Products and Processes in the Age of the Internet of Things

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„Es wäre heute nicht so, wie es ist, wäre es damals nicht gewesen, wie es war.“

Casper, 2011

My Family

Abstract

Digital technologies influence the everyday lives of individuals, organizations, and society in a variety of ways. One emerging digital technology that has been the subject of much debate in recent years is the Internet of Things (IoT). In the IoT, originally physical objects are equipped with sensors, actors, computing logic, and communication technology. These technology-equipped physical objects, also referred to as smart things, build the nucleus of the IoT. Beyond their role as nucleus of the IoT, smart things can also form product systems, consisting of closely interacting smart things, as well IoT ecosystems, consisting of interacting product systems. The diversity of application fields of the IoT, e.g., Smart City, Smart Mobility, Smart Health, Smart Home, and Smart Factory, provides organizations with a wide range of opportunities. In particular, the IoT affects two elements crucial to an organization's survival in competitive markets: products and processes. Due to the high potential of the IoT, this doctoral thesis shows how the IoT influences products and processes separately as well as products and processes within an integrated view simultaneously.

By connecting the physical with the digital world, the IoT can broaden the range of a product's functions, e.g., by enabling new digital service offerings. Thus, new products emerge and established products can be further developed. Based on the potential to address customer needs through innovative products, organizations have to decide which smart thing characteristics should be considered by their products in the future (research article #1 and #2). Extending the results of research article #1, research article #2 proposes two classification schemes for smart things, each involving different levels of detail, i.e., a taxonomy of individual smart things and related smart thing clusters. These classification schemes can support organizations, for example, in the development process of smart products. Beyond their influence on products, digital technologies such as the IoT affect business processes along the entire value chain of an organization. However, organizations are still struggling to digitalize business processes and face high levels of uncertainty when determining which technologies they should adopt in order to improve their business processes. To reduce this uncertainty, research article #3 presents a method that guides organizations step-by-step through the identification and selection of digital technologies best suited for improving their business processes. Crucially, the IoT can also affect products and process simultaneously. Based on their fundamental characteristics, smart things can serve as boundary object between customers and organizations, resulting in innovative forms of customer-company and company-company interactions. These innovative inter-

actions lead to changes in the participants' processes and value propositions. In response, research article #4 presents a domain-specific modeling language that includes all relevant actors – e.g., customers, organizations, and smart things – for designing IoT scenarios with innovative value propositions from a process-oriented and structural view. Research article #5 is thematically linked to research article #4, providing an economic decision model that helps manufacturing organizations to determine and select an optimal sequence of IoT projects with the aim of incorporating IoT technology into the organization's products, processes, and infrastructure. In particular, the economic feasibility of IoT scenarios in the manufacturing context which were developed with the domain-specific modeling language (research article #4) can be evaluated using the decision model.

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I. Introduction[1]

Digital technologies, also known as SMAC technologies (i.e., Social, Mobile, Analytics, and Cloud), have led to profound changes in our private and professional lives (Bharadwaj et al. 2013; Borgia 2014; Legner et al. 2017). One digital technology that has received considerable attention in recent years is the Internet of Things (IoT). The IoT involves physical objects equipped with sensors, actuators, computing logic, which are able to communicate via the Internet (Oberländer et al. 2018; Porter and Heppelmann 2014; Rosemann 2013; Yoo et al. 2012). These physical objects, usually referred to as smart things, are the nucleus of the IoT and connect the physical with the digital world (Borgia 2014).

The IoT can be assigned to the third wave of IT that have changed business and society (Legner et al. 2017; Porter and Heppelmann 2014). The first wave replaced physical mediums, such as paper, by automating the processing of data and led to a higher productivity in work processes (Legner et al. 2017; Porter and Millar 1985). The second wave, influenced by the emergence of the Internet, enabled new types of business models and value propositions by connecting companies with each other and with customers in a new way. While the first two waves of IT primarily affected the collaboration between companies (e.g., in supply chains), the third wave is changing the nature of products by embedding IT, such as sensors, actuators, computing components, and connectivity, into products (Uckelmann et al. 2011). Equipping products with digital capabilities is a fundamental characteristic of digitalization in general and the IoT in particular (Porter and Heppelmann 2014; Rosemann 2013). The technical preconditions that enable smart things to form the nucleus of the IoT are miniaturization, increased processing power, affordable and reliable storage capacity, and communication bandwidth (Legner et al. 2017; Yoo et al. 2010).

As a fast-moving, global megatrend, digitalization transforms value networks across all industries and presents organizations with many challenges (Collin 2015). When it comes to digital technologies in general and to the IoT in particular, many organizations are uncertain as to which technologies have the potential to enhance their processes, products, services, and business models (Legner et al. 2017). Despite the prevailing uncertainty, the IoT holds enormous potential for organizations. Digital technologies such as the IoT make it possible for internal processes to be handled more efficiently (i.e., they have a positive impact on quality, flexibility,

[1] This Section is partly comprised of content taken from the research articles included in this thesis. To improve the readability of the text, I omit the standard labeling of these citations.

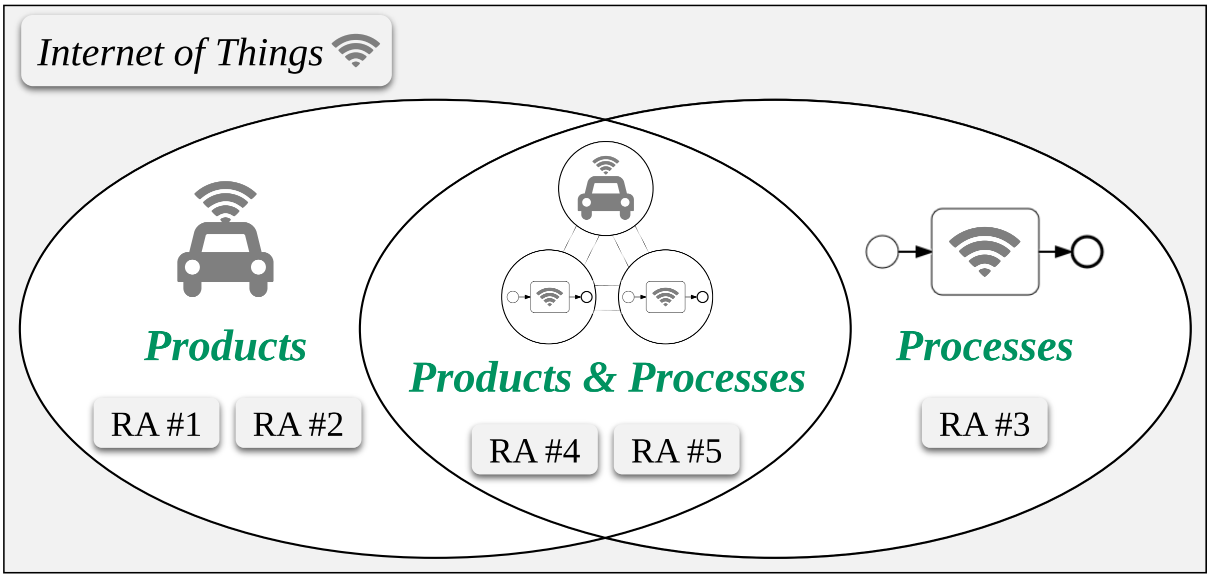
throughput times, and costs) and allow the development of entirely new business models, products, and services (Gimpel et al. 2018; Legner et al. 2017). By 2015, IoT market spending amounted to USD 690 billion and could reach USD 11.3 trillion by 2025 (IDC 2019; Johansson et al. 2019). Unsurprisingly, consulting and market research organizations attribute an enormous economic value to the IoT, which was also ranked as an important trend in the Gartner Hype Cycle for five years in a row (Gartner 2017; Panetta 2018). The IoT's potential is evident in the diversity of its possible application fields, e.g., Smart City, Smart Mobility, Smart Health, Smart Home, and Smart Factory (Borgia 2014). Due to its high potential in different applications fields, an in-depth understanding of the IoT is a necessary prerequisite. In particular, products (i.e., and related services) which form part of the business model as well as processes are essential elements for organizations to survive in competitive markets (Gimpel and Röglinger 2017). How *products* and *processes* are influenced by the IoT will be motivated in the following.

Innovative technologies such as the IoT have led to the integration of information technologies in many *products* (e.g., to enable new service offerings). New products and digital services emerge and existing products and related services are complemented and/or enriched by digital technologies such as the IoT (Legner et al. 2017). As a result, offering digital services in addition to a physical product is increasingly becoming a prerequisite for market entry in many industries (Fleisch et al. 2015; Porter and Heppelmann 2014; Yoo et al. 2012). Due to these technological developments, customers demand ever more integrated, convenient, and individual solutions (Gimpel et al. 2018). In a 2019 study by the Harvey Nash Group and KPMG, over 3,600 participating organizations estimate that, within the next three years, "*44% of organizations are undergoing some kind of major digital change that will fundamentally impact their organization. This is either through introducing new products and services that will be equal to or more dominant than existing ones (38%) or – more radically – fundamentally changing their business model, for instance moving from selling products to selling services (6%). A further 41% of organizations will be introducing new products and services to supplement existing ones*" (Harvey Nash Group and KPMG 2019). In a study involving over 50 organizations, Gimpel et al. (2018) found that smart products and services are understood to hold huge potential to enrich companies' value propositions. Based on the potential of the IoT, organizations have now to decide how the IoT should be used to enrich already existing products or to develop entirely new products (Porter and Heppelmann 2014).

Process orientation as an important paradigm with the goal of designing and redesigning organizations' internal operations (Recker and Mendling 2016) is also affected by digital technologies such as the IoT (Legner et al. 2017). Business Process Management (BPM), which is the underlying management discipline of process orientation, focuses on two overarching topics: business processes improvement and BPM capability development (vom Brocke and Rosemann 2015). *Process* improvement (i.e., the improvement of organizations' business, support, and management processes), in particular, has long been recognized as an important topic and continues to be a top priority topic for process managers (Harmon and Wolf 2016). The 2019 study by the Harvey Nash Group and KPMG confirms that improving businesses processes is still ranked as number two of the top five priorities by company boards (Harvey Nash Group and KPMG 2019). Common goals of process improvement are reduced costs and throughput times, and increased flexibility, quality, and process innovation (Dumas et al. 2018b). The digitalization has an ever-increasing influence on the processes of established organizations, leading to significant changes in their existing work routines (Lasi et al. 2014; Legner et al. 2017). Companies in many industries are still trying to increase the automation and digitalization of their business processes (Legner et al. 2017; Matt et al. 2015). Nevertheless, due to the current lack of in-depth knowledge, organizations are still struggling to identify which digital technologies they should adopt in order improve their business processes (HBRAS 2015; Legner et al. 2017).

In addition to the individual design and redesign of products and processes, *products* and *process* can be influenced simultaneously by the IoT. The fundamental characteristics of smart things, such as sensors, actuators, computing logic, and the ability to communicate via the Internet (Fleisch et al. 2015), enable the (remote) integration of different actors, such as customers and organizations, with the goal of creating value for both sides in an innovative way (Beverungen et al. 2017). For example, in a business-to-customer (B2C) context, a smart thing can integrate a customer, who uses the device, and an organization, which can use the device in order to provide its knowledge and skills. Thereby, the integration changes the customer's behavior (i.e., its processes) and the organization's processes. In addition, smart things not only integrate customers and organizations. In a business-to-business (B2B) context, for example, they can also integrate organizations with the aim of building so-called product systems, consisting of interacting smart things, and IoT ecosystems, consisting of interconnected product systems. Similar to the B2C context, the integration of organizations leads to changes in operations within and among participating organizations (Legner et al. 2017; Porter and Heppelmann 2015; Beverungen et al. 2017). In a hospital, for example, an interconnected inventory management system can order new drugs from a supplier when the current stock falls below a defined threshold. In this case, staff need no longer assess stock levels, create order forms, or contact suppliers. Nest's Learning Thermostat provides another example. Nest's Thermostat uses weather data from third-party suppliers in order to optimize energy consumption in a household (Google 2019a, 2019b). To engage in this system, the supplier of weather data has to ensure that its own processes enable the provision of weather data. A third example is that of connected smart factories. Here, the production of a smart product with different manufacturing stages in different organizations can be coordinated autonomously by the machines involved and by the smart product itself. Prerequisite is a shift from rigid production lines toward flexible and connected production networks. These examples show, beside the individual influence on products and processes, the IoT can affect products and processes of an organization simultaneously. As a result, in the age of the IoT, products and processes must be viewed as more integrated than before.

Figure 1: Assignment of the Research Articles to the Structure of the Doctoral Thesis



RA = Research Article

This cumulative doctoral thesis consists of five research articles. As this thesis deals with key issues related to the Internet of Thing, it is relevant for researchers and practitioners alike. Figure 1 shows how the individual research articles are assigned to the overarching topics of *products* and *processes*, as well as to the integrated perspective of both *products and processes*. This structure can also be found in Section II, which is outlined in the following.

The age of the IoT has seen a shift in the nature of products towards smart products – namely, smart things. Thus, an in-depth understanding of smart things as the nucleus of the IoT is a prerequisite to tap the full potential of the IoT (i.e., in research or practice). This thesis firstly provides two classification schemes involving different levels of detail (i.e., a taxonomy of smart things and related smart thing clusters) developed in order to support organizations in, for example, the development of smart products (Section II.1 – including research articles #1 and #2). Secondly, this thesis enables a process-oriented view by addressing a method providing guidance how organizations can optimally exploit the digitalization potential of their business processes (Section II.2 – including research article #3). Thirdly, as the IoT can affect both simultaneously, integrated approaches to products and processes are becoming increasingly important. Thus, this thesis proposes a domain-specific modeling language that allows users to analyze and design the introduction of smart things and their impact on underlying processes. In addition, this thesis provides an economic decision model for evaluating the economic feasibility of introducing smart things and the associated adaptation of the underlying processes (Section II.3 – including research articles #4 and #5). In Section III, this doctoral thesis is summarized once again, followed by a preview on future research. Section IV comprises all references included in this doctoral thesis. Section V (Appendix) includes additional information on all research articles (V.1), my individual contribution to these articles (V.2), and the research articles themselves (V.3 - V.7).

II. Overview and Context of the Research Articles[2]

1. The Nature of Smart Things

While, in earlier times, products consisted of purely mechanical, mechanical and electrical, or mechanical and electronical components, nowadays, many products are physical objects combined with digital technologies such as sensors, actors, data storage, and computing logic, and have the ability to communicate via the Internet (Oberländer et al. 2018; Porter and Heppelmann 2014; Rosemann 2013; Yoo et al. 2012). These *"smart connected products"* (Porter and Heppelmann 2014) – also referred as to smart things – form the nucleus of the IoT. Equipped with digital technologies, smart things enable the connectivity of the physical with the digital world (Borgia 2014; Porter and Heppelmann 2014; Rosemann 2013). The connection of the physical with the digital world extends the range of product functions and changes the role of the service of a product towards a digital service which in turn enables innovative value propositions. As a result, smart things enable established organizations to better-differentiate their products from those of competitors (Porter and Heppelmann 2014; Legner et al. 2017). The influence of the IoT can already be observed in the product development process (i.e., multi-perspective engineering involving mechanical and software engineers), because it leads to a change in how new products are designed (Fichman et al. 2014; Porter and Heppelmann 2014). Due to the potential of the IoT, organizations have to decide which smart thing characteristics should be addressed by new products or be incorporated into existing products to address customers' needs in a new way (Fichman et al. 2014; Porter and Heppelmann 2014).

Despite the need for detail insights into smart things in supporting organizations with profound knowledge (e.g., for product development), the academic literature has failed to provide appropriate works until now. The literature has discussed the IoT from multiple perspectives. For example, Atzori et al. (2010), Kortuem et al. (2010), J. LaBuda and Gillespie (2017), and Laya et al. (2014) all focus their work on technical fundamentals and needs. Other authors set the focus on a business-to-business (B2B) perspective, where the IoT is primarily used in logistic and supply-chain processes (Geerts and O'Leary 2014; Witkowski 2017). The IoT has also been discussed from a business-to-consumer (B2C) perspective, e.g., addressing challenges and opportunities for business models in the age of the IoT (Bucherer and Uckelmann 2011; Dijkman et al. 2015; Ju et al. 2016; Porter and Heppelmann 2014; Rosemann 2013; Turber et

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al. 2014). In line with the B2C perspective, Oberländer et al. (2018) examined how individual smart things extend classical B2C interactions, leading to innovative business-to-thing (B2T) interactions and related innovative value propositions. The work of Oberländer et al. (2018) is complemented by Beverungen et al. (2017) who show that smart things integrate organizations and customers in their role as boundary objects.

While the individual contribution of these works is undisputable, smart things are nevertheless treated as a black box in all of these works. Only Barker et al. (2014), Dorsemaine et al. (2015) and Mountrouidou et al. (2019) examine smart things in detail, but focus on technical details. As smart things have a variety of different characteristics in reality – ranging from smart pill boxes to smart learning cameras (Borgia 2014; Porter and Heppelmann 2014; Oberländer et al. 2018), a detailed understanding of these characteristics beyond technical details is a necessary prerequisite for organizations to tap the full potential of the IoT. In order to provide a better understanding of smart things, research article #1 and research article #2 examine the individual smart thing as the nucleus of the IoT. As research article #2 is an extension of research article #1 and represents more recent results, only article #2 is discussed here. The results of research article #2 are twofold: Firstly, in order to capture the nature of an individual smart thing, a taxonomy based on the method by Nickerson et al. (2013) has been developed. Taxonomies are classification approaches consisting of dimensions and related characteristics, which help to understand, describe, analyze, and classify objects of interest (i.e., smart things as the nucleus of the IoT) (Miller and Roth 1994; Nickerson et al. 2013). The development and validation of the taxonomy were based on the latest insights from the IoT literature and on a sample of 200 smart things chosen from all important IoT application fields across the B2C domain. Secondly, based on the classified sample of 200 smart things, a hierarchical cluster analysis was conducted in order to identify which combinations of smart thing characteristics typically occur together (Everitt et al. 2010; Ferreira and Hitchcock 2009; Fraley and Raftery 2002; Kaufman and Rousseeuw 2009). To confirm robustness, clarity, and meaningfulness, the identified clusters were evaluated using the Q-Sort. The Q-Sort is a statistical approach used to evaluate the validity and reliability between two or more judges (Carter et al. 2007; Fleiss 1971; Nahm et al. 2002; Oberländer et al. 2018; Rajesh et al. 2011; Stephenson 1935; Thomas and Watson 2002). In the following, the taxonomy and related smart thing clusters are described in more detail.

The taxonomy of individual smart things (Figure 2) consists of eleven dimensions, each featuring between two and four characteristics. Dimensions and the related characteristics are structured in four layers, giving overarching form to the taxonomy. Thereby, each dimension (i.e., the related characteristics) can be nominal (i.e., there is no natural order) or ordinal (i.e., there is a natural order) scaled and can be exclusive (i.e., if exactly one characteristic applies) or non-exclusive (i.e., if more than one characteristic applies). The layers are based on established IoT (technology) stacks, which can be found in the works of Fleisch et al. (2015), Porter and Heppelmann (2014), and Yoo et al. (2012). Although there are differences in the detail of these works (i.e., in the structuring and labeling), the layers of IoT stacks are largely identical. The taxonomy proposed in research article #2 based on the following layers: *thing*, *interaction*, *data*, and *service layer*.

Figure 2: Multi-layer Taxonomy of Smart Things

						Dimension Properties	
	Dimension	**Characteristics**				**Scale**	**Exclusivity**
Service	**Ecosystem Integration**	None	Proprietary	Open		Ordinal	ME
	Value Proposition	Thing-centric	Service-centric			Nominal	ME
	Offline Functionality	None	Limited			Nominal	ME
Data	**Data Usage**	Transactional	Analytical (basic)	Analytical (extended)		Ordinal	ME
	Data Source	Thing State	Thing Context	Thing Usage	Cloud	Nominal	NE
Interaction	**Partner**	User(s)	Business(es)	Thing(s)		Nominal	NE
	Multiplicity	One-to-one	One-to-many			Nominal	ME
	Direction	Unidirectional	Bi-directional			Nominal	ME
Thing	**Autonomy**	None	Self-Controlled	Self-Learning		Ordinal	ME
	Acting Capabilities	Own	Intermediary			Nominal	NE
	Sensing Capabilities	Lean	Rich			Ordinal	ME

ME: Mutually exclusive NE: Non-exclusive

On the *thing layer*, being the bottom-most layer, the purely physical thing is transformed into a smart thing by equipping with *sensing* (i.e., ability to collect *lean* or *rich* data about the environment) and *acting* capabilities (i.e., the ability to influence the environment via *own* or *intermediary* actors) (Borgia 2014; Rijsdijk and Hultink 2009). It is also on the thing layer that the smart thing's *autonomy* (i.e., its ability to act in a *self-controlled* or *self-learning* manner) is considered. The *interaction layer* allows for smart things to be embedded into the digital world (e.g., enabled by a connection to the Internet). Thereby, a smart thing can remotely interact with and be remotely accessed by other *partners* (i.e., *users*, *business*, and *smart things*) (Beverungen et al. 2017; Bucherer and Uckelmann 2011). The interaction layer also takes account of the number of interactions in which a smart thing is simultaneously engaged (Oberländer et al. 2018; Porter and Heppelmann 2014). Described as *multiplicity*, the engagement of a smart thing can be distinguished into *one* and *many* (Oberländer et al. 2018; Suchman 2009). The interaction layer also covers the *direction* of the smart thing's interaction, described by a *unidirectional* or *bidirectional* flow of data. The next layer, the *data* layer, describes whether the *data source* of a smart thing is internal (i.e., *thing state*) or external (i.e., *context*, *usage*, *cloud*), and how data is used by a smart thing (i.e., *transactional*, *analytical basic,* or *analytical extended*) (Borgia 2014; Porter and Heppelmann 2015).

The top-most layer, the service layer, refers to the service a smart thing can provide. Here, o*ffline functionality* determines whether a smart thing can provide *no* or *limited* service without an internet connection. As smart things comprise of a physical object combined with a digital service, the *value proposition* of a smart thing can be *thing-centric* (i.e., main purpose is found in the physical function of the thing, which is merely enhanced by a digital service) or *service-centric* (i.e., the smart thing cannot be used independently from its related digital service). The term *value proposition* is central to this thesis and is defined here in line with the service literature. Based on the smart thing's fundamental characteristics to bridge the physical with the digital world, the physical object is inseparable connect with a digital service. The related service literature defines value propositions as mutual invitations from actors to engage in a service. Thus, to realize a service in the age of the IoT (i.e., a digital service), at least two actors (e.g., an organization represented by a smart thing and a customer) have to accept their invitation and are then connected by their value proposition to realize the digital service (Beverungen et al. 2018; Beverungen et al. 2017; Chandler and Lusch 2015; Lusch and Vargo 2014). Further to this, a smart thing's ability to integrate in broader contexts, such as ecosystems, can be distinguished in *none* (i.e., not able to integrate in an ecosystem), *proprietary* (i.e., compatible with smart things from the same provider) and *open* (i.e., compatible with smart things from other providers) (Mattern and Flörkemeier 2010; Oliva and Kallenberg 2003; Porter and Heppelmann 2014; Velamuri et al. 2011).

Based on the classification of 200 smart things, a hierarchical cluster analysis was conducted and five clusters were identified. Each cluster presents a group of smart thing characteristics that typically occur together. By applying cluster analysis, two main groups according to the smart thing's value proposition could be identified (i.e., whether a smart thing has a thing- or service-centric related purpose). Within these two main groups, further sub-groups could be identified based on the smart thing's increasing level of smartness, as represented by dimensions such as autonomy, data usage, and ecosystem integration. The first main group with a thing-centric purpose includes *Standalone Thing-Centric Executants* and *Connected Thing-*

Centric Performer. The second main group with a service-centric purpose includes *Standalone Service-Centric Monitors*, *Connected Service-Centric Performers*, and *Self-Learning Service-Centric All-rounders*. Figure 3 gives a detailed overview of the characteristics of the different groups.

Figure 3: Composition of the Five Smart Thing Clusters

		Cluster				
		Standalone Thing-Centric Executant	**Connected Thing-Centric Performer**	**Standalone Service-Centric Monitor**	**Connected Service-Centric Partner**	**Self-Learning Service-Centric All-rounder**
		38	40	51	32	39
		19%	20%	26%	16%	20%
Service	**Ecosystem Integration**	None [34] (90%)	Open [20] (50%)	None [47] (92%)	Open [23] (72%)	Open [21] (54%)
	Value Proposition	Thing-centric [35] (92%)	Thing-centric [39] (98%)	Service-centric [41] (80%)	Service-centric [32] (100%)	Service-centric [38] (97%)
	Offline Functionality	Limited [36] (95%)	Limited [38] (95%)	None [47] (92%)	None [32] (100%)	None [38] (97%)
Data	**Data Usage**	Analytical (basic) [27] (71%)	Transactional [18] (45%) Analytical (basic) [18] (45%)	Analytical (basic) [35] (69%)	Transactional [17] (53%) Analytical (basic) [11] (34%)	Analytical (ex-tended) [22] (56%)
	Data Source	Thing context [19] (50%) Thing Usage [32] (84%)	Thing State [16] (40%) Thing context [31] (78%)	Thing context [24] (47%) Thing Usage [39] (77%)	Thing context [22] (69%) Thing Usage [17] (53%)	Thing context [21] (54%) Thing Usage [36] (92%) Cloud [15] (39%)
Interaction	**Partner**	User(s) [38] (100%)	User(s) [39] (98%) Thing(s) [17] (43%)	User(s) [50] (98%)	User(s) [31] (97%) Thing(s) [23] (72%)	User(s) [39] (100%) Thing(s) [19] (49%)
	Multiplicity	One-to-one [37] (97%)	One-to-many [38] (95%)	One-to-one [30] (59%)	One-to-many [28] (88%)	One-to-many [33] (85%)
	Direction	Unidirectional [22] (58%)	Bi-directional [23] (58%)	Unidirectional [35] (69%)	Unidirectional [22] (69%)	Bi-directional [34] (87%)
Thing	**Autonomy**	None [23] (61%)	Self-Controlled [21] (53%)	None [28] (55%)	Self-Controlled [17] (53%)	Self-Learning [16] (41%)
	Acting Capabilities	Own [26] (68%) Intermediary [38] (100%)	Own [37] (93%) Intermediary [37] (93%)	Intermediary [51] (100%)	Own [17] (53%) Intermediary [30] (94%)	Own [36] (92%) Intermediary [38] (97%)
	Sensing Capabilities	Lean [33] (87%)	Lean [33] (83%)	Lean [36] (71%)	Lean [31] (97%)	Rich [35] (90%)

[…]: total number of smart things (…): relative number of smart things

Both the taxonomy of individual smart things and the smart thing clusters emphasize that smart things should not be treated as a black box. This new understanding of smart things facilitates the adoption and affordance of smart things in further settings, and provides a basis for the use of smart things in broader contexts such as IoT ecosystems. In addition, practitioners might leverage the results in, for example, product development processes. In this case, the clusters would provide an initial understanding of common types of smart products available on the market. The taxonomy could then be used to discuss in more detail the fundamental characteristics a smart product should address. In addition to the influence they have on products, digital technologies such as the IoT also influence processes along the value chain of an organization which, in turn, offers a high potential for improving the effectiveness and efficiency of business processes.

2. Exploiting the Digitalization Potential of Business Processes

Digitalization, as an emerging topic, influences the design and redesign of business processes across an organization's entire value chain (i.e., business, support, and management processes) (Matt et al. 2015; Porter and Heppelmann 2015). By bridging the gap between the physical and the digital world, digital technologies in general – and the IoT in particular – enable new opportunities in the field of business process improvement, for example, providing innovative ways to gather data, increase process efficiency, and process automation (e.g., autonomous execution of individual tasks up to entire processes) (Del Giudice 2016; Janiesch et al. 2017). Nevertheless, organizations are still struggling with both the digitalization and automation of their business processes, and remain highly uncertain as to which digital technologies hold the potential to improve their business processes (Ackx 2014; Legner et al. 2017). Due to the high potential for improving business processes on the one hand and the prevailing uncertainty of organizations when it comes to the selection of digital technologies on the other, a profound knowledge that guides organizations in exploiting the digitalization potential of their business processes is in high need.

The existing literature provides a huge variety of approaches aiming to improve business processes (Dumas et al. 2018b; van der Aalst 2013; Vanwersch et al. 2016). For example, some works consolidate the diverse ideas of process improvement in so-called process enhancement or process redesign patterns (Dumas et al. 2018c; Limam Mansar and Reijers 2007; Recker and Mendling 2016). Other works focus on approaches which prioritize process improvement projects which are evaluated in terms of their influence on process performance (Darmani and Hanafizadeh 2013; Limam Mansar et al. 2009; Linhart et al. 2015; Ohlsson et al. 2014). In addition, there are holistic approaches, such as frameworks, which provide organizations with methods for generating improvement ideas along different decision dimensions (Vanwersch et al. 2016). Although these works represent a significant contribution to the knowledge of business process improvement, they fail to link the fields of business process improvement and digitalization. To connect these fields, research article #3 of this doctoral thesis proposes a method which guides organizations in evaluating which digital technologies they should consider in order to exploit the digitalization potential of their business processes. Thereby, research article #3 goes beyond the evaluation of IoT technologies (e.g., smart things), and enables organizations to identify and select digital technologies independently of a particular type of digital technology. To support the selection of digital technologies, a method based on the action design research (ADR) (Gregor and Hevner 2013; Rijsdijk and Hultink 2009; Sein et al.

2011) and the situational method engineering (SME) approach has been developed (Braun et al. 2005; Vanwersch et al. 2016). In line with ADR, the method has been co-developed with, and continually evaluated by, five organizations along two design cycles (i.e., first cycle with five and second cycle with three organizations).

The method (Table 1) consists of five elements (E), namely: activities (i.e., E.1 – tasks with the goal of creating outputs), techniques (i.e., E.2 – instructions for the execution of an activity), tools (i.e., E.3 – to support the execution of a related activity), roles (i.e., E.4 – actors executing or involved in the execution of an activity) and a distinct output (i.e., E.5 – output such as the documentation of an activity) (Braun et al. 2005; Vanwersch et al. 2016). The method comprises four activities, each including techniques, tools, roles and a distinct output. Each of the activities is briefly described in the following: In activity one, the focus is on the selection and modeling of a process whose digitalization potential has to be exploited. Thereby, the method targets intra-organizational core and support process. After modeling the process, sub-processes are prioritized to provide an order of sub-processes (output of activity one). In activity two, suitable digital technologies are linked with related sub-processes. Firstly, digital technologies and related sub-processes are preselected (medium list) according to potential knock-out criteria (e.g., sub-process does not have digitalization potential, digital technology is too expensive). Secondly, the remaining digital technologies are prioritized depending on their potential to support the remaining sub-processes. The output of activity two is a shortlist of the most suitable digital technologies. In activity three, further evaluation perspectives important for the final assessment of the digital technologies are prioritized. The further evaluation perspectives comprise fundamental process perspectives (e.g., information, product, and customer), goals (e.g., operational performance and strategic fit), and risks (i.e., during the implementation and use of digital technologies) (Chapman and Ward 2003; Limam Mansar et al. 2009). The output of activity three is an assessment of further evaluation perspectives. In activity four, which is based on all of the previous results, the selected digital technologies undergo a final assessment involving the further evaluation perspectives. The output of activity four is a final list of the prioritized digital technologies that are best suited to support the selected business process.

Table 1: Overview Method for Exploiting the Digitalization Potential of Business Processes

Activity (E.1)	Technique (E.2)	Tool (E.3)	Role (E.4)	Output (E.5)
Activity 1: Selection and modelling of business process	- Select and model business process of interest - Focus on behavioral process perspective and include end-to-end perspective - Determine relative importance of sub-processes	- Established business process modelling language (e.g., BPMN) - Evaluation matrix for pairwise comparison of sub-processes based on a rating scale (i.e., AHP scale)	- Process owner - Selected process participants - BPM expert (if available and necessary)	- Process model structured into weighted sub-processes
Activity 2: Preselection of suitable digital technologies	- Select digital technologies appropriate for process in focus (medium list) - Determine extent to which these technologies can support sub-processes - Choose digital technologies with highest potential for the process in focus (shortlist)	- Evaluation matrix for assessment of digital technologies based on a rating scale (i.e., AHP scale)	- Process owner - Selected process participants - Technology experts	- Shortlist of digital technologies suitable to support the process from a behavioral perspective
Activity 3: Inclusion of further evaluation perspectives	- Consider further evaluation perspectives (i.e., other process perspectives, goals, risks) and related criteria - Determine the relative importance of criteria for the organization in focus	- Hierarchical decomposition of further evaluation perspectives - Evaluation matrix for pairwise comparison of perspectives and criteria based on a rating scale (i.e., AHP scale)	- Process owner - (Senior) Management - Business Development	- Assessment of further evaluation perspectives that complement the behavioral process perspective
Activity 4: Final assessment of digital technologies	- Consider shortlisted digital technologies in detail - Assess how these technologies influence the defined criteria - Identify digital technologies that perform best across all evaluation perspectives	- Evaluation matrix for assessment of preselected digital technologies based on a rating scale (i.e., AHP scale)	- Process owner - Selected process participants - (Senior) Management - Business Development	- Final ranking that represents the prioritized shortlist of preselected digital technologies

The proposed method aims to reduce organizations' uncertainty when it comes to the evaluation of digital technologies. A detailed description of activities and further related elements (i.e., techniques, tools, roles and a distinct output) guides organizations through an evaluation of digital technologies in order to reveal those best suited to improving specific business processes. As mentioned above, in addition to the individual design and redesign of products and processes, products and processes can be simultaneously influenced by the IoT. The fact that smart products can remotely integrate different actors (i.e., customers and organizations) leads to innovative types of interactions between the actors involved. The innovative interactions in turn influence the processes of the actors involved.

3. Integrated View of Products and Processes in the Age of the Internet of Things

Enabled by its fundamental characteristics (i.e., sensors, actuators, computing logic, and the ability to communicate via the Internet) (Fleisch et al. 2015), smart things become a new class of actors who can act autonomously and replace traditional customer-organization relationships by acting as autonomous intermediary between customers and organizations (Oberländer et al. 2018). By assuming the role as intermediary or more precisely as boundary object, smart things integrate customers and organizations remotely with the goal of creating value for both sides (i.e., results in the emergence of innovative value propositions) (Beverungen et al. 2017; Nicolescu et al. 2018). Thereby, the integration leads to innovative types of customer-organization-relationships which in turn leads to changes in the processes of the actors involved. For example, in a B2C context, by integrating customers (i.e., using the smart thing changes user behavior) and organizations (i.e., providing knowledge and skills via the smart thing can require an alignment of the underlying processes), the smart thing can change the behavior and the processes of the actors involved (Gimpel and Röglinger 2017; Legner et al. 2017; Porter and Heppelmann 2014, 2015). Beside this, smart things can also integrate, e.g., in a B2B context, organizations among each other with the aim of building so-called product systems, consisting of interacting smart things, and IoT ecosystems or systems of systems, consisting of interconnected product systems. This new form of interconnected systems involves the interplay of value propositions which lead to innovative services and exceed the value propositions of individual organizations. Yet, in order to engage in such interconnected systems, organizations may need to (re-) align their processes (Porter and Heppelmann 2014).

In the age of the IoT, it is therefore increasingly important for organizations to take an integrated view of products and processes. In order to address this topic, research articles #4 and #5 suggest ways in which organizations can be supported in the introduction of smart things and the possible (re-) alignment of the underlying processes. Research article #4 provides a domain-specific modeling language that involves all relevant actors (e.g., customers, organizations, and smart things) for analyzing and designing IoT scenarios (e.g., in B2C and B2B contexts) from a process-oriented and structural view. Research article #5 is thematically linked to research article #4 in that it presents an economic decision model which helps manufacturing organizations to determine an optimal sequence of IoT projects with the aim of incorporating IoT technology into their products, processes, and/or infrastructure. For example, the decision model can be used to evaluate the economic feasibility of an IoT scenario developed using the modeling language from research article #4. In order to evaluate a certain IoT scenario, firstly, a pool of potential IoT project candidates have to be determined. Secondly, by applying the economic decision model to the project candidates, appropriate IoT projects can be selected and their optimal sequence scheduled.

Thanks to their ability to integrate various actors (e.g., customers, organizations, and smart things), smart things are a prerequisite for building complex interaction relationships, such as IoT ecosystems, which are enabled by interconnected product systems or so-called smart service systems (SSS). Thereby, SSS can be defined as dynamic resource configurations that include people, organizations, information, and smart things capable of learning, dynamic adaptation, and decision-making. By interacting with other SSS, SSS can create innovative services (Beverungen et al. 2017; Lim and Maglio 2018; Medina-Borja 2015; Wuenderlich et al. 2015). However, smart things in broader contexts such as IoT ecosystems respectively SSS have so far received little academic attention. The IoT literature is instead focused on definitions of SSS (Beverungen et al. 2017; Lim and Maglio 2018), the role of individual smart things (Beverungen et al. 2017; Püschel et al. 2016), and smart thing relationships based on simple interactions (Oberländer et al. 2018). Further, the literature provides modeling approaches with reference to the IoT, however, these approaches either focus on technical details or are limited to a distinct domain (Christoulakis and Thramboulidis 2016; De et al. 2011; Meyer et al. 2019; Xu et al. 2012). The literature also provides a huge number of approaches to service modeling (Alter 2012; Becker et al. 2010; Cardoso 2013; Cardoso et al. 2013; OMG 2015; Razo-Zapata et al. 2015). However, there remains an absence of work linking the literature on the IoT with an appropriate approach for representing SSS. Research article #4 therefore responds to this absence, proposing a domain-specific modeling language (DSML) for analyzing and designing SSS. The DSML draws on the literature on service science and the IoT as justificatory knowledge. To develop the DSML, the design science research approach (Gregor and Hevner 2013; Peffers et al. 2007) was combined with the domain-specific modeling language engineering method (Frank 2013). The result of this development process is an abstract – i.e., semi-formal – metamodel for describing how to build a conceptual model (Eriksson et al. 2013) and a concrete syntax – i.e., textual and graphical notational elements for representing diagrams (Mannadiar 2010). The DSML has been evaluated by modeling fictitious and real-world examples, interviewing domain experts, and conducting a competing artefact analysis and its discussion along different design objectives.

The purpose of the DSML is to enable the modeling of SSS and innovative services, both of which are influenced by the IoT (Beverungen et al. 2017; Lim and Maglio 2018; Porter and Heppelmann 2014; Maglio et al. 2009). To enable the modeling of SSS, the DSML consists of four overarching components: *resources*, *relationships*, *service systems*, and *service*. *Resources* can be divided into *individuals*, *smart things*, *digital hubs*, and the *physical environment*. Individuals are humans and can be further distinguished into *active* and *passive* individuals. Active individuals directly participate in a service (e.g., by using a smart camera to surveil the own house), while passive individuals indirectly participate (e.g., benefiting from a smart thermostat that regulates the temperature for all residents) (Alter 2008, 2012; Böhmann et al. 2014; Maglio and Spohrer 2008). Smart things can take on the role as boundary object with the goal of integrating different service systems (Beverungen et al. 2017). Thereby, smart things can be further distinguished into *self-dependent* and *dependent* smart things. Self-dependent smart things can act autonomously in a goal-oriented way without external intervention and, in some cases, without external triggers. These actions are enabled by extended data analysis (i.e., diagnostic, predictive, or prescriptive) or self-x functions (e.g., self-learning or self-optimizing). Dependent smart things, on the other hand, require external triggers for every task and have only basic data analysis (i.e., descriptive) and self-x functions (e.g., self-controlled). The same distinction holds for digital hubs. However, unlike smart things, digital hubs exist only in the digital world (i.e., they are software components and have no representation in the real world) (Batool and Niazi 2017; Beverungen et al. 2017; National Science Foundation 2014). In terms of ecosystem integration, already introduced in Section II.1, both smart things and digital hubs can be *proprietary*, i.e., compatible with the same provider, or *open*, i.e., compatible with foreign providers (Püschel et al. 2016). The *physical environment* has a passive role compared to other resources. Smart things and individuals have the ability to observe the physical environment's properties (e.g., temperature) (Borgia 2014).

Resources are interconnected through *relationships*. Relationships can be distinguished into *interactions*, *parameterizations*, and *observations*. *Interactions* enable the exchange between resources, and occur, for example, when data is exchanged, functions are triggered, or events are reported (Oberländer et al. 2018; Suchman 2009). *Parametrization* refers to all relationships wherein one resource determines the goals of another resource so that one resource commits itself to achieve the agreed goal (Encarnação and Kirste 2005). Only individuals, self-dependent smart things, and self-dependent digital hubs can parametrize other resources. *Observation* refers to the collection of data (e.g., information about the properties of an object such as movements), for example, by the integrated sensors of a smart thing (Perera et al. 2014; Streitz et al. 2005). In the context of SSS, smart things and individuals can observe the properties of other resources. As digital hubs do not have a physical representation, they can neither observe or be observed.

Service systems can be classified as *smart service systems* (SSS) and *service systems*. *SSS* must include a self-dependent smart thing, whereas *service systems* exclude self-dependent smart things (i.e., are dynamic resource configurations that include, for example, people, organizations, information, and dependent smart things). SSS and service systems can be further distinguished into *atomic (smart) service systems* and *composed (smart) service systems*. Atomic service systems are, e.g., individuals, self-dependent digital hubs, dependent digital hubs, or dependent smart things, whereas atomic SSS are represented by an individual self-dependent smart thing (Oberländer et al. 2018). Composed service systems are service systems that include at least one further service system. The same holds for composed SSS, i.e., a composed SSS contains at least one further SSS or service system (Maglio et al. 2009; Nielsen et al. 2015). The interaction of (smart) service systems, connected by their value propositions (i.e., as introduced in Section II.1), leads to the creation of a service that benefits all of the actors involved.

The DSML and its components are briefly demonstrated using the example of the so-called *Coming Home Service*. The Coming Home Service is designed to regulate the temperature of a smart home via *Nest's learning thermostat* when the house owner is entering or leaving a predefined area around the house in his smart car. To realize the Coming Home Service, the house owner defines a simple recipe, i.e., sequence of commands based on the web-platform IFTTT (If This Then That). To visualize and describe the Coming Home Service, the DSML provide two views: a *structural* and a *behavioral view*. Figure 4 shows the *structural view*, also called *service system model*, visualizing, for example, which (smart) service systems contribute to the service, which resources are grouped in which service systems, how (smart) service systems and resources interact via a distinct relationship or which smart things act as boundary object. Figure 5 shows the *behavioral view* (i.e., process-oriented view), also called the *service description model*, adding a textual description to the structural view with the purpose of describing the process of service creation.

Figure 4: Integrated Service System Model with Highlights for the Coming Home Service

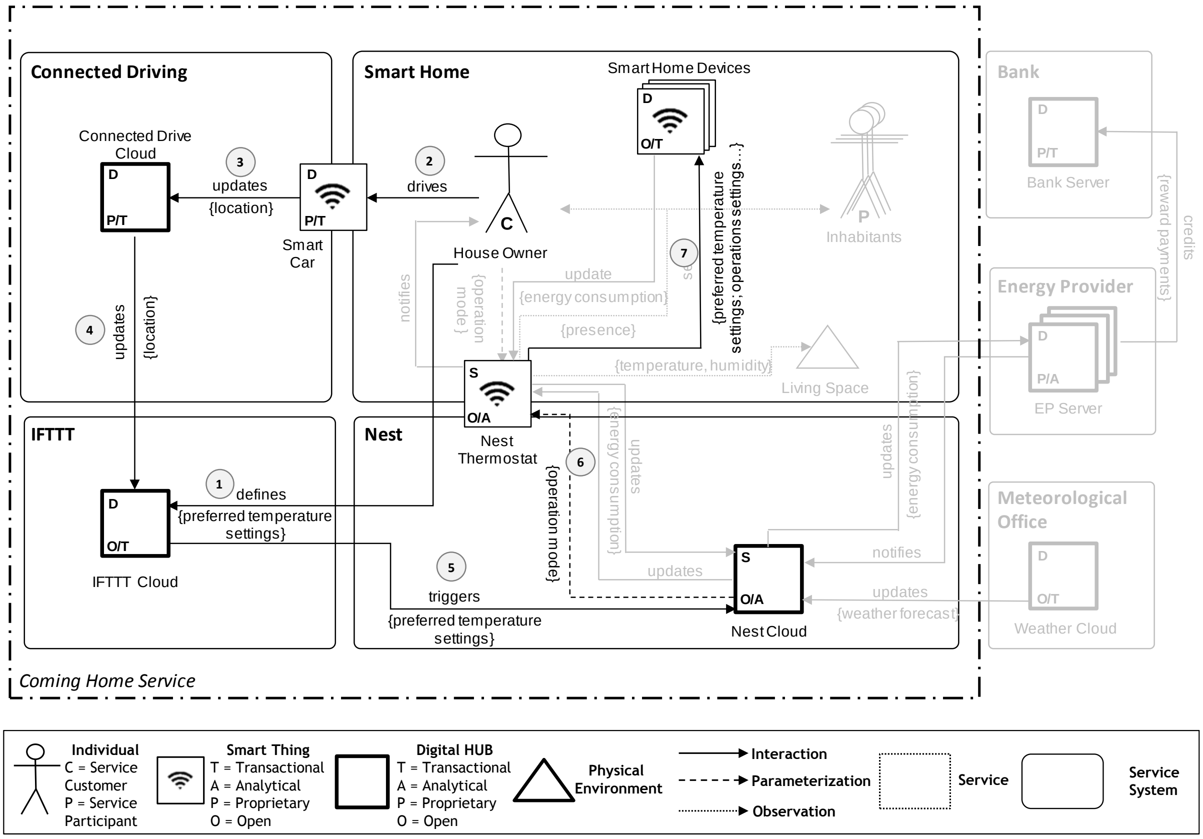


Figure 5: Service Description Model for the Coming Home Service

Coming Home Service

Involved Service Systems (top level): Connected Driving, IFTTT, Smart Home, Nest

Purpose: Smart home gets set to preferred temperature settings when house owner is leaving a predefined area with his car.

Service Description:

(1) House Owner *defines* recipe with preferred temperature settings on the IFTTT Cloud

(2) House Owner *drives* Smart Car

(3) Smart Car uses its <u>self-observation function</u> to track its location and *updates* Connected Drive Cloud regarding location property

(4) Connected Drive Cloud *updates* IFTTT Cloud regarding location property

(5) IFTTT Cloud *triggers* Nest Cloud based on predefined recipe with preferred temperature settings when predefined location limitation is reached

(6) Nest Cloud *parameterizes* Nest Thermostat to new operation mode {preferred temperature settings,….}

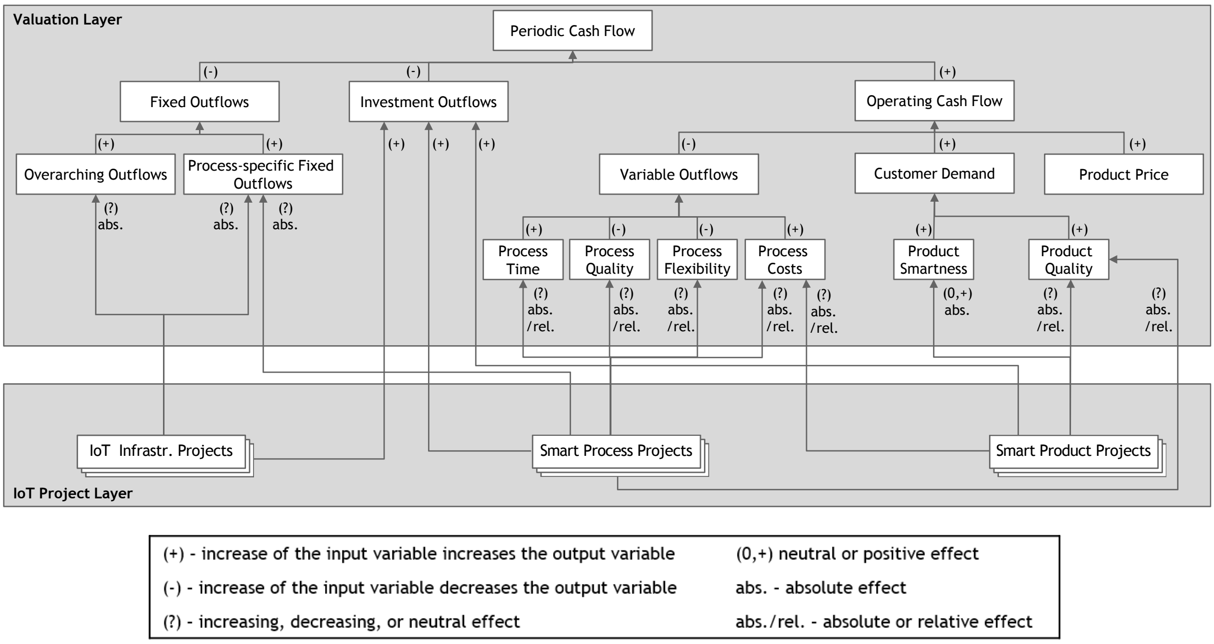
(7) Nest Thermostat dynamically adapts its operations settings and *sets* Smart Home Devices to reach the preferred temperature

The Coming Home Service, visualized and described in Figure 4 and Figure 5, shows that a smart thing in its role as a boundary object can integrate different actors such as customers, organizations, or smart things. Thereby, the actors are grouped in (smart) service systems. Each (smart) service system provides a value proposition whose interplay with the value propositions of other (smart) service systems enables the Coming Home Service. Furthermore, as the example shows, the integration of smart things can lead to entirely new processes for both organizations and customers. For example, in the case of Nest: By providing smart things (Nest Thermostat) and digital hubs (Nest Cloud) as a new class of actors, an entirely new process has emerged for Nest. Thereby, Nest only represents a part of the process, and it is only the interconnection of all relevant (smart) service systems which enables the Coming Home Service to function effectively.

Organizations may be interested in evaluations of the economic feasibility of IoT scenarios developed using the DSML from research article #4. Research article #5 picks up this topic by supporting organizations in this decision process. However, most of the IoT literature focuses on describing the impact of the IoT on products, processes, and business models (Boos et al. 2013; Bucherer and Uckelmann 2011; Fleisch et al. 2015; Porter and Heppelmann 2014). Very few works focus on an economic perspective regarding the IoT (Lee and Lee 2015). Hence, research article #5 provides an economic decision model to assess which IoT investments (i.e., IoT projects) lead to the largest increase in the long-term firm value of an organization. Thereby, research article #5 focuses on manufacturing companies. By determining an optimal sequence of IoT projects, the decision model indicates whether it is a product, process, and/or infrastructure project that an organization should execute next. The decision model builds on value-based management (VBM) (i.e., value contributions to a company's long-term firm value are used for control purposes) (Buhl et al. 2011; Rappaport 1986; vom Brocke and Sonnenberg 2015) and project portfolio selection (PPS) (i.e., determining an optimal project portfolio) (Archer and Ghasemzadeh 1999) as justificatory knowledge. In order to develop the decision model, the design science research approach was applied (Gregor and Hevner 2013). The evaluation was conducted in line with the evaluation framework by Sonnenberg and vom Brocke (2012) (i.e., deriving design objectives, feature comparisons and expert interviews, demonstrations using a prototype).

As illustrated in Figure 6, the economic decision model is structured on two layers: a valuation layer and an IoT project layer. The purpose of the *valuation layer* is to transform the effects of IoT projects into value which contributes to the long-term firm value. This value contribution (i.e., represented by the periodic cash flow) consists of three overarching factors: *investment outflows*, *fixed outflows*, and *operating cash flows*. Investment outflows occur when implementing projects. Fixed outflows consist of process-specific outflows (i.e., outflows linked to a production process) and overarching outflows (i.e., outflows which not linked to a specific process, but which affect the whole organization such as maintenance costs for information systems). Operating outflows result from variable outflows (i.e., outflows refer to the execution of a production process), the product price, and the related customer demand for a product (Fähnle et al. 2018; Lehnert et al. 2016). The *IoT project layer* comprises the IoT project types, namely, *smart product projects*, *smart process projects*, and *IoT infrastructure projects*. Smart product projects aim to equip products with IoT technology in order to enhance the product's smartness and quality, both of which influence customer demand (Anderson et al. 1994; Fähnle et al. 2018). Smart product projects also lead to investment outflows and costs incurred during the production. By incorporating IoT technology into a process, smart process projects improve the production process in terms of predefined performance criteria (i.e., time, quality, flexibility, costs) (Dumas et al. 2018a; Fähnle et al. 2018). In addition, smart process projects enhance the product quality on the one hand and cause process-specific fixed outflows and investment outflows (e.g., for the initial equipment of production machines) on the other. IoT infrastructure projects provide the infrastructure necessary to enable smart product and smart process projects. IoT infrastructure projects influence both types of fixed outflows and can lead to investment outflows (Fähnle et al. 2018).

Figure 6: Economic Decision Model for Determining Value Contribution of IoT Projects



The economic decision model supports different types of constraints derived from the PPS (e.g., project exclusiveness, interdependencies, and precedence constraints) and BPM literature (e.g., critical time, quality, and flexibility boundaries). Furthermore, the decision model supports constraints relating to product smartness (e.g., a maximum possible product smartness, minimum product quality, and maximum supply capacity) (Lehnert et al. 2016; Liu and Wang

2011; Perez and Gomez 2016). Based on these constraints, the decision model determines the project portfolio with the highest value contribution within different scenarios (e.g., mandatory projects, budget constraints). Thereby, each project portfolio represents a sequence of different projects. The portfolio that fulfills the relevant constraints and offers the highest value contribution should be selected (Fähnle et al. 2018). A possible sequence of projects is described in the following: An organization would like to further develop an existing product, turning into a smart product equipped with sensors, actuators, connectivity, and data analytics. To realize this, a smart product project must be carried out. To produce the new smart product, the organization must ensure that the production process features the appropriate technological capabilities. Further, the process must be economically viable (e.g., in terms of the costs, time, and quality of process execution). A prerequisite is the execution of a smart process project. In order to provide a digital service, the organization must ensure that appropriate underlying infrastructure is in operation (e.g., a cloud infrastructure operated by an external provider). A prerequisite is the execution of an IoT infrastructure project. This example shows, introducing a smart thing, for example as a new product, may require an (re-) alignment of the underlying processes and infrastructure. As several project candidates have the potential to realize a certain IoT scenario, organizations have to identify those IoT projects which lead to the largest increase in the long-term firm value.

In sum, this doctoral thesis reveals how the IoT influences products and processes both individually and simultaneously. With the potential to extend the functionality of products, it becomes increasingly important for organizations to decide which smart thing characteristics their products should feature in order to fulfill customer needs. Furthermore, digital technologies in general and the IoT in particular have the potential to improve the effectiveness and efficiency of business processes. Despite prevailing uncertainty when it comes to the selection of digital technologies, the potential for process improvement outweighs possible challenges. Furthermore, the IoT can influence products and processes simultaneously. The introduction of smart things as a new class of actors leads to new forms of interactions between customers and organizations, and organizations among one another. On one hand, the introduction of smart things has enormous potential to enable innovative value propositions. On the other hand, the introduction of smart things can be associated with efforts for organizations, as underlying processes may need to be (re-) aligned. In Section III, this doctoral thesis concludes with a short summary and provides an outlook on future research.

III. Summary and Future Research[3]

1. Summary

Digital technologies continue to have a significant impact on our private and professional lives. One emerging technology that provides a huge potential in various application fields is the Internet of Things (IoT). Equipped with sensors, actors, computing logic, and communication technology, physical objects are transformed into so-called smart things which form the nucleus of the IoT. Due to its potential in a variety of application fields, the IoT is particularly interesting for organizations. Thereby, two elements of organizations that ensure surviving in competitive markets are influenced by the IoT: namely, products and processes. Consequently, this doctoral thesis examines how the IoT influences products and processes individually and products and processes simultaneously. Firstly, the thesis comes in response to the rise of the IoT and the ongoing transformation of many regular products into smart things. This change means that organizations must now decide which smart thing characteristics should be incorporated into products of the future in order to address customer needs. Secondly, this thesis addresses the fact that, despite a prevailing uncertainty about digitalization, organizations must evaluate which digital technologies – e.g., the IoT – improve the effectiveness and efficiency of their business processes. Thirdly, as the IoT can also influence products and processes simultaneously, this thesis show how organizations can analyze and design which innovative value propositions are enabled by smart things (e.g., in a broader contexts such as IoT ecosystems) and how underlying processes are influenced by the introduction of smart things.

Smart things beyond technical details have been treated by the academic literature as black box so far. However, a thorough understanding of smart things is a prerequisite to tap the full potential of the IoT (e.g., in a development process of smart products, their role in broader contexts such as IoT ecosystems). In order to provide such an understanding, section II.1 examines the change from physical objects to smart things. For this purpose, research article #2 comes as an extension of research article #1 and investigates individual smart things by proposing two classification schemes with different levels of detail, i.e., a taxonomy of smart things and related smart thing clusters. The taxonomy captures the nature of an individual smart thing and its various characteristics. Based on characteristics which typically occur together, the smart

[3] This Section is partly comprised of content taken from the research articles included in this thesis. To improve the readability of the text, I omit the standard labeling of these citations.

thing clusters represent common types of smart things available on the market. Thereby, taxonomy and smart thing clusters facilitate the adoption of smart things in further settings and lay the foundation for future investigations of the role of smart things in broader contexts such as IoT ecosystems. Furthermore, practitioners can use the taxonomy and clusters in different stages of product development processes.

As organizations are still uncertain when it comes to the digitalization of their business processes, and because the literature has so far failed to provide appropriate suggestions, Section II.2 examines how organizations can be helped to decide which digital technologies they should adopt in order to exploit the digitalization potential of their business processes. Research article #3 address the topic by proposing a method to guide organizations step-by-step through the identification and selection of suitable digital technologies to improve the effectiveness and efficiency of their business processes. Thereby, research article #3 helps organizations to identify and select from a wide variety of digital technologies beyond the IoT.

Based on their fundamental characteristics, smart things can serve as boundary objects with the goal of integrating either customers and organizations or organizations with one another. The introduction of smart things leads to new types of interactions which, in turn, enable innovative value propositions. Simultaneously, the introduction of smart things can lead to changes in the involved actors' processes. To address this topic, Section II.3 sets the focus on an integrated view of products and processes in the age of the IoT. Research articles #4 and #5 propose how organizations can be supported when introducing smart things and (re-) aligning related processes. Research article #4 proposes a domain-specific modeling language (DSML) that includes all relevant actors for analyzing and designing IoT scenarios in different contexts. Thereby, it becomes obvious to organizations which smart things should be considered, for example, to participate in IoT ecosystems, and how the underlying processes are influenced. Research article #5 picks up the topic, providing an economic decision model that helps manufacturing organizations to determine the optimal sequence of IoT projects (i.e., smart product, smart process, and IoT infrastructure projects) with the goal of incorporating IoT technology into an organization's products, processes, and/or infrastructure. Further, the economic decision model can be used to determine the economic feasibility of IoT scenarios which have been developed with the DSML from research article #4.

2. Future Research

As with any research project, the articles included in this doctoral thesis are subject to some limitations. Section II.1 discusses how, in the age of the IoT, ordinary physical products transform towards smart products or so-called smart things. However, as the academic literature has largely treated smart things as black box, a clearer, more detailed understanding of individual smart things is needed. To this end, research article #2 provides two classification schemes – i.e., a taxonomy of smart things and related smart thing clusters – which provide detailed insights into individual smart things. Nevertheless, the results have some limitations. Firstly, the taxonomy is based on a sample from the B2C domain which represents only a specific time period. Therefore, the taxonomy should be applied in other contexts such as the B2B domain (i.e., the industrial IoT). As the digitalization is a rapidly-evolving domain, the characteristics of smart things may be influenced by the development of other digital technologies such as Artificial Intelligence or Blockchain. Lastly, as the taxonomy and clusters focus on individual smart things, future research should examine the role of smart things in broader contexts (i.e., IoT ecosystems), as well as their adoption and affordance in other settings.

In addition to their impact on products, digital technologies (e.g., the IoT) influence processes along the value chain of organizations. Therefore, Section II.2 investigates how organizations can be helped to determine which digital technologies are suitable for exploiting the digitalization potential of their business processes. However, the method proposed by research article #3 has the following limitations: Firstly, as the academic literature has failed to provide an accepted definition of digital technologies, the proposed method from research article #3 could also be applied to non-digital technologies. As a result, the method will need to be re-evaluated against an accepted definition of digital technologies. Secondly, the evaluation of the method involved only a small number of cases, future research should therefore carry out subsequent evaluations involving additional cases. As the method has been developed with a focus on individual processes, in the future it should be applied to the entire process-architecture of an organization, as well as to value networks. Further, the method's focus on the improvement of individual business processes addresses only an exploitative mode. However, to tap the full potential of digitalization, the method should be further developed towards an explorative mode, i.e., focus on the investigation of new business models and value propositions.

As the introduction of smart things can affect the processes of the actors involved, Section II.3 takes an integrated view of products and processes. To address this topic, research article #4 proposes a DSML for analyzing and designing IoT scenarios. The fact that the IoT is a fast-moving domain means that updates to the DSML will be required, particularly with regard to the featured concepts (e.g., actors, relationships, and related attributes, as well as notional elements). In addition, and in order to ensure the real-world fidelity of the DSML, the evaluation activities should be extended to include further contexts and settings. The primary goal of the DSML is to provide relevant concepts for modeling IoT scenarios, however, in order to guide organizations step-by-step through the modeling of IoT scenarios, the DSML should be further developed towards a method (see research article #3). Research article #5 proposed an economic decision model to help manufacturing organizations determine which IoT technology they should incorporate into their products, processes, and infrastructure, and in which sequence this should take place. In addition to the potential to enhance its real-world fidelity (e.g., stochastic instead of deterministic parameters, evaluation in further settings, application of software prototype to real-world data), the economic decision model would benefit from a transfer to further processes along the value chain as well as from a transfer to value networks or ecosystems. Currently, the decision model can be only applied to a single process in a manufacturing context.

In summary, this doctoral thesis has examined the influence of the IoT on products and processes individually and products and processes simultaneously. This work contributes to the descriptive knowledge by providing a taxonomy and related smart thing clusters (research articles #1 and #2), and a DSML for SSS modeling (research article #4). It also contributes to the prescriptive knowledge with a method for exploiting the digitalization potential of business processes (research article #3), and an economic decision model to support the evaluation of IoT projects (research article #5). Throughout, a shift from individual product and processes toward interconnected products and processes can be observed (i.e., in value networks and IoT ecosystems). While this doctoral thesis deals with the descriptive knowledge of products and processes in an interconnected context (i.e., research article #4), future research should focus on prescriptive knowledge of products and processes in an interconnected context (i.e., partly fulfilled by research articles #4 and #5).

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V. Appendix

1. Index of Research Articles

Research Article #1: What's in a Smart Thing? Development of a Multi-layer Taxonomy

Püschel LC, Schlott H, Röglinger M (2016) What's in a Smart Thing? Development of a Multi-layer Taxonomy. In: *Proceedings of the 37th International Conference on Information Systems*, Dublin, Ireland.

(VHB-JOURQUAL 3: Category A)

Research Article #2: Unblackboxing Smart Things - A Multi-Layer Taxonomy and Clusters of Smart Things

Püschel LC, Röglinger M, Brandt R (2019): Unblackboxing Smart Things - A Multi-Layer Taxonomy and Clusters of Smart Things. Submitted to: *IEEE Transactions on Engineering Management*.

(VHB-JOURQUAL 3: Category B)

Research Article #3: How to Exploit the Digitalization Potential of Business Processes

Denner MS, Püschel LC, Röglinger M (2018): How to Exploit the Digitalization Potential of Business Processes. In: *Business & Information System Engineering*.

(VHB-JOURQUAL 3: Category B)

Research Article #4: Capturing Smart Service Systems – Development of a Domain-specific Modeling Language

Rocco H, Püschel LC, Röglinger M (2019): Capturing Smart Service Systems – Development of a Domain-specific Modeling Language. Appears in: *Information Systems Journal*.

(VHB-JOURQUAL 3: Category A)

Research Article #5: Business Value of the IoT – A Project Portfolio Selection Approach

Fähnle A, Stohr A, Püschel LC, Röglinger M (2018): Business Value of the IoT – A Project Portfolio Selection Approach. In: *Proceedings of the 26th European Conference on Information Systems*, Portsmouth, England.

(VHB-JOURQUAL 3: Category B)

2. Individual Contribution to the Included Research Articles

This thesis is cumulative and consists of five research articles which build the main body of this work. All included research articles have been written in constellations with multiple researchers. Thus, in this Section, I will provide insights into the project constellations and my individual contribution to each of the research articles.

Research article #1 (Püschel et al. 2016), which is part of Section II.1, has been developed with two further co-authors. Based on an extensive literature review and a gathered real-world sample, I had a main role in developing the taxonomy of smart things and its dimensions and characteristics. In addition, I was highly involved in evaluating and applying the taxonomy in order to demonstrate its applicability and generality. I was involved in developing and reworking text sections throughout the article. As this article project was undertaken in the early stages of my PhD, the article benefitted significantly from the feedback of my doctoral supervisor Maximilian Röglinger. In sum, we jointly elaborated the article's content and I was substantially involved in each part of the project.

Research article #2 (Püschel et al. 2019), which is also part of Section II.1, has been written in a team of three co-authors. Research article #2 reworks and extends the main result of research article #1, after they have been presented at the International Conference in Information Systems (ICIS). I was the leading author who developed the main results, i.e., the further development of taxonomy and the derivation of smart thing clusters, of the article and was responsible for the content development. Further, I was mainly responsible for conducting an update of the literature throughout all sections. I was involved in the evaluation of the taxonomy as well as of the related smart thing clusters within the author team and with a team of academic researchers. Although the article and especially its revisions were, to a large extent, my own work, the other co-authors were involved in each part of the project, and helped discuss and improve the article.

Research article #3 (Denner et al. 2018), which is presented in Section II.2, was developed by a team of three co-authors. Based on an initial idea of one of the co-authors, the team jointly conceptualized and elaborated the article's structure and content. I was primarily responsible for developing the method for exploiting the digitalization potential of business processes. I was also responsible for evaluating the method in interviews with practitioners from different contexts. Further, I was involved in reworking text sections throughout the article. As this article project was undertaken in the early stages of my PhD, the article benefitted significantly from the feedback of my doctoral supervisor Maximilian Röglinger. Throughout, I was substantially involved in all parts of the project.

Research article #4 (Huber et al. 2019), which is part of Section II.3, was developed with two further co-authors. I was centrally involved in conducting the literature review, which served to collect relevant domain knowledge on the Internet of Things. Further, I was centrally involved in developing the domain-specific modeling language based on the results of our literature review. Furthermore, I was involved in evaluating the domain-specific modeling language based on modeling fictive and real-world examples, interviewing domain experts, as well as conducting a competing artefact analysis and its discussion along different design objectives. I was involved in developing and reworking text sections throughout the article.

Research article #5 (Fähnle et al. 2018), which is also part of Section II.3, was written by a team of four co-authors. This article was presented at the European Conference on Information Systems (ECIS) by a co-author and myself in Portsmouth, England. All co-authors jointly developed the basic concept for the article and elaborated the article's content. I had a main role in developing the decision model, which reflects the research objective of this project. I was involved in conceptualizing, developing, and reworking text sections throughout the article. In sum, we jointly elaborated the article's content and I was substantially involved in each part of the project.

3. Research Article #1: What's in a Smart Thing? Development of a Multi-Layer Taxonomy

Authors: Püschel LC, Röglinger M, Schlott H

Published in: Proceedings of the 37th International Conference on Information Systems, 2016

Abstract: Digital technologies immerse in our private lives and force businesses to rethink existing work practices. Among the emerging digital technologies, the Internet of Things (IoT) is attributed disruptive potential, as it refers to the equipment of physical things with sensor and communication technologies and to the integration of these things into the networked society. Until today, the IoT is low on theoretical insights. Most notably, smart things, which constitute a vital building block of the IoT and the foundation of IoT-based business models, have been neglected by academic research. Taking a smart thing's perspective, our study aims to complement extant work on the IoT. We offer a multi-layer taxonomy of smart things that comprises ten dimensions structured along the architectural layers of existing IoT stacks (i.e., the thing itself, interaction, data, and services). To evaluate our taxonomy, we used a sample of 50 real-life smart things from the B2C context.

Keywords: Internet of Things, Digital Technologies, Smart Things, Taxonomy

4. Research Article #2: Unblackboxing Smart Things - A Multi-Layer Taxonomy and Clusters of Smart Things

Authors: Püschel LC, Röglinger M, Brandt R

Extended Abstract (submitted working paper)[4]

The Internet of Things (IoT), which describes the equipment of physical objects with sensors, actuators, computing logic, and connectivity, has attracted much attention in recent years. Although many facets of the IoT are being explored, existing works either treat smart things as a black box or focus on technical characteristics. However, a profound understanding beyond technical details is key for tapping the potential of the IoT. Hence, we examined the following research question: What non-technical characteristics can be used to distinguish smart things?

To answer this question, we analyzed smart things on two granularity levels. On a fine-grained level, we developed a taxonomy (i.e., empirically and/or conceptually derived groupings in terms of dimensions and characteristics) that enables classifying individual smart things via dimensions and characteristics. On a coarse-grained level, we inferred smart thing clusters, each covering a typical combination of characteristics. To build and validate our taxonomy, we applied the taxonomy development method as per Nickerson et al. (2013) and used a sample of 200 smart things as well as the latest IoT literature. With Nickerson et al. (2013) recommending to build on and update existing taxonomies, we used Püschel et al. (2016) taxonomy as a starting point who had developed a preliminary smart thing taxonomy some years ago. The developed taxonomy of individual smart things consists of eleven dimensions, each featuring between two and four characteristics. Dimensions and the related characteristics are structured in four layers, giving overarching form to the taxonomy. Thereby, the taxonomy comprises the entire spectrum of characteristics by structuring smart things on the basis of four layers: *thing*, *interaction*, *data*, and *service layer*. After developing the taxonomy, two authors evaluated the taxonomy by independently classifying the sample of 200 smart things. The agreement of the authors was measured in terms of dimension- and object-specific hit rate. The related hit rates confirmed that the taxonomy is clear in terms of dimensions and characteristics.

[4] At the time of publication of this thesis, this paper is in the review process of a scientific journal. Thus, I provide an extended abstract that consists of the paper's content.

Based on our taxonomy, we aimed at understanding on a more coarse-grained level which characteristics of smart things typically occur together. While such a high granularity supports product development, it is too detailed for managerial purposes. Hence, we set out to identify smart things clusters by applying cluster analysis to the sample of 200 smart things according to the taxonomy. We used Ward's agglomerative algorithm and the Manhattan metric as distance measure, as both have proven useful in combination and fit our data. To determine the optimal number of clusters, we evaluated the different cluster solutions quantitatively (i.e., applying established indices to determine optimal number of clusters) and qualitatively (i.e., discussing each cluster solution in terms of their interpretability). Finally, we chose a five cluster solution, as each cluster could be reasonably interpreted standalone and in relation to the other clusters. To structure the clusters, we split them according to their value proposition, which was the first division performed by the cluster algorithm. We found that, in subsequent divisions, the clusters remained either thing- or service-centric. To evaluate the clusters, we applied the Q-sort, a statistical approach used to classify items (i.e., smart things as Q-set) in accordance with predefined constructs (i.e., the clusters) by two or more judges (P-set). The judges' agreement forms the basis for assessing reliability and validity. These results reflect substantial agreement.

The theoretical contribution of our work is twofold: First, we proposed a literature-backed and broadly validated taxonomy, which enables the in-depth classification of smart things. The dimensions of the taxonomy foster the taxonomy's understandability and to cover relevant perspectives on smart things from the physical product to digital services. Second, we inferred and validated five smart thing clusters based on the classified sample, each representing a typical combination of characteristics, which reduce the combinatorial diversity of smart things and provide high-level insights into the smart things currently on the market. The taxonomy and the clusters show that smart things should not be treated as black box but classified according to defined characteristics, as these characteristics determine in which scenarios smart things can be used. From a managerial perspective, the taxonomy and the clusters guide engineering managers specifically in early phases of the product development process (i.e., ideation of new product ideas), as they structure the design space of smart things ranging from a non-technical perspective on different granularity levels.

Keywords: Internet of Things, Digitalization, Smart Thing, Taxonomy, Cluster Analysis

References

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Püschel L, Schlott H, Röglinger M (2016) What's in a Smart Thing? Development of a Multi-layer Taxonomy. In: 37th International Conference on Information Systems (ICIS)

5. Research Article #3: How to Exploit the Digitalization Potential of Business Processes

Authors: Denner MS, Püschel LC, Röglinger M

Published in: Business & Information System Engineering, 2018, 60(4), 331–349

Abstract: Process improvement is the most value-adding activity in the business process management (BPM) lifecycle. Despite mature knowledge, many approaches have been criticized to lack guidance on how to put process improvement into practice. Given the variety of emerging digital technologies, organizations not only face a process improvement black box, but also high uncertainty regarding digital technologies. This paper thus proposes a method that supports organizations in exploiting the digitalization potential of their business processes. To achieve this, action design research and situational method engineering were adopted. Two design cycles involving practitioners (i.e., managers and BPM experts) and end-users (i.e., process owners and participants) were conducted. In the first cycle, the method's alpha version was evaluated by interviewing practitioners from five organizations. In the second cycle, the beta version was evaluated via real-world case studies. In this paper, detailed results of one case study, which was conducted at a semiconductor manufacturer, are included.

Keywords: Business Process Improvement, Business Process Management, Digital Transformation, Digital Technologies, Situational Method Engineering, Action Design Research

6. Research Article #4: Capturing Smart Service Systems – Development of a Domain-specific Modeling Language

Authors: Rocco H, Püschel LC, Röglinger M

Appears in: Information Systems Journal, 2019

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), i.e. 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 analyzing to what extent it meets domain-specific design objectives compared to competing artifacts. To demonstrate the DSML, we included a complex real-world scenario centered around the Nest Learning Thermostat.

Keywords: Service Science; Smart Service Systems; Internet of Things; Domain-specific Modeling Language; Design Science Research

7. Research Article #5: Business Value of the IoT – A Project Portfolio Selection Approach

Authors: Fähnle A, Stohr A, Püschel LC, Röglinger M

Published in: Proceedings of the 26th European Conference on Information Systems, 2018

Abstract: The Internet of Things (IoT) counts among the most disruptive digital technologies on the market. Despite the IoT's emerging nature, there is an increasing body of knowledge related to technological and business topics. Nevertheless, there is a lack of prescriptive knowledge that provides organizations with guidance on the economic valuation of investments in the IoT perspective. Such knowledge, however, is crucial for pursuing the organizational goal of long-term value maximization. Against this backdrop, we develop an economic decision model that helps organizations determine an optimal IoT project portfolio from a manufacturer's perspective and complies with the principles of project portfolio selection and value-based management. For our purposes, IoT project portfolios are compilations of projects that aim to implement IoT technology in an organization's production process, products, or infrastructure. Our decision model schedules IoT projects for multiple planning periods and considers monetary as well as monetized project effects. On this foundation, it determines the project sequence with the highest value contribution. To evaluate our decision model, we discussed its real-world fidelity and understandability with an industry expert renowned for its proficiency in IoT technology, implemented a software prototype, and demonstrated its applicability based on real-world data.

Keywords: Internet of Things, Economic Valuation of IoT, Value-Based Management, Project Portfolio Management