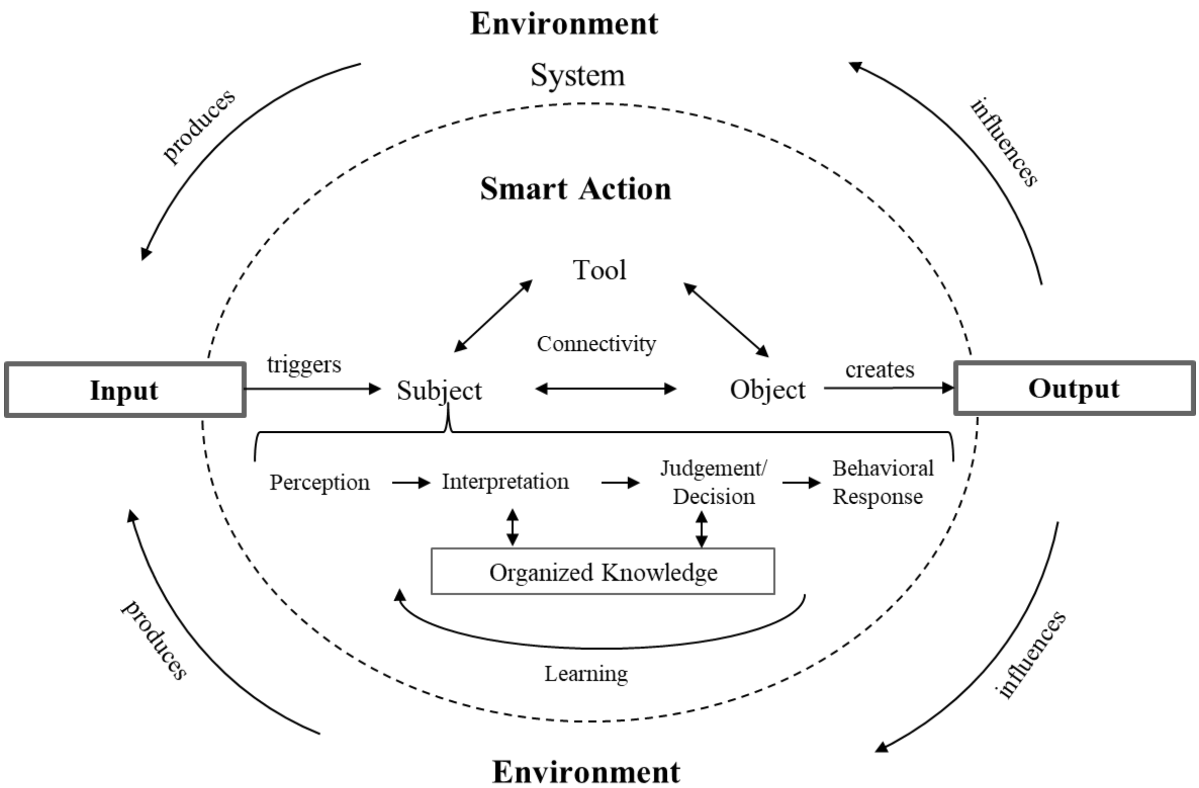

Figure 3: The concept of smartness

As depicted in the center of Figure 3, the actors participating in the interactions are at the core of smart actions. They can be divided into two categories: those carrying out actions (subjects) and those acted upon (objects) (Benbunan-Fich 2019). A smart action usually begins through an input (stimulus from the environment) that triggers the subject. The subject then acts upon an object. The subject's action, which is often carried out through a tool (e.g., a smartphone), is derived through a sequence of information processing steps. These include perception, interpretation, judgment, and the ultimate behavioral response (Fischer et al. 2020). After the behavioral response, the subject analyzes the output and evaluates the action's result. It then incorporates the evaluation in its organized knowledge to learn from and optimize subsequent actions. Finally, if an external observer perceives the smart action's output as smart, smartness manifests. Understanding whether an action is trivial or not is of course dynamic and depends on the observer. For example, it is arguable if a toothbrush capable of telling its user that too much pressure is exerted is perceived as smart. Further, contemporary smart actions could soon be perceived as trivial due to technological developments.

In addition to coding and identifying insights and concepts in literature, as mentioned above, grounded theory techniques were simultaneously applied. Through constantly comparing the understanding of smartness with existing knowledge on the topic and through the theoretical sensitivity for similar phenomena (Urquhart 2012), it became clear that the identified concepts can be related to three existing theories: The activity theory (Engeström 1999), the general systems theory (Bertalanffy 1968), and the cognitive information processing theory (Greifeneder et al. 2011). With these theories, the conceptualization of a smart action can be based on a stable foundation of knowledge.

To conclude, research article #1 investigates smartness in the IS literature. While research on smart things and smart service systems continues to receive broad attention, a clear understanding of its meaning has been lacking. By using grounded theory techniques based on a structured literature review (Wolfswinkel et al. 2013), a theory-based concept was developed to understand smartness from an IS perspective. The concept demonstrates that smartness only manifests and becomes perceivable through smart actions. The insights gained are relevant to the theoretical discourse about understanding the concepts and relationships involved in creating smartness via digital technologies. The developed concept of a smart action lays the foundation for improved systematic analysis and development of smart service systems.

With the improved understanding of smartness in IS research, interdependencies with related topics in the context of digital transformation must be understood. This understanding is vital to develop and implement smart service systems systematically and effectively. In practice, the necessity of using digital technologies to smartify routines and products has been highlighted, and there is awareness of their importance. However, practitioners struggle to understand how to undergo their organizations' digital transformation. They lack a holistic perspective and understanding of relevant fields of action and topics that should be considered.

The struggle primarily comes from the complexity of digital transformation entailing changes at multiple levels, such as organizational structures, customer involvement, and business models (Legner et al. 2017). Additionally, academic work often focuses on single facets of digital transformation instead of taking a holistic perspective (Hess et al. 2016). For example, Lee et al. (2015) discuss the transformation of businesses from an IT ambidexterity perspective and highlight the importance of organizational agility. Keen and Williams (2013) stress that solely adapting the business model and digital business strategy is not sufficient and that organizations should increase their flexibility in adapting to fast-changing environments. However, these relevant but very specific perspectives on certain aspects of digital transformation hamper a holistic view. This complicates the development of an effective and sustainable company-wide approach for digital transformation. A holistic understanding of the required action fields, as well as their interplay, is therefore required. Because of the topic's significance, research paper #2 proposes a holistic framework for digital transformation consisting of six action fields.

The framework was developed in three phases. First, desk research was done to review the academic work and build upon the existing knowledge. To complement theoretically derived insights, application-oriented work from industry experts (e.g., white papers and consultancy studies) were included in the literature review. By confirming the research gap and deriving a selection of important topics and relevant fields of action, framework development followed. This second phase draws on the existing literature as well as qualitative exploratory interviews with practitioners from more than 50 established organizations involved in digital transformation. Interviews with domain experts and cross-checking insights and proposed changes to the framework with existing literature resulted in an iterative development process. To validate the framework in different contexts and critically challenge it with a broad audience, the framework was presented and discussed at industry conferences and workshops. Finally, the framework was applied to Carl Zeiss, a global manufacturer of optical systems. Demonstrating a possible application helped to gain further insights using the framework and refining the framework and its description.

The framework for digital transformation consists of the following fields of action: customer, value proposition, operations, data, organization, and transformation management (Figure 4). Every field of action comprises four action(able) items. From an overarching perspective, the customer and value proposition action fields represent an external, inside-out perspective, whereas operations and organization represent an internal, outside-in perspective. The data action field links both perspectives. Transformation management complements the topics and underlines the importance of managing the transformation. Each field of action and its action items are described in the following paragraphs.

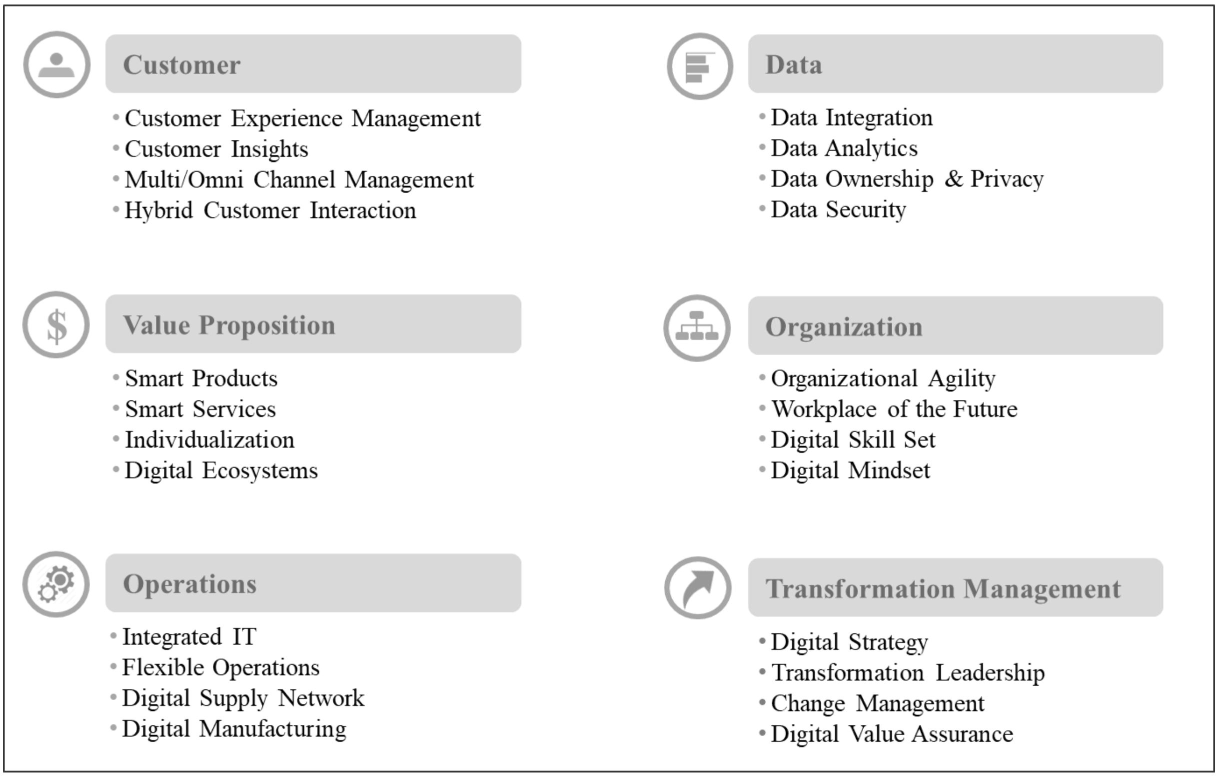

Figure 4: Digitalization requires mastering six action fields

The customer and value proposition action fields are of prime importance for organizations, as customers are no longer passive recipients. Instead, customers define how they would like to interact with organizations, using multiple channels and deviating from organization-defined interaction patterns (Hosseini et al. 2017). This requires hybrid customer interaction management that can navigate non-linear customer journeys (Nüesch et al. 2015). These days customers expect the purchase, product use, or service component to be a positive and ideally an incomparable experience (Gentile et al. 2007). This can be achieved by using digital technologies to collect and use data and to analyze it for relevant customer insights to individualize the service and make it smart (Porter and Heppelmann 2015). Thus, to deliver such a positive customer experience, organizations need to rethink their value proposition in terms of their product and service portfolio. This research project revealed that customers demand individual solutions (Hosseini et al. 2017).

Further, existing (traditional) competitive advantages erode as new competitors access markets due to low entry barriers. They push the disintermediation of companies that do not add value from a customer perspective. The most challenging competitors are often not organizations from the same industry but digital leaders. The interviewed experts in the research project felt that smart products (smart things) would have great potential if their value proposition is enriched via smart services (Porter and Heppelmann 2014, 2015). While thing-centric services are strongly tied to physical products, complementary smart services can use physical products as value carriers. Extending an organization's value proposition by offering smart services and by integrating other value-adding partners helps to integrate products into wider product systems. This forms new value-creation relationships that result in digital ecosystems (Weill and Woerner 2013). The competition base then shifts from single products to smart products and interconnected smart service systems that integrate different value systems.

From an internal as well as external perspective on digital transformation, data is the connecting action field. The interviewed experts were convinced that data was the foundation of success. To learn how to absorb, analyze, and turn data into an asset, organizations must first tackle the challenge of data integration: the process in which heterogeneous data from different sources is retrieved, combined, and made accessible (Porter and Heppelmann 2015). Once data integration is mastered, organizations should choose the suitable data analysis approach (Shmueli and Koppius 2011). By exploring data via advanced analytics, organizations can identify the customers' behavioral patterns or improve the availability of production facilities, to name but two examples. However, topics such as data privacy, ownership, and security are viewed as challenges that hamper progress (DalleMule and Davenport 2017).

From an internal perspective on the organization, the operations and organization action fields are important. For operations, the focus is usually on gaining efficiency in the organization. As the digital and physical worlds are merging, organizations need to rethink their operating models, processes, and supply networks. The is project's interviews highlighted the importance of an integrated IT (Lee et al. 2015), letting components, systems, networks, and software work in unity. The interviewed experts emphasized that offering smart products and services depends on seamless data processing and systems integration. They stressed that organizations need to develop flexible operational capabilities to design processes and production facilities appropriately (Lasi et al. 2014). Digital manufacturing systems and digital supply networks play an increasingly important role in complementing flexible operations and implementing Industry 4.0's desired efficiency gains (Chen et al. 2015; Khaitan and McCalley 2015). Both enable the exchange of resources, products, services, and data among participating organizations to leverage strengths for producing products faster (Lasi et al. 2014).

To meet fast-changing customer demands and deliver innovative value propositions through smart service systems, changes in the organizational structures are required. Adjustments to organizational setups to foster agility require drawing from new approaches (Sambamurthy et al. 2003), such as agile project management or design thinking. Another important step in changing established approaches and routines to develop innovative solutions, such as smart service systems, is utilizing the support of communication- and knowledge-intensive work. The workforce needs the right tools (such as collaboration platforms and video communication tools) to collaborate effectively, which is summarized under the action item "workplace of the future" (Brynjolfsson and McAfee 2014). However, providing the right tool set is not per se sufficient, as fostering the digital mindset and skills is also required to use the tools (Kane et al. 2015; Schmidt and Rosenberg 2015). The dynamic assembly of employees in project teams that are equipped with the required technologies, suitable skills, and the right mindset is key in developing and implementing innovative and digital solutions.

The last action field, transformation management, can be interpreted as the how-to for approaching this transformation. It is less specific about digital topics and focuses on typical transformation topics concerning designing roles and responsibilities for transformation (transformation leadership) (Weill and Woerner 2013). In complementing leadership, the organization requires the appropriate approach to manage the change to get its employees on board for the transformation (Kane et al. 2015). Both are key capabilities in operationalizing the digital strategy, which incorporates the vision, goals, opportunities, and activities to maximize digital technologies' benefits (Hess et al. 2016). In this context, digital value assurance ensures that the strategy is set out in a portfolio of manageable projects whose performance can be measured (Kane et al. 2015).

To sum up, the developed framework for digital transformation is structured along with six fields of action and assigned action items, providing descriptive knowledge on the central aspects of this fundamental shift. It enables a holistic perspective on the topic and contextualizes different research streams. Regarding its practical contribution, it prevents organizations from being trapped in a silo mentality, with individual departments striving for partial solutions. It also positions the development and implementation of smart service systems in the overall context of digital transformation.

2 Developing smart service systems

Following from the two different perspectives on smart service systems that provide a fundamental understanding, the next step is developing these systems. As outlined in the introduction (Section I), there are multi-facetted and complex challenges around developing smart service systems, for example, their interdisciplinary nature. This requires development teams to include experts with various domain backgrounds (Huber et al. 2019; Zheng et al. 2020), specifically mechanical, electrical, and software engineers who need to collaborate. When designing product-related services, the same applies to service design teams that usually consist of maintenance support engineers, remote support engineers, and service quality tracking experts. The complexity increases when both teams need to collaborate during the design process. This multi-disciplinary setup often leads to iterative and recurring design cycles, resulting from poor communication and different understandings (Zheng et al. 2020). To enable a shared understanding and to provide a communication and collaboration tool, conceptual modeling languages display a common approach (Wand and Weber 2002). They are applied in all kinds of domains, such as service engineering and business process management, and are often used to reduce complexity.

There are several approaches for modeling services and service systems. Ranging from rather technical languages that focus on machine-to-machine communication to conceptual ones that facilitate the communication within service design teams. Prominent examples are the approaches of Razo-Zapata et al. (2012) and Cardoso (2013), or the ones provided by the Object Modeling Group (OMG 2017). The same accounts for modeling languages from the IoT domain, most of which are restricted to distinct applications or focus on technical details (Christoulakis and Thramboulidis 2016; Meyer et al. 2019).

An approach to model the central concepts and characteristics of smart services systems is however lacking. Yet, it is precisely this gap that makes it difficult to model smart service systems and facilitate communication and collaboration in the design team. The latter also requires the modeling language to be easy understandable, so that it will be accessible to experts from different domains. Research article #3, therefore, developed a domain-specific modeling language that reconstructs the central concepts, relationships, and characteristics of smart service systems. It provides a common nomenclature and detailed descriptions of central concepts, a visual and simple representation of the essential components, and can be used to model and analyze smart service systems.

For the development, the design science research approach of Peffers et al. (2007) was used, as modeling languages are valid design artifacts (March and Smith 1995). As this is a generic research process, it needs to be complemented by a research method that fits the artifact type. Therefore, research article #3 adopted Frank's (2013) method for developing domain-specific modeling languages. Being a standalone method, this approach partially overlaps with that of Peffers et al. (2007). Therefore only some steps were used. The approach Peffers et al. (2007) proposed consists of six phases: problem identification, definition of design objectives, design and development, demonstration, evaluation, and communication. The result is an abstract metamodel and concrete syntax. The abstract (semi-formal) metamodel describes how to develop a conceptual model and defines modeling rules. The concrete syntax (textual and graphical notational elements) is used to model smart service systems visually. To ensure its usefulness, the domain-specific modeling language was evaluated by modeling various real-world and fictitious examples and by interviews with domain experts. To evaluate its contribution against competing modeling approaches, a feature comparison was conducted (Siau and Rossi 1998).

In the following paragraphs, the major concepts, relationships, and characteristics of the domain-specific modeling language are briefly named and described. At its core, the modeling language consists of four overarching components: resources, relationships, service systems, and services.

Resources are further divided into individuals, smart things, digital hubs, and the physical environment:

- Individuals are differentiated into active and passive ones. Active individuals directly participate in a service (e.g., by driving a smart car), while passive individuals indirectly participate (e.g., being the passenger) (Böhmann et al. 2014; Maglio and Spohrer 2008).
- Smart things take on the role of boundary objects between a service consumer and service provider and connect different service systems (Beverungen et al. 2019). They can be further be divided into self-dependent and dependent smart things. Self-dependent smart things can act autonomously in a goal-oriented way without external intervention and even without external triggers (e.g., a smart car that drives autonomously). These actions are enabled by extended data analysis (diagnostic, predictive, or prescriptive) or self-x functions (e.g., self-learning). Dependent smart things require external triggers and have only basic data analysis (e.g., descriptive) and basic self-x functions (e.g., self-controlling).

- The same distinction applies to digital hubs, but they only exist in the digital world and have no physical representation (Batool and Niazi 2017). Smart things as well as digital hubs are either proprietary, as in being only compatible with the same provider, or open, meaning that they are compatible with other service providers (Püschel et al. 2016).
- The physical environment takes on a rather passive role (e.g., animals being close to a smart car). Smart things and individuals, however, have the ability to observe the physical environment's properties (e.g., detecting animals in the vicinity) (Borgia 2014).

Resources are interconnected through relationships, which can be distinguished as interactions, parameterizations, and observations:

- Interactions enable exchanges between resources and occur when data is exchanged, functions are triggered, or events are reported (Oberländer et al. 2018).
- Parametrization refers to all relationships wherein one resource determines another's goals so that the resource commits itself to achieve a predefined goal (Encarnação and Kirste 2005). Only individuals, self-dependent smart things, and self-dependent digital hubs can parametrize other resources.
- Observation refers to accessing and collecting data through sensors (e.g., the smart car sensing animals in the vicinity) (Perera et al. 2014; Streitz et al. 2005). In the context of smart service systems, only smart things and individuals can observe the properties of other resources or the physical environment.

Service systems can be classified into normal service systems and smart service systems. The latter must include at least one self-dependent smart thing, whereas the former excludes self-dependent smart things (e.g., service systems that include people or entire organizations). In addition, (smart) service systems are differentiated into atomic or composed ones. This enables the description of nested service system structures, where one service system is part of a bigger service system or different ones at the same time (Porter and Heppelmann 2014). The domain-specific modeling language therefore differentiates between atomic and composed (smart) service systems (Maglio et al. 2009; Nielsen et al. 2015).

Having described all central components, subcomponents, characteristics, and interrelationships, the modeling language's abstract syntax is defined. To use the modeling language, a concrete syntax that displays every component and characteristic by a notational element is required. In addition, the modeling language differentiates between a structural and behavioral view of the metamodel (Kurpjuweit and Winter 2007). Each view is geared toward a specific modeling goal and includes partially different concepts and relationships. The structural view focuses on the interplay of service systems, resources, and relationships. When applied in practice, this structural view leads to an integrated service system model. The behavioral view focuses on the process of value co-creation and leads to a service description model that describes the sequence of steps leading to the relevant service.

To demonstrate the developed modeling language, an exemplary smart service system is modeled below. The most central resource of this smart service system is Google's Nest learning thermostat. It is a self-dependent smart thing that connects individuals, smart things, and digital hubs to optimize the temperature and other settings of private homes (NEST, 2017). Figure 5 shows the integrated service system model of the Nest scenario. It includes an energy saving service, a coming home service, and a rush hour reward service. On the highest level of aggregation, it includes seven service systems with related resources and relationships. In the example, the Nest thermostat has relationships with all other resources of the smart home service system (e.g., the homeowner and other smart home devices). It also serves as a boundary object between the smart home and the Nest service system. The thermostat is connected to the resources of other service systems via the Nest cloud.

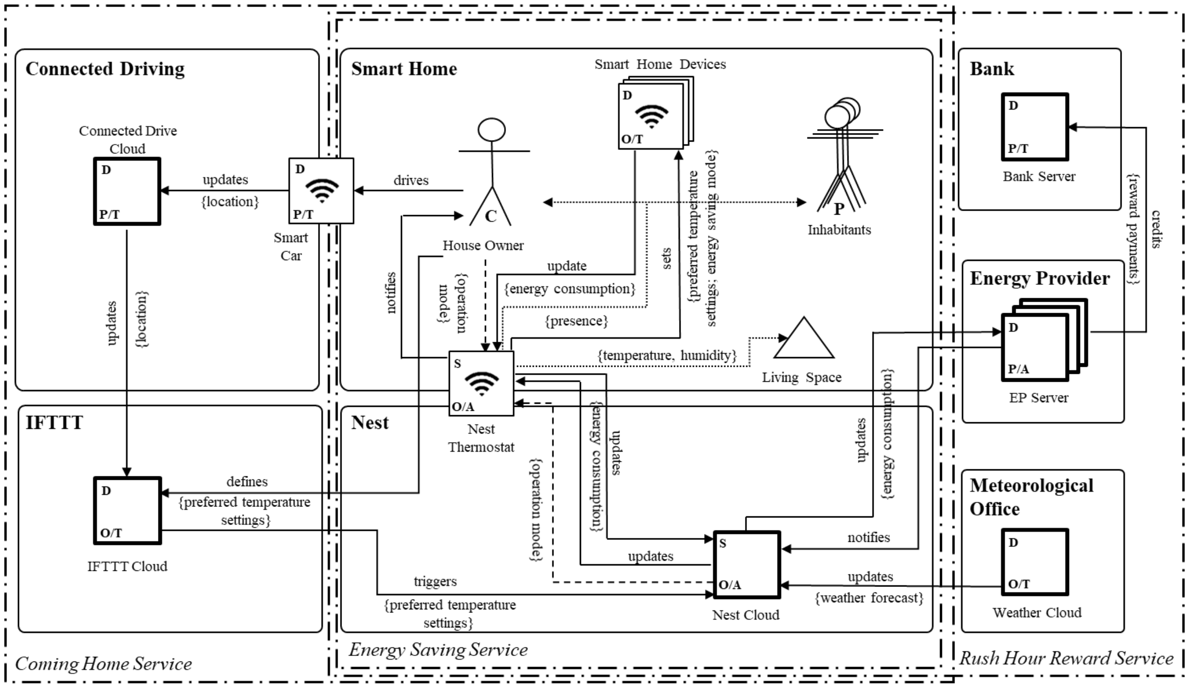

Figure 5: Integrated service system model of the Nest scenario

To conclude, the developed domain-specific modeling language for smart service systems structures, defines and describes the central concepts involved in creating smart service systems. It provides role definitions and a modeling tool (graphical notions) to conceptualize smart service systems. The modeling language serves as a foundation for explanatory research, as for example, the metamodel can be used to derive hypotheses about which factors inhibit the adoption of smart service systems. Due to its modular structure, it can be developed further by extending concepts or specifying existing ones. Practitioners are supported by a common nomenclature of central concepts and a collaboration tool when analyzing or developing smart service systems.

3 Implementing smart service system

In addition to the challenges with understanding and developing smart service systems, manufacturers face difficulties when implementing them. Whereas the "why" in the context of developing and offering smart service systems has been researched extensively, the "how" remains poorly understood. Manufacturers struggle to identify the required changes and lack guidance on how to transform their organizations. Thereby, identifying and developing the capabilities required for smart service systems are major hurdles. Capabilities in this context are understood as the organizational ability to use certain resources (e.g., digital technologies) to perform specific tasks (e.g., offering smart services). The complexity arises when there are different perspectives on the set of capabilities required to implement smart service systems. Whether and how much change is necessary depends on the product, market, and current business model the manufacturer has in place. Most manufacturers still focus on a once-off product sale and regard services as a by-product, meaning that they are far from offering smart service systems.

To implement smart service systems and offer them to customers, manufacturers must complement their strengths in manufacturing-related capabilities (e.g., product design). Most manufacturers specifically need to complement the IS capabilities required for optimizing the benefits of digital technologies and offering smart services (Lund and Karlsen 2020; Moeuf et al. 2020). By making services a central business component, fundamental changes related to the business model are also required. Services are not only created (or co-created with the customer) and delivered in different ways – they are also sold and priced differently. To take full advantage of the opportunities in offering smart service systems, manufacturers need to transform their business models from making once-off product sales to providing products as well as services.

To give manufacturers an overview and understanding of the capabilities required to implement and offer smart service systems, research articles #4 and #5 take two different perspectives. Research article #4 sheds light on the IS capabilities required to implement smart service systems in manufacturing. Research article #5 complements this by investigating the capabilities required to shift the business model to becoming a provider of a product-service system (PSS). The developed maturity model maps the required capabilities to different PSS types, arranged in a maturing manner related to their service focus and along different organizational dimensions.

As the literature on the capabilities required to implement smart service systems in manufacturing is usually categorized in the broader concept of Industry 4.0, research article #4 investigates IS capabilities in an Industry 4.0 context through a multi-step research process. First, to build upon existing knowledge on Industry 4.0 capabilities, a structured literature was conducted. The approach of Wolfswinkel et al. (2013) was applied again, as explained and applied in research article #1 (Section II.1). Due to the topic's interdisciplinary nature, articles from nine research databases (e.g., Emerald and Science Direct) were included, focusing on publications from 2009 to 2019. As the initial search resulted in many publications that did not really address the topic, several filter criteria were applied. The final literature sample of 42 publications was carefully read and coded. With the coding and structuring of important findings, an initial version of a framework structuring relevant IS capabilities for Industry 4.0 was developed. Through constant comparison with existing theories from (non-)IS domains, as in research article #1, the author team concluded that the value chain of Porter (1998) would be best to structure the framework.

To iteratively evaluate the framework for its structure, completeness, and comprehensiveness, ten semi-structured interviews with domain experts were conducted. In addition, to test the framework for its understandability and applicability (Sonnenberg and vom Brocke 2012), the framework was applied at a German manufacturer for metal and tube processing solutions. The objective was to identify the company's status quo regarding relevant IS capabilities and define its desired target state in three years as well as to reflect on chances and challenges. Finally, because Industry 4.0 is a fast-developing field, the author team checked for new and prominent publications for each capability.

As outlined above, the framework structures relevant IS capabilities for Industry 4.0 along Porter's (1998) value chain model, grouping them as primary and support capabilities. Primary capabilities focus on offering product-service solutions and their technical implementation. Support capabilities focus on improving support processes and collaboration within and outside the organization to increase the effectiveness of primary capabilities. Figure 6 shows the framework with all its capabilities. Primary and support capabilities are grouped along three dimensions, according to their focus and to ease their understanding. Each capability is briefly explained in the following paragraphs.

The first dimension of primary capabilities begins with the connection to the product and ends with the advanced analytical services based on. Capabilities to manage the technology stack to assess and store data are grouped under the Connect & Store dimension (Schuh et al. 2020). These include capabilities to connect products and product-systems (Schuh et al. 2020) and enable a connection to customers in order to monitor product usage and analyze customers' needs (Beverungen et al. 2019; Siggelkow and Terwiesch 2019). As accessed (product) data also needs to be stored, capabilities to continuously collect and store data are an essential part of this dimension (Emmanouilidis et al. 2019; Schuh et al. 2020).

After data has been collected and made accessible, the Understand & Act dimension contains capabilities to process (un-)structured data automatically (Alcácer and Cruz-Machado 2019; Schuh et al. 2020). These capabilities are about transforming data into information, which requires processing large amounts of data. This includes data categorization, characterization, consolidation, and classification. As data is made processable, capabilities for performing descriptive and diagnostic data analysis to gain important insights from data are required (Dai et al. 2020; Porter and Heppelmann 2014). To use the analyzed insights, capabilities for advanced and embedded analytics tools enable the automatic monitoring of product usage and manufacturing processes as well as real-time decisions to respond to unwanted deviations (Waschull et al. 2020; Wagire et al. 2021).

The last dimension for primary capabilities, Predict & Self-optimize, contains extended analytical capabilities for predictive and prescriptive purposes as well as for autonomous systems (Porter and Heppelmann 2015; Schuh et al. 2020). With predicting events and time series, digital technologies can also suggest decision options based on the result and even prescribe recommended actions (Baptista et al. 2018; Frank et al. 2019). To enable products or production systems to act autonomously, capabilities for self-optimization are needed. These capabilities enable the product or system to make and deploy automated decisions (Waschull et al. 2020). In addition, and especially in the context of providing automated PSSs to customers, capabilities for the autonomous provision of products and services become increasingly important (Oztemel and Gursev 2020; Shinohara et al. 2017).

Supporting the effectiveness of primary capabilities, Strategy displays one of the three support capability dimensions. It contains capabilities related to general (strategic) management to define and manage the Industry 4.0 transformation. This includes capabilities for the strategic evaluation of customer and technology trends to ensure long-term competitiveness (Neirotti et al. 2018; Schroeder et al. 2019). In the context of identifying trends, capabilities for data-based product and service innovation are required (Neirotti et al. 2018; Weking et al. 2020). Another important strategic aspect addresses capabilities to readjust sales and service provisioning structures, as the delivery of (smart) service systems implies major changes at an organization. This capability dimension was added by the interviewed industry experts, who stressed their importance and above all negligence in academic work. Capabilities to leverage partner networks complement this dimension. Those capabilities enable the effective development and utilization of partnerships (e.g., technology partners) to complement manufacturers' capabilities through external partners (Wagire et al. 2021; Zacca et al. 2015).

The Technology dimension groups capabilities related to technical knowledge, which are required to digitalize support processes and ensure the safe use of Industry 4.0 technologies. This includes capabilities to support the digitalization of processes and a seamless operations backend (i.e., support processes) to provide value propositions to customers (Wagire et al. 2021; Waschull et al. 2020). Technological capabilities to ensure a seamless human-machine collaboration (Patterson 2017; Wittenberg 2016) and for an intra-organizational information exchange (Emmanouilidis et al. 2019; Endert et al. 2014) are also important. The first is about providing flexible and customizable user interfaces. The latter ensures a user-oriented information exchange within the organization, for example, to ease the development of digital products. Capabilities for the governance of data, security topics, and liability complement this dimension (Schuh et al. 2020).

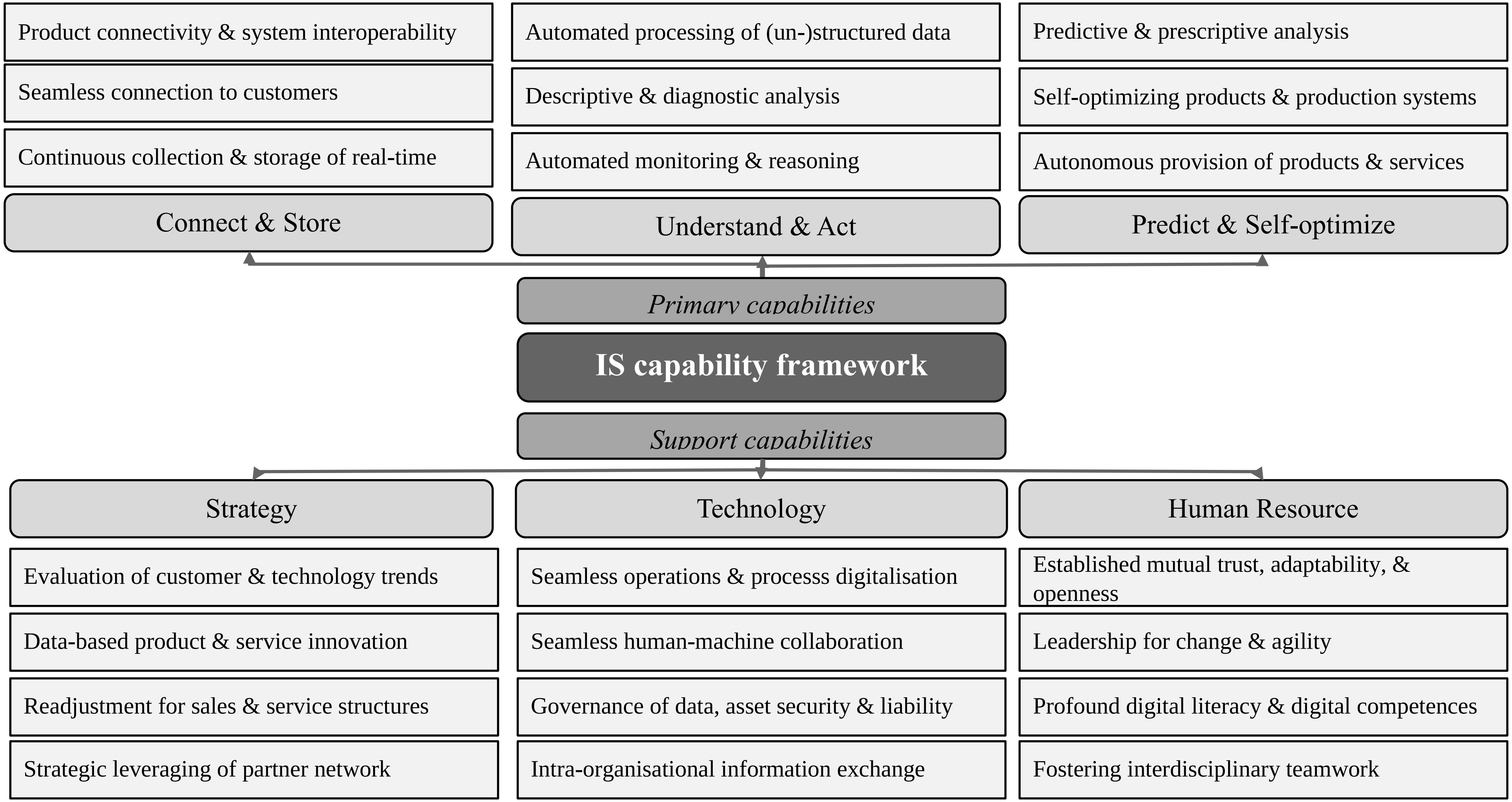

Figure 6: IS capability framework for Industry 4.0

The last dimension, Human Resources, groups capabilities related to cultural aspects, including technology acceptance and use. As a building block for smart service systems, capabilities regarding establishing mutual trust, adaptability, and openness are required to get customers as well as employees and ecosystem partners on board (Bienhaus and Haddud 2018). To strengthen the mutual trust, capabilities for strong and committed leadership are also required. Manufacturing companies must employ an agile leadership that facilitates change and encourage employees to accept and embrace it (Benešová and Tupa 2017; Wagire et al. 2021). For effective collaboration, employees need general and role-specific (digital) competencies (i.e., digital literacy) (Wagire et al. 2021). Due to the interdisciplinary teams involved in the development process, redefinitions of organizational structures and routines for interdisciplinary teamwork are therefore required (Waschull et al. 2020).

In sum, research article#4 contributes a theoretically well-founded and practically relevant IS capability framework to implement smart service systems in the context of Industry 4.0. The framework complements knowledge on Industry 4.0 by taking an IS perspective on the required capabilities. It supports practitioners by providing a holistic overview of relevant IS capabilities to implement smart service systems in manufacturing. It also adds to descriptive knowledge on Industry 4.0 and establishes the foundation for further theorizing.

Offering smart service systems to customers requires most manufacturers to develop new capabilities in the context of their business model transformation. There are various business models for product and service bundles, which differ in terms of how central and important the service component is. Among several possible combinations, three main types of PSSs are addressed in the literature: (a) product-oriented, (b) use-oriented, and (c) result-oriented (Tukker 2004; Tukker and Tischner 2017). In a product-oriented PSS, the business model is mainly focused on selling products with some additional services. With a use-oriented PSS, a product's use or availability is sold, shifting the focus to the service of using the product. When it comes to a result-oriented PSS, the customer and product manufacturer agree in advance on the result the supplier should deliver. With a result-oriented PSS, the service component of the business model can be regarded as the dominant one. The product manufacturer sells all kinds of services to make sure that the product's result is on the agreed level. The product itself is seen as the entity that delivers the service and plays a secondary role. Each type of PSS requires different sets of capabilities, especially with the increasing focus on selling product-related services. Manufacturers often struggle to identify and develop the required capabilities. Particularly for product-centric manufacturers, a PSS requires a comprehensive mapping of current capabilities, along with a concrete definition of a target state for the business transformation.

To support product manufacturers in their transformation to a certain PSS type, research article#5 developed a maturity model for the transition from being product-oriented to becoming service-oriented. Although there are several maturity models in the context of PSS (e.g., Exner et al. 2018; Paschou et al. 2020), the existing literature has neglected to group established PSS types with corresponding capabilities. This makes it difficult for manufacturers to assess whether their maturity level is sufficient in meeting the desired PSS type. It is also unfortunate that existing models do not provide a comprehensive perspective on the capabilities of a certain PSS type. The developed PSS maturity model (PSSMM) bridges the gap among common PSS types and relevant capabilities.

When developing this PSSMM, we followed the approach of Becker et al. (2009), comprising eight phases. While the first four phases are central to the model's design and development, the last four cover the transfer and evaluation. In phase 1, the problem was defined, and an appropriate research question was derived. Next, in phase 2, the domain literature was checked for existing maturity models in the context of the research question and for the research gap. In phase 3, the development strategy for the maturity model was determined. As there is no maturity model that provides a holistic perspective on the required capabilities for a specific PSS type, a new model has to be developed. In phase 4, the model was iteratively developed. This was accomplished by first building upon existing maturity models in a PSS context. This resulted in the first draft of the PSSMM. The model was further developed by analyzing the domain-specific literature on PSS capabilities. Phase 5 and 6 focused on finding the right strategy to evaluate and communicate the model to experts. Phase 7 was about operationalizing the evaluation strategy. This was accomplished by conducting a focus group discussion with domain experts. In addition, the PSSMM was evaluated for its use at a vacuum pumps manufacturer. Phase 8 was about publishing the PSSMM.

The PSSMM and its overarching structure is presented in the following paragraphs. The developed maturity model is in accordance with the PSS types of Tukker mentioned above (Tukker 2004; Tukker and Tischner 2017), displaying the maturity model's rows. The "pure product" is set as the initial maturity level and the three main PSS types as the remaining levels. A maturity level denotes the extent to which a capability is typically developed for a specific PSS type. The levels are arranged to their maturity in terms of their service focus. This allows organizations to identify where to develop the necessary organizational capabilities toward a target type of PSS. To structure the required capabilities (the lines of the maturity model), the socio-technical perspective of Cleven et al. (2014) was chosen. This offers a holistic view on the organization by including societal and technical aspects and has five focus areas: strategy, culture, structure, practices, and IT.

As it is generally the case with maturity models, the definition of a target state does not primarily depend on the pursuit of higher levels of maturity but on organization-specific factors (such as customer requirements and economic aspects). Certain PSS types can be skipped, and different PSS types can be implemented at the same company, be it for varying markets or separate customer segments. The PSSMM in Table 1 provides a comprehensive overview and is described below.

The focus area strategy describes the extent to which an organization focuses on enriching its value creation with services until service is at the core of its business model (service focus) (Gudergan et al.

2015; Pigosso and McAloone 2016). This strategic shift creates the necessary precondition for an organization to develop and implement a successful PSS. Customer centricity then becomes essential for service value co-creation with the customer (customer involvement) (Exner et al. 2018; Tukker and Tischner 2017). To succeed in the PSS transformation, management needs to allocate substantial resources to manage the transition (management commitment to PSS) (Oliveira et al. 2018; Rapaccini et al. 2013).

Next, culture includes capabilities for effective and efficient collaboration (internal collaboration) (Schroeder et al. 2019; Waschull et al. 2020) and to ensure commitment to the organization's PSS vision (employee commitment to PSS) (Bienhaus and Haddud 2018). These capabilities can be regarded as the counterplay to capabilities for 'management commitment for PSS' in the strategic dimension. To complement this, capabilities to enable the development of relevant soft and hard skills are required (skills training) (Lund and Karlsen 2020).

In terms of structure, PSS transformation requires changes to how the product is marketed and how value is delivered (sales channels) (Kiel et al. 2017a). With mature PSS types, the product itself becomes a new and essential channel. Capabilities to effectively integrate partners into the manufacturer's value proposition become increasingly important with mature PSS types to complement capabilities (e.g., digital capabilities) they lack (partner integration) (Benitez et al. 2020; Exner et al. 2018a). When the business model depends less on product sales, the organization must manage the change in cash flow from once-off product purchases to continuous payments for services (capital management) (Kamal et al. 2020; Zhang and Banerji 2017).

The focus area practices include dimensions in the context of changing existing routines and processes to offer PSS. The first is about how a customer interaction needs to be initialized for services (customer interaction and service initiative) (Brambila-Macias et al. 2018). This is important, as a mature PSS implies more customer interaction and responsibility for product performance. The second capability dimension addresses how to design a high-quality PSS, focusing on new methods and tools (PSS design methods and tools) (Weking et al. 2020). Since a mature PSS has a strong focus on product availability, product performance measurement has become increasingly relevant for providing and pricing services (Kamal et al. 2020; Selviaridis and Wynstra 2015). This goes hand in hand with capabilities required to automate the service provision, which is crucial to ensure service availability (Müller et al. 2018). A mature PSS also requires capabilities to develop and offer suitable pricing models that are increasingly distinguished by performance-oriented payment structures (pricing mechanism) (Porter and Heppelmann 2014; Selviaridis and Wynstra 2015). The last capability dimension, life cycle management, is key in accompanying the customer holistically - before, during, and after product use (Tukker and Tischner 2017).

IT provides the foundation on which PSSs, especially service-focused PSSs, can be developed and operated. IT's role determines whether it merely supports business or goes further by facilitating the organization's strategic objectives (Wessel et al. 2021). Being a driver for a service-oriented PSS, a fundamental building block is a continuous connection to products (Schumacher et al. 2016; Wagire et al. 2021). Capabilities for connectivity and data access are therefore needed. Further, to provide data-driven services, such as predictive maintenance, it is necessary to collect relevant product data (data collection) (Alcácer and Cruz-Machado 2019; Neff et al. 2014) and analyze it (data analysis) (Frank et al. 2019; Porter and Heppelmann 2015). This enables real-time performance measurement and payment determination. Due to the increased collection of data that passes through PSS value chains, capabilities in IT security and compliance enable the development of comprehensive IT security concepts (Preuveneers et al. 2018).

To conclude, the presented PSSMM provides relevant capabilities on the interconnection of PSS types and different organizational perspectives. It takes the interdisciplinary and holistic nature of PSSs into account. Regarding the practical contribution, manufacturers are provided with an applicable model to capture the status quo as well as the desired target state. With this model, manufacturers are guided throughout the far-reaching PSS transformation to implement and offer smart service systems.

Focus area	Capability dimension	Maturity level			
		1. Pure product	**2. Product-oriented PSS**	**3. Use-oriented PSS**	**4. Result-oriented PSS**
Strategy	**Service focus**	Focus on the physical product; no additional services	Limited focus on PSS; additional services like consulting, maintenance, or recycling	Focus on PSS; warranty of the availability of the physical product along with services	Focus on mature PSS as core BM; highly integrated product-service bundles to offer result as a service
	Customer involvement	No or little involvement in the product design	Growing participation in designing and evolving the product and additional services	Increasing cooperation with the customer and integration into PSS design processes	Partner-like collaboration and intensive communication for PSS development
	Management commitment for PSS	No resource allocation for PSS development and implementation	Little effort to create services to accompany the product; ad hoc resource allocation in organizational changes	Medium effort for creating well-functioning PSS; continuous resource allocation	Significant efforts to achieve a high-performing PSS; substantial and continuous resource allocation
Culture	**Internal collaboration**	Independent work or partly homogenous teams	Occasional work in interdisciplinary teams	Work in interdisciplinary teams	Team-oriented, cross-team, cross-domain, and cross-organizational work, continuous exchange with value-added partners
	Employee commitment for PSS	Product-oriented way of thinking; working for developing and selling physical products	Product-oriented way of thinking; working to offer services to complement the product	Thinking in terms of customer usage; working to provide PSS solutions with a higher level of service integration	Thinking in terms of customer results; working for delivering results as a service
	Skill training	No training or further education regarding PSS skills	Occasional in terms of PSS development, training for product-related consultation	Selective training courses on specific topics for PSS development and implementation	Structured training courses on all relevant PSS topics, such as development, implementation, sales, customer contact, leadership, and management
Structure	**Sales channels**	Traditional and web-based channels for product sales	Traditional and web-based channels for product and service sales	Traditional and web-based channels or products as a point of sale	Traditional and web-based channels and products as a point of sale to develop an integrated view on results
	Partner integration	Only suppliers as value-adding partners; clear organizational boundaries	Additional value-adding partners for service-creation and initial involvement of and cooperation with customer as a partner	Blurred boundaries between the company, suppliers, and service-creation partners; close cooperation with customer as a partner	Strong collaboration and integration of value-added partners and customers for PSS co-creation; company is deeply integrated into customers' processes and BM
	Capital management	Bearing all costs until the point of sale; management of once-off payments for each product sale	Bearing all costs until the point of sale; management of one-time payment for the product and demand-driven service provision income	Bearing of production and development costs for products and services until a predefined point of time; ongoing payments for usage	Bearing all the costs for PSS until the end-of-life cycle; continuous and success-related payments for the PSS operation
Practices	**Customer interaction and service initiative**	Interaction focuses on product purchase and emerging operation problems; customers are responsible for operations	The customer drives interaction; interactions are predefined in the service contract; mostly topic-driven services related to maintenance	PSS provider initiates services and is responsible for ensuring perpetual availability; planned interactions	Proactive and automated service interaction; connected through predefined touchpoints and processes; result as continuously monitored parameter for service initiative
	PSS design methods and tools	No approach for service or PSS development	Standard (management) approaches for product development; partial use of PSS methods and tools	Selected approaches and formalized development processes for PSS; appropriate tools for development and implementation	Company-specific and individualized PSS approaches plus fast development cycles and prototyping; continuous improvement and use of methods
	Product performance measurement	No need to measure product performance; measuring product quality by internal tests only	No need to measure product performance but occasional insights through maintenance services; measuring product quality to provide advice and guidance to customers	Measurement of product performance and usage to guarantee and optimize product availability	Well-defined measures and feedbacks are systematically used for payments, maintenance, and new service development
	Automated service offering	No service provision	Almost no automation; rule-based, or instinct-driven service provision	Partly automated or modularized services are provided	Most services with the customer or value-creation partners are automated and/or modularized; optimisation toward minimizing human interaction in the service process

	Pricing mechanism	Fixed once-off payment (pay for the product)	Once-off payment for the product and situational service fees (pay for the product or service order)	Ongoing payments like leasing, renting or sharing (pay on availability)	Customer-specific, result-based payments based on service level agreement (pay on production)
	Life cycle management	Development, production, sale, and shipment; no responsibility for the operation	Development, production, sale, and shipment; no responsibility for operation but a reactive provision of services	Development, production, sale, shipment, maintenance, and usage phase; responsible for guaranteeing the product usability	Managing everything until the end of the product life cycle; responsible for delivering results and productivity
IT	**Role of IT**	IT as supporting function; intra-organizational focus	Supporting function, partly as the driver of value creation and change; intra-organizational focus	IT as an enabler and diver for value creation and change; enabler of product availability; inter-organizational focus	IT as an enabler and driver for value creation and change; enabler of enhanced product performance, inter-organizational focus
	IT security and compliance	Security of highly critical assets; isolated IT security activities	Protection of highly critical assets and initially also of external processes	Intra- and inter-organizational IT security activities	Intra- and inter-organisational IT security activities; security by design in product and service development process
	Connectivity and data access	No access to the product after the point of sale	Indirect, situational data access to customers; possible manual data exchange	Frequent data exchange with OEM; mainly reading rights	Continuous data exchange; full access to the product
	Data collection	No collection of customer's product data	Reactive and manual collection of data; no defined data collection strategy	Partly automated collection of data; high-level requirements of data that needs to be stored	Highly automated data collection; specific requirements concerning data that needs to be stored regarding volume, velocity, and variety
	Data analysis	No analysis of product usage or descriptive analysis of internal product testing	Descriptive and diagnostic analysis of product data; initially for service provision	Diagnostic and predictive analysis of product data; focus on keeping the promise of availability	Predictive and prescriptive analysis; focus on the result optimization

Table 1: Maturity model for PSS

III. Conclusion

1 Summary

The increasing use and connection of digital technologies are changing the way products and services are developed and offered. Especially in the context of the IoT, technical developments make it possible to equip traditional products with digital technologies (e.g., for sensing and communication). These technologies enable new forms of intelligence and transform products into smart things that can offer smart services. With smart things at their core and smart services as their value proposition, smart service systems bring new forms of capabilities, such as being self-organizing and self-optimizing. They offer new value propositions beyond the existing ones based on traditional products (regarding their physical usability). This development is expected to entail fundamental shifts at manufacturers and revolutionize entire industries. Despite the growing importance of smart service systems, their nature remains poorly understood. Challenges arise because there is no common understanding of what smartness means and how it relates to the organizations' overall digital transformation. The development of smart service systems and associated organizational changes are challenging and hamper scientific progress and practical application. Against this backdrop, this dissertation addresses the foundations of smart service systems and provides guidance on their development and implementation.

On the topic of *understanding smart service systems*, Section II.1 lays the foundation by providing two conceptual perspectives. Research article #1 investigates how smartness is understood and how it manifests. It takes an IS perspective due to the growing importance of digital technologies and especially of smart things in creating smartness. As a result, research article #1 provides a thorough understanding of smartness in IS literature and develops the concept of a smart action. This conceptualization depicts that smartness involves a reproducible set of actors and components as well as a template for how they interact. It provides a theoretical lens for understanding and analyzing smartness. Smart actions can therefore be interpreted as the nucleus for smart service systems. This understanding and contribution to descriptive knowledge on smartness serves as a basis for further sense-making and design-oriented research (Gregor 2006; Gregor and Hevner 2013). Research article #2 supplements the fundamental understanding by embedding the topic into the overall context of digital transformation. Due to the dependence of smart service systems on digital technologies and smart things, researchers and practitioners need to understand how the subject matter relates to other digital transformation topics. Research article #2, therefore, provides a conceptual framework for digital transformation, consisting of six action fields. These action fields – value proposition, customer, operations, data, organization, transformation management – structure the topics involved in realizing digital technologies. The framework provides descriptive knowledge on digital transformation by structuring and describing relevant fields action and actionable topics are related to. The framework connects the topic of using smart things and developing smart service systems to highly interdependent topics, such as data management and transformation management. To summarize, while research article #1 sheds light on how smartness manifests in the context of digital technologies, research article#2 complements it with a holistic perspective on the topic of transforming an organization to integrate digital technologies.

On the topic of *developing smart service systems*, research article #3 develops a domain-specific modeling language for smart service systems in Section II.2. Due to the interdisciplinary nature of smart service systems, development projects require experts with different domain backgrounds. The communication and collaboration among these experts often result in challenges related to a lack of a common understanding and ineffective design activities in development projects. To close this gap, the modeling language reconstructs central concepts and relationships involved in smart service systems. It also synthesizes and extends knowledge from the IoT and service domain by introducing a unified nomenclature and adding to descriptive knowledge. The modeling language adds to prescriptive knowledge, as its abstract and concrete syntax was tested in multiple real-world scenarios and evaluated for use by different domain experts. This enabled the identification and description of relevant concept characteristics that can be interpreted as design decisions for practitioners. In short, research article #3 gives researchers and practitioners a hands-on tool to develop and analyze smart service systems.

On the topic of *implementing smart service systems,* Section II.3 sheds light on the required capabilities required to implement and offer smart service systems. Research article #4 takes an IS perspective on the topic to account for the IS capabilities required to integrate digital technologies and realize smart service systems. The framework is structured along the value chain model of Porter (1998), distinguishing among primary (technical) and support (strategic, operational, and cultural) capabilities. The framework complements knowledge on implementing smart service systems in manufacturing by taking an IS perspective, which is only superficially addressed in existing work. It provides a foundation for further theorizing (Gregor 2006; Gregor and Hevner 2013), such as understanding the dependencies of capabilities and deriving design actions to guide manufacturers' transformations. To complement the understanding of the required capabilities for smart service systems, research article #5 takes a business model perspective. It identifies the capabilities required to offer different types of product and service bundles. The theoretical contribution of the developed maturity model in research article #5 lies in mapping relevant organizational capabilities to distinct business model types. The model provides a holistic overview of relevant capabilities to realize the business model and guides manufacturers throughout their far-reaching business model transformation. To conclude, research article #4 structures and describes capabilities relevant to realize smart service systems, while research article #5 takes a business model perspective on offering smart service systems.

2 Future research

This dissertation advances knowledge about smart service systems. As any research endeavor, the results of this dissertation are subject to some limitations that display potential avenues for future research. In the following, an overview is provided which discusses these limitations and makes recommendations for advancing research on smart service systems.

Regarding *understanding smart service systems* (Section II.1), research articles #1 and #2 add to descriptive knowledge on digital transformation, the IoT, and smart service systems. Research article #1 investigates the concept of smartness in IS research, proposes a conceptualization of smartness, and demonstrates that smartness manifests in smart actions. The developed concept can be used as a theoretical lens in future IS research. Nevertheless, the interpretation and use of the concept are for now restricted by the field of research (IS research) and its understanding. The concept should therefore be further developed and incorporate knowledge from other relevant domains concerning smartness research, such as biology and psychology. The type of theory developed – the concept of smart actions – is limited in its interpretation and use. The concept provides a theory for description and analysis (Gregor 2006; Gregor and Hevner 2013). This type of theory is a solid foundation for researchers when applying more advanced, complex, and detailed theories. Theories for explanation built on the concept of smart actions promise a deeper understanding of the underlying concepts. Theories for design and action should also guide practitioners in building and designing smart things and smart service systems effectively. The concept could be used to analyze real-world cases of smart service systems in a first step to derive insights, recognize patterns, and theorize about them.

Similar limitations apply to research article #2, which proposes a framework to structure digital transformation endeavors. It embeds the topics of smart things and services into the overall context of digital transformation. Further research is required in order to provide models and methods to guide organizations about operationalizing the framework. Practitioners need to understand how to assess the importance of distinct action fields and action items in relation to their organization’s context (e.g., small vs. large firms). Lessons learned and design actions would guide practitioners in their transformation endeavors. Another limitation comes with topicality and also applies to research article #1. Ever-shorter development cycles result in countless new technologies emerging every year. In addition, the reinforcement and combination of extant technologies continues and leads to new insights, facilitating the refinement of existing theories and knowledge on the topic (Arthur 2009). To cope with this dynamic and complex environment, efforts to advance research activities should focus on repeatedly adjusting and re-evaluating both artifacts. This could, for example, be achieved by updating recent publications and especially by including application-oriented work.

Regarding *developing smart service systems* (Section II.2), research article #3 provides a domain-specific modeling language for smart service systems. The modeling language provides a tool for communication and for the analysis of existing as well as the development of smart service systems. To use the modeling language effectively, subsequent research should develop a method on how to use it (Wand and Weber 2002). Deriving a step-by-step approach would guide researchers and practitioners on applying the modeling language in a targeted manner and could include important modeling questions. Applying the modeling language to various examples would also enrich insights on smart service systems and the modeling language. For example, applying it to different examples in a specific domain (such as smart homes) would validate its usefulness and evaluate its completeness for reconstructing central concepts (e.g., actors and relationships). Due to the modular structure of the developed modeling language, it can easily be extended and refined. By modeling various real-world examples, missing concepts as well as patterns and related insights could be derived. These insights can be compared with those of other domains and used to generate general recommendations for design and action (Gregor 2006; Gregor and Hevner 2013).

Regarding *implementing smart service systems* (Section II.3), research articles #4 and #5 take two different perspectives and provide knowledge on how to transform organizations to realize smart service systems. Research article #4 takes an IS perspective and develops a framework with relevant IS capabilities to use digital technologies in the Industry 4.0 context. Research article #5 complements this view by taking a business model perspective and mappings required capabilities to distinct types of business models in a maturity model. A major limitation of both articles lies in their descriptive nature. Both treat the identified capabilities separately and do not elaborate on their interplay. This interconnection, however, is key in understanding and effectively developing necessary capabilities. Further research needs to shed light on cause-and-effect relationships among capabilities. This knowledge is crucial for strategies on capability development and when taking long-term decisions about which capabilities to keep (and develop) in-house.

Further, both articles keep their capability definitions and descriptions on a rather abstract level to ensure broad applicability. Future research could adapt the developed models to specific industries and products to specify the identified capabilities and complement missing ones. Both models were applied for demonstration in two different manufacturing companies. Applying them with a methodologically sound approach and at more manufacturing organizations would however enrich insights on capability development and related challenges. Practitioners would benefit from detailed descriptions on how to use the model and from derived insights with general applicability.

Beyond the limitations of the individual research articles, there are of course also overarching limitations and research gaps on the topic of smart service systems, which provide suggestions for future research. To name one concrete subject, the systematic development of smart service systems displays an under-researched and highly important topic. Missing methods and tools for the systematic developments of smart service systems still hinder progress and realization in practice. For instance, the lack of methods on how to innovate and design smart service systems makes it difficult for practitioners approaching the topic. Although first publications adapt existing and established innovation concepts to the domain of smart service systems, as for example, the smart service canvas (Poeppelbuss and Durst 2019), an overall approach is missing. For instance, future research could adapt existing innovation processes to the development of smart service systems or even develop new concepts and approaches for this purpose. In addition, insights from successful and unsuccessful innovation projects for smart service systems would enable an exchange of experience and provide the opportunity to learn from. Conducting case study research in a structured approach, as for example Yin (2009) proposes, displays a promising step to take. Due to the growing importance of designing smart service systems, researchers as well as practitioners would greatly contribute to the analysis and knowledge transfer.

In sum, the ability to understand, develop and implement smart service systems will gain further importance. It has been my intention and it is my hope that this thesis supports researchers and practitioners by providing novel perspectives on smart service systems.

IV. Publication Bibliography

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V. Appendix

1 Index of Research Articles

Research Article #1: Conceptualizing smartness – results from analyzing leading information systems literature

Huber R, Lockl J, Röglinger M, Weidlich R. Conceptualizing Smartness – Results from Analyzing Leading Information Systems Literature. Submitted to (1st revision on-going): Schmalenbach Journal of Business Research.

(VHB-JQ3: Category B)

Research Article #2: Structuring digital transformation: A framework of action fields and its application at ZEISS

Gimpel H, Hosseini S, Huber R, Röglinger M, Probst L, Faisst U (2018). Structuring digital transformation: A framework of action fields and its application at ZEISS. Journal of Information Technology Theory and Application, 19(1): 31-54.

(VHB-JQ3: Category C)

Research Article #3: Capturing smart service systems: Development of a domain-specific modeling language

Huber R, Püschel L, Röglinger M (2019). Capturing smart service systems: Development of a domain-specific modeling language. In: Information Systems Journal, 29(6): 1207-1255

(VHB-JQ3: Category A; listed in the Senior Scholars' Basket of Journals of the Association for Information Systems)

Research Article #4: Disentangling capabilities for Industry 4.0 - an information systems capability perspective

Huber R, Oberländer A, Faisst U, Röglinger M. Disentangling capabilities for Industry 4.0 - an Information Systems capability perspective. Submitted to: Information Systems Frontiers.

(VHB-JQ3: Category B)

Research Article #5: A product-service system maturity model for manufacturers – lessons learned from its application in the service department

Häckel B, Huber R, Stahl B, Stöter M, Faßl J, Motyka S, Berger T. A product-service system maturity model for manufacturers – lessons learned from its application in the service department. Submitted to (1st revision on-going): International Journal of Production Research. Earlier version published in: Proceedings of the 16th Conference on Wirtschaftsinformatik, Duisburg-Essen, Germany, 2021.

(VHB-JQ3: Category B)

2 Individual Contribution to the Research Articles

This dissertation is cumulative and consists of five research articles that comprise the main body of work. All articles were developed in teams with multiple co-authors. This section provides details on the respective research settings and highlights my individual contributions to each article.

Research article #1, which is part of Section II.1, was developed in a team of four authors. All co-authors jointly developed the article's basic concept and created the content. During the literature review, I was part of organizing, analyzing, and coding relevant publications, in particular for literature in the context of smart services and smart service systems. Further, I was centrally involved in developing the concept of a smart action based on the results of the literature review. In addition, I guided one co-author who was in an early stage of his academic career on how to derive parts of the conceptual model and how to write an academic paper. Overall, the authors made equal contributions to the content of the research article, and I was involved in each part of the project.

Research article #2, which is part of Section II.1., was developed with five co-authors. Four academic scholars and one, who served as digital transformation officer at ZEISS during the creation of this paper. I was centrally involved in conducting the literature review, which served to collect relevant domain knowledge on digital transformation and to identify relevant fields of action. In addition, I was involved in coding important findings found in the literature as well as from the interviews and workshops conducted with domain experts. Furthermore, I was involved in applying the framework at ZEISS to demonstrate a possible application and contribution to practice. The application was conducted based on extensive discussions with ZEISS' digital transformation officer.

Research article #3, which is part of Section II.2, was developed with two co-authors. I was involved in all steps of the research process. This involved the screening of domain literature, which served as the starting point to build up and extend domain knowledge on IoT, smart things, and smart service systems. I was centrally involved in the development of the domain-specific modeling language for smart service systems by developing concepts and modeling examples. Furthermore, I prepared and conducted expert interviews for evaluating the modeling language for smart service systems. I was also involved in the feature comparison of the developed modeling language against competing artefacts.

Research article #4, which is part of Section II.3, was developed with three co-authors. Two of them being academic scholars and one serving as Chief Technology Officer at Cognizant at that time. I was centrally involved in all steps of the research process, beginning with a review of domain literature to build on existing knowledge on Industry 4.0 capabilities. Further, I was involved in developing the capability framework based on the results of the literature review. For refining the framework and extending it with capabilities neglected in research, I was centrally involved in conducting interviews with domain experts in practice.

Research article #5, which is part of Section II.3, was developed with six co-authors. Three of them being academic scholars and the other ones working for Pfeiffer Vacuum at that time. The academic co-authors jointly developed the article's basic concept and created the content. This started with a review of relevant domain literature in context of PSS capabilities. Further, I was centrally involved in developing the maturity model for PSS capabilities based on the results of our literature review. In addition, I guided one co-author who was in an early stage of his academic career on how to derive parts of the conceptual model and how to write an academic paper. Further, together with all co-authors, I was involved in applying the maturity model at the service department of Pfeiffer Vacuum and for deriving insights from this application in practice.

3 Research Article #1: Conceptualizing smartness – results from analyzing leading information systems literature

Authors: Huber R, Lockl J, Röglinger M, Weidlich R.

Working Paper

Extended Abstract:

Over the last years, the term ‘smartness’ has entered widespread use in research and in daily life. It has emerged with and been used in various applications of the Internet of Things (IoT), such as smart factories and smart supply chains. In information systems (IS) research, the term has become increasingly important. Smartness appears in various contexts and forms, from descriptions of the intelligent use of resources (e.g., smart vehicle charging) to general characteristics (e.g., smart products) (Weber 2017). In the IS literature, smartness is often connected to recent IoT-related technological developments, building upon sensors, connectivity, information exchange, and data processing, as well as capabilities for inferring and reasoning (Velsberg et al. 2020; Alt et al. 2019). For example, Beverungen et al. (2019) define smart things as boundary objects interacting among customers and service providers, whereas Oberländer et al. (2018) define smart things as physical things equipped with own agency and human-like cognitive characteristics. However, rapid technological development and careless use of the term mean that, in IS research, a common understanding of smartness has not yet been established (Alter 2019). And while it is recognized that smartness encompasses more than the use of information technology, a unified conceptualization of how it is created also remains lacking. This lack of knowledge hampers scientific progress as well as clear-headed decision-making in industry. Our research project intends to fill this gap by answering the following research question: *What is smartness and how does it manifest in IS research*?

To understand smartness in IS literature, we conducted a structured literature review for identifying and connecting concepts linked to smartness that repeatedly appear in IS research. We followed an approach, proposed by Wolfswinkel et al. (2013), to conceptualize smartness and its manifestations by using and combining Grounded Theory techniques on the base of a structured literature review. Thereby, we aim to develop a thorough and well-grounded analysis of smartness which reveals connections between related concepts and develops a clear concept of smartness itself. We found that smartness occurs through actions, in which smart things and individuals interact, process information, and make data-based decisions that are perceived as smart.

The contribution of this research project is manifold. First, we propose the concept of a 'smart action' and derive a general definition of smartness in the context of IS research. Further, our findings augment knowledge about how smartness is formed, offering a new perspective on smartness and providing a concept to describe and analyze interactions that take place in a smart action. The concept of a smart action will unify and increase understanding of 'smartness' in IS research. Also, our work and the conceptualization of a smarntess provides a theoretical lens to analyze smart actions in a structured manner. It rovides the required foundation for further theory-led research, such as theories for explanation and prediction as well as for design and action (Gregor 2006).

Keywords: smartness; smart action; smart thing; internet of things; digital technologies; literature review; grounded theory

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4 Research Article #2: Structuring digital transformation: A framework of action fields and its application at ZEISS

Authors: Gimpel H, Hosseini S, Huber R, Röglinger M, Probst L, Faisst U.

Published in: Journal of Information Technology Theory and Application, 2018, 19(1): 31-54.

Abstract: Digital products and services are an integral part of everyday life for both individuals and organizations. Further, given that digitalization greatly impacts our society and in particular how customer and organizations interact, organizations need to react to changing business rules and to leverage opportunities associated with digital technologies. Accordingly, the chief information officer (CIO) role is frequently a flexible one in the sense that it encompasses a much broader perspective on organizations than before. Most of the CIOs or newly appointed chief digital officers (CDOs) whom we interviewed in the course of our study recognized the need for change catalyzed by emerging digital technologies, but they typically lacked comprehensive knowledge on how to scope digital transformation initiatives. Against this background, we develop and validate a holistic framework of action fields for digital transformation. Our framework builds on extant literature and a series of exploratory interviews with over 50 organizations, and we have validated it in numerous contexts. In this paper, we present our framework and demonstrate its application at ZEISS, one of the organizations that participated in our study.

Keywords: digital transformation, digital strategy, digitalization, digital economy, framework

5 Research Article #3: Capturing smart service systems – development of a domain-specific modeling language

Authors: Huber R, Püschel LC, Röglinger M.

Published in: Information Systems Journal, 2019, 29(6): 1207-1255.

Abstract: Over the last years, the nature of service has changed owing to conceptual advances and developments in information technology. These developments have given rise to novel types of service and smart service systems (SSS), ie, resource configurations capable of learning, dynamic adaptation, and decision making. Currently, the internet of things (IoT) is turning physical objects into active smart things, bridging the gap between the physical and the digital world. Smart things advance SSS as they observe the physical environment, access local data, immerse into individuals' everyday lives and organizational routines. In line with the emergent nature of both phenomena, the impact of the IoT on SSS yet needs to be explored. Building the basis for explanatory and design-led research and for the analysis and design of SSS, a means for the conceptual modeling of SSS that accounts for novel IoT-enabled concepts is in high need. Hence, we designed, demonstrated, and evaluated a domain-specific modeling language (DSML) for SSS. We evaluated the DSML by using it in the modeling of real-world scenarios from all functional IoT domains, by submitting it to the scrutiny of industry experts, by discussing it against generic DSML requirements, and by analysing to what extent it meets domain-specific design objectives compared with competing artefacts. To demonstrate the DSML, we included a complex real-world scenario centred around the Nest Learning Thermostat.

Keywords: design science research, domain-specific modeling language, internet of things, service science, smart service systems

6 Research Article #4: Disentangling capabilities for Industry 4.0 - an information systems capability perspective

Authors: Huber R, Oberländer AM, Faisst U, Röglinger M.

Working Paper

Extended Abstract:

Technological leaps have always had the power to affect entire industries implying paradigm shifts. Indeed, leaps in technology have led to industrial revolutions with enormous ramifications for production methods, value chains, and social structures (Baines et al., 2017). Within the last decade, digital technologies such as cloud computing, the Internet of Things, and artificial intelligence have brought our physical and digital worlds into close contact, so much so that they have triggered the fourth industrial revolution – also known as Industry 4.0 (Weking et al., 2020). Products are now increasingly complemented with digital services, which changes how manufacturers invent, create, and deliver products and services.

Despite its enormous potential, only a minority of manufacturers, and even less among small- and medium-sized ones, have successfully realised Industry 4.0 technologies, applications, or digital product solutions (Moeuf et al. 2020). Realising the potential of Industry 4.0 requires manufacturers to transform themselves and to complement their strengths in manufacturing-related core capabilities by novel information systems (IS) capabilities (Baines et al. 2017). Significant challenges in this regard stem from a lack of overview and understanding regarding the IS capabilities required for their Industry 4.0 transformations (Ghobakhloo 2018). However, such a holistic capability overview is a crucial foundation for long-sighted decisions regarding organisational, management, and employee development. Hence, our research seeks to answer the research question: *Which IS capabilities do manufacturers need to realise Industry 4.0?*

To answer this question, we iteratively developed and evaluated a conceptual framework for the IS capabilities that manufacturers need to make the most of Industry 4.0. The resulting IS capability framework for Industry 4.0 is strengthened by thorough theoretical research, having first been developed in line with a structured literature review that took special note of Wolfswinkel et al. (2013). To further evaluate the framework on its relevance, clarity, and complementary capabilities that had yet to be considered in the literature, we conducted 10 semi-structured interviews with a range of experts at work in academia and industry. As for the

framework's practical use, we demonstrate a possible application of the framework with a German manufacturer of metal and tube processing solutions.

Our work contributes a theoretically well-founded and practically relevant IS capability framework for Industry 4.0. Although there is substantial work and knowledge on Industry 4.0, the framework is novel as it provides a range of requisite capabilities by taking an overdue IS perspective on Industry 4.0. Second, by evaluating and iteratively developing this framework in consultation with a diverse panel of senior industry executives, we were able to complement capabilities neglected by research so far and also ensure a high practical value of the framework. Third, its modular nature makes it a suitable foundation for further theorising on Industry 4.0, which will aid anyone wishing to understand, for instance, the dependencies of capabilities and derive design actions for manufacturers to guide their Industry 4.0 transformations (Gregor 2006). Fourth, this framework supports practitioners not only in recognising and comprehending all of the relevant IS capabilities for their Industry 4.0 transformations. It also supports them in assessing and developing the necessary IS capabilities and guides them through the vagaries of transforming their organisation.

Keywords: industry 4.0, fourth industrial revolution, information systems capabilities, capability framework

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7 Research Article #5: A product-service system maturity model for manufacturers – lessons learned from its application in the service department

Authors: Häckel B, Huber R, Stahl B, Stöter M, Faßl J, Motyka S, Berger T.

Working Paper

Extended Abstract:

Technological leaps, such as the current emergence of digital technologies, possess the immense power to trigger industrial revolutions that reverberate through entire industries, creating seismic shifts in value chains and product propositions. In manufacturing, the embedding of physical products with computing logic and internet connection has led to connected products capable of learning – a major technological breakthrough (Zheng et al. 2020). This development in manufacturing has opened up new opportunities in value creation and propositions. Chief among these new opportunities is the design of new business models, as manufacturers are upgrading their physical products with digital services to develop integrated product-service systems (PSS) (Ardolino et al. 2018). As data-driven business models, the essence of which is to deliver the product and its use or performance, PSSs allow manufacturers to differentiate themselves from competitors and enter new partnerships (Tukker and Tischner 2017).

Any PSS-driven business model, however, requires the whole organisation to adapt. Many manufacturers find it particularly challenging to identify and develop the new capabilities as well as the different configurations of capabilities necessary to deploy certain PSS types (Lund and Karlsen 2020). While the 'why' often appears straightforward, the 'how' remains unclear. Particularly for product-centric manufacturers, PSS-transformation is an ambitious goal and requires a comprehensive mapping of current capabilities along with a concrete definition of a target state. To support product manufacturers as they transform into a certain PSS type, we aim to answer the following research question: *Which capabilities do manufacturers require to offer a certain type of PSS?*

The identification, prioritisation, and development of these required capabilities is best conducted with reference to so-called maturity models (MMs). Therefore, we have developed the PSS Maturity Model (PSSMM). When developing this PSSMM, we followed the example of Becker et al. (2009) as well as a well-established design approach in the field of MMs (e.g., Schumacher et al. 2016; Wagire et al. 2020). The PSSMM provides an integrated view with five focus areas, 20 capability dimensions, and further associated capabilities. Further, the PSSMM has been

applied in the service department of a manufacturer of vacuum pumps, where valuable lessons were learned.

The PSSMM makes two main contributions to the field, one theoretical and one practical. The theoretical contribution is that the structure of the PSSMM integrates well-established PSS types with an overarching perspective that covers all of our capability dimensions. As a result, we provide relevant PSS capabilities in the interconnection of PSS types along with a comprehensive organisational perspective, which takes account of the interdisciplinary and holistic nature of this work. As for the practical contribution, we provide manufacturers with an applicable model to capture the status quo as well as the target state. By way of this model, we also offer guidance throughout the far-reaching PSS-transformation.

Keywords: product-service systems, maturity model, industry, PSS-transformation, organisational capabilities

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