

Understanding Product Lifecycle Management in Manufacturing Industries

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Abstract

In the digital age, manufacturing industries are in constant motion. Driven by tremendous advances of information technology and as response to a variety of challenges in highly competitive market places, a set of product-related processes, methodologies, and information and communication technologies emerged over the last decades. In brief, product lifecycle management is a business strategy that aims at navigating industrial products from early design and manufacturing to actual usage and support to ultimate disposition. Relevant and timely in research and practice, product lifecycle management manifests as (1) challenging in practice, (2) influenced by emerging digital technologies, and (3) novel to information systems.

In this sense, the cumulative dissertation at hand represents a continuation and extension of existing research on product lifecycle management. In detail, the objective of the dissertation is to understand (1) challenges, (2) developments, and (3) transformation processes of product lifecycle management in manufacturing industries occupying an information systems point of view. The *first article* explores challenges in product lifecycle management by taking the example of the automotive industry. Subsequent *articles two, three, and four* represent the main part of the dissertation. They address pivotal developments in product lifecycle management adopting lifecycle, stakeholder, and discipline perspectives. The *fifth article* thematizes a transformation project as longitudinal case study. Conclusively, the *sixth article* charts the research field employing bibliometric methods.

Considering limitations by the ample scholarly field, heterogeneous contextual settings and scientific communities, and the mainly qualitative research strategy, the dissertation contributes as follows: For research, the work at hand extends the body of knowledge in information systems and product lifecycle management. Thereby, the application of information systems foundations and methodologies supports advanced insights into the socio-technical dimensions of product lifecycle management. For practice, the work at hand offers business- and technology-oriented executives in strategic research & development and IT engineering departments valuable knowledge for the design, implementation, and advancement of product lifecycle management in manufacturing industries.

Kurzfassung

Die produzierenden Industrien befinden sich im digitalen Zeitalter in steter Bewegung. Getrieben durch tiefgreifenden technologischen Fortschritt und als Antwort auf eine Vielzahl an Herausforderungen in hochkompetitiven Märkten haben eine Reihe an produktbezogenen Prozessen, Methoden und Informations- und Kommunikationstechnologien in den letzten Jahrzehnten an Bedeutung gewonnen. Zusammengefasst ist Product Lifecycle Management ein strategischer Ansatz, der darauf abzielt, industrielle Produkte beginnend bei der frühen Entwicklung und Produktion über die eigentliche Nutzung und Wartung bis hin zur Deposition zu steuern. Relevant und zeitgemäß in Wissenschaft und Praxis zeigt sich Product Lifecycle Management als (1) herausfordernd in der Praxis, (2) beeinflusst von aufstrebenden digitalen Technologien und (3) neu im Bereich der Wirtschaftsinformatik.

In diesem Sinne stellt die vorliegende kumulative Dissertation eine Fortführung und Erweiterung bestehender Forschung zu Product Lifecycle Management dar. Im Detail ist es Ziel der Dissertation, (1) Herausforderungen, (2) Entwicklungen und (3) Transformationsprozesse im Product Lifecycle Management in produzierenden Industrien aus dem Blickwinkel der Wirtschaftsinformatik besser zu verstehen. Der *erste Artikel* exploriert Herausforderungen im Product Lifecycle Management am Beispiel der Automobilindustrie. Darauf folgende *Artikel zwei, drei und vier* stellen den Hauptteil der Dissertation dar. Sie adressieren zentrale Entwicklungen aus einer Lebenszyklus-, Stakeholder- und Disziplinperspektive. Der *fünfte Artikel* thematisiert ein Transformationsprojekt als longitudinale Fallstudie. Abschließend kartographiert der *sechste Artikel* das Forschungsfeld mithilfe von bibliometrischen Methoden.

Unter Berücksichtigung von Limitationen durch das weitläufige Forschungsfeld, heterogene Rahmenbedingungen und Forschungsströmungen sowie den überwiegend qualitativen Forschungsansatz leistet die Dissertation Beiträge wie folgt: Für die Forschung erweitert die vorliegende Arbeit die Wissenssammlung der Wirtschaftsinformatik und von Product Lifecycle Management. Dabei unterstützt die Anwendung ihrer Grundlagen und Methoden verbesserte Einblicke in die sozio-technischen Dimensionen von Product Lifecycle Management. Für die Praxis bietet die vorliegende Arbeit Geschäfts- und Technologie-orientierten Führungskräften in strategischen Forschungs- & Entwicklungs- und IT Engineering-Abteilungen wertvolles Wissen für die Gestaltung, Implementierung und Weiterentwicklung von Product Lifecycle Management in produzierenden Industrien.

Part A – Research Summary

Introduction and background

In the digital age, manufacturing industries are in constant motion. Driven by tremendous advances of information technology (*technology push*) and as response to a variety of challenges in highly competitive market places (*market pull*), a set of product-related processes, methodologies, and information and communication technologies emerged over the last decades (Terzi et al. 2010; Stark 2015). In brief, product lifecycle management represents a “business activity of managing, in the most effective way, a company’s products all the way across their lifecycles” (Stark 2015, p.1). Thereby, complex industrial products – for example automotive systems – are imagined, defined, realized in the beginning-of-life, supported, used in the middle-of-life, and retired, deposited in the end-of-life stage (Terzi et al. 2010; Stark 2015). Recent figures published by *Accenture* (2016) which predict the product lifecycle management market to grow at an annual rate of 5.9 percent reaching US\$ 50 billion in 2019 reinforce this prominence.

The research area at hand seems relevant and timely as product lifecycle management represents an established field of research and practice, yet is (1) challenging in practice, (2) influenced by emerging digital technologies, and (3) novel to information systems: First, as comprehensive concept with various stakeholders involved, implementing and cultivating product lifecycle management remains demanding (Garetti et al. 2005). Second, novel digital technologies embodying in digital product innovation and process innovation lead to a continuous advancement (Fichman et al. 2014). Finally, research on product lifecycle management is primarily technically oriented whereas socio-technical aspects are often neglected (David and Rowe 2015). In this sense, the dissertation at hand represents a continuation and extension of existing research on product lifecycle management as its nature becomes more integrated and complex. In essence, addressing recent calls for research (David and Rowe 2015), the subsequent dissertation goal statement is formulated:

The dissertation at hand aims to understand (1) challenges, (2) developments, and (3) transformation processes of product lifecycle management in manufacturing industries occupying an information systems point of view.

In particular, pivotal developments in terms of lifecycle, stakeholder, and discipline perspectives (Eigner and Stelzer 2008; Eigner and Roubanov 2014) stand in the center. Thereby, the dissertation is grounded on several adjacent research domains to address

the interdisciplinary character of the subject (David and Rowe 2015). To cover the dissertation goal statement, the dissertation draws up on relevant scholarly works in a plurality of disparate research communities: (1) Product lifecycle management (e.g., Terzi et al. 2010), (2) closed-loop product lifecycle management (e.g., Kiritsis 2011), (3) engineering collaboration (e.g., Büyüközkan and Arsenyan 2012), (4) new product (-service-systems) development (e.g., Nambisan 2013), and (5) product lifecycle management IT/IS project management (e.g., Bokinge and Malmqvist 2012). Subsequent to this *introduction and background*, the next section *dissertation outline* presents the guiding research questions and associated articles. Finally, the *conclusion* discusses contributions to research and practice, limitations as well as conceivable avenues for further research.

Dissertation outline

The outline of the cumulative dissertation at hand is organized along the research framework by Hevner et al. (2004). Embedded in environment and knowledge base, the dissertation comprises three guiding research questions (GRQ I, II, III) and a literature review (GRQ LR). Each guiding research question is addressed by an associated article (Article #1-6). Figure 1 visualizes this outline of the dissertation. Upon the character of product lifecycle management as rich and diverse phenomenon, multi-methodological and -theoretical research designs are leveraged for each guiding research question.



Figure 1: Outline of the dissertation

Guiding research question I

The first research question aims to identify challenges in product lifecycle management in manufacturing industries as introductory part of the dissertation. In spite of some related research studies with rather narrowly drawn boundaries, it is generally not understood which challenges manufacturers are confronted with (Hewett 2010). Beside technical aspects particularly social issues such as knowledge management in the context of product lifecycle management are scrutinized inadequately (David and Rowe 2015). The article “*Challenges in Product Lifecycle Management - Evidence from the Automotive Supply Industry*” with the specific research question “*What are challenges in product lifecycle management in the automotive supply industry?*” represents the empirical motivation and foundation of the dissertation. Resting upon a single-case study research design following the guidelines by Yin (2003) at a European player for mechatronic products, this *article #1* explores obstacles in product lifecycle management in the automotive supply industry. Thereby, upon the novelty the grounded theory paradigm (Strauss and Corbin 1990) acts as qualified theoretical base. As main findings, nine socio-technical obstacles are identified, illustrated, and discussed.

Guiding research question II

The second research question strives to deepen the understanding of a more integrative product lifecycle management and represents the center of the dissertation. This overarching purpose is operationalized in three individual research questions:

GRQ II A. In particular, research question II A targets to grasp the role of product usage for product development in a closed-loop approach. Currently, product lifecycle management focuses on early product design stages neglecting later product usage phases (Kiritsis 2011). Recently, physical products get augmented with digital components that afford transparency throughout the whole lifecycle, yet upon the complexity and diversity of opportunities the role of later lifecycle stages for product development is not understood (Yoo et al. 2010). The article “*Digital Product Innovation in Manufacturing Industries - Towards a Taxonomy for Feedback-driven Product Development Scenarios*” with the specific research question “*What are dimensions and characteristics that describe feedback-driven product development scenarios?*” contributes to sensemaking in the *lifecycle dimension* of product lifecycle management (Eigner and Stelzer 2008). Combining a multiple-case study (Yin 2003) in manufacturing branches and a literature review (vom Brocke et al. 2009), this *article #2* develops a taxonomy (Nickerson et al. 2013). In doing so, the general systems theory

(Checkland 1981) represents a suitable theoretical foundation. As central outcome a taxonomy for feedback-driven product development scenarios is designed, evaluated, and illustrated.

GRQ II B. More precisely, research question II B strives to shed light on inter-organizational aspects of product lifecycle management. Novel modes in organizational forms (Nambisan 2013) and amendments in supporting information systems (Eigner and Roubanov 2014) have added intricacy to collaborative product development. This resulted in lack in understanding the heterogeneous manifestations of inter-organizational collaborations (Büyüközkan and Arsenyan 2012). The article “*Defining Archetypes of e-Collaboration for Product Development in the Automotive Industry*” with the specific research question “*What are potential archetypes of e-collaboration for product development?*” makes a contribution to understand the *stakeholder dimension* of product lifecycle management (Eigner and Stelzer 2008). Integrating both a literature review (vom Brocke et al. 2009) and a multiple-case study (Yin 2003) in the automotive ecosystem, this *article #3* works out patterns of e-collaboration for product development using an archetype approach (Greenwood and Hinings 1993). At that, the socio-technical systems theory (Bostrom and Heinen 1977) acts as well-accepted theoretical lens. In sum, four archetypes of e-collaboration for product development are proposed, described, and validated.

GRQ II C. Specifically, research question II C reaches out to study methods for product lifecycle management of digitized products. Within the context of increasingly IT-infiltrated products, on the one hand the design (Heppelmann and Porter 2014) and on the other hand the engineering and innovation processes (Nambisan et al. 2017) are influenced profoundly. Consequently, unprecedented cross-disciplinary methods from relevant disciplines such as software or service engineering need to be created (Broy and Schmidt 2014). The article “*Towards a Method Compendium for the Development of Digitized Products - Findings from a Case Study*” with the specific research question “*What are methods for the development of digitized products?*” contributes to clarify aspects of the *discipline dimension* of product lifecycle management (Eigner and Stelzer 2008). Leveraging a longitudinal single-case study (Yin 2003) in the form of secondary data (Heaton 2004) from a player in the global materials handling and intralogistics branch, this *article #4* derives methods for the development of digitized products. Upon the recency the grounded theory paradigm (Strauss and Corbin 1990) serves as adequate basis. As results, method-related insights and a set of concrete methods are carved out.

Guiding research question III

The third research question aspires to investigate transformation processes in product lifecycle management as final part of the dissertation. After identifying challenges and enhancing understanding of main developments, an examination how industrial manufacturing companies approach and realize advancements in product lifecycle management is valuable (Bokinge and Malmqvist 2012). This is especially relevant as these information systems projects regularly miss their targeted project goals (Fichman et al. 2013). The article “*The Evolution of IS Projects in Manufacturing Industries: The Case of Product Lifecycle Management*” with the specific research question “*How do product lifecycle management information systems projects in manufacturing industries evolve over time?*” makes a contribution to shrink the uncertainty gap regarding transformation activities. Exploiting primary and secondary data (Heaton 2004) from a longitudinal single-case study (Yin 2003) at a leading automotive supplier, this *article #5* examines the dynamics of an information systems project from January 2016 to April 2017. Thereby, the framework by Batenburg et al. (2006) rooted in the IT-business alignment (Henderson and Venkatraman 1993) represents a suitable foundation. Overall, the timewise evolution, sensemaking, and implications on project management are shown.

Literature review

In parallel to the empirical part of the dissertation, the literature review aims to work up the knowledge base of product lifecycle management. Available literature reviews to portray the strongly disseminated state-of-the-art (David and Rowe 2015) are characterized by their qualitative nature – and as a consequence their limited scope and rigor (Zupic and Cater 2015). Despite initial efforts (Bhatt et al. 2015) a systematic mapping of the field still represents a research gap. The article “*Mapping the Field of Product Lifecycle Management: A Bibliometric Study*” with the specific research question “*How is the field of product lifecycle management in manufacturing industries organized?*” contributes to a science mapping of the area. Also exploiting established methods for literature reviews (Webster and Watson 2002), this *article #6* is mainly grounded on bibliometric methods (e.g., citation analyses) following Zupic and Cater (2015). Thus, (1) the documents, authors, and journals with the most impact, (2) the intellectual structure, (3) the intellectual structure of emerging literature, (4) the social structure, and (5) the topics associated with the field are revealed.

Conclusion

Over the last decades, product lifecycle management has flourished to a pivotal management strategy in industrial companies. Yet, defiant in practice, amplified by digital technologies, and underrepresented in information systems, the present dissertation strives to understand (1) challenges, (2) developments, and (3) transformation processes of product lifecycle management in manufacturing industries adopting an information systems perspective.

For research, the dissertation contributes to the body of knowledge in information systems and product lifecycle management. Following the information systems research framework by Hevner et al. (2004), exploratory, descriptive, and explanatory knowledge to enhance understanding as well as useful artifacts to solve real-world problems are provided. The dissertation is unique in the sense that product lifecycle management is strengthened in the information systems domain. In that regard, the application of its underlying foundations and methodologies (Hevner et al. 2004) facilitates to conceive the “human and managerial dimensions of product lifecycle management” (David and Rowe 2015, p.273) beyond the technical ones.

For practice, the dissertation targets business- and technology-oriented audience from strategic research & development and IT engineering departments in manufacturing industries. For this audience, it provides a valuable overview of relevant aspects, viable guidelines, and beneficial tools for the design, implementation, and advancement of product lifecycle management.

However, potential constraints need to be taken into account: First, upon the ample field of product lifecycle management solely selected issues can be addressed within the limited scope. Second, the dissertation is anchored in heterogeneous contextual settings (such as the materials handling and automotive industry) and scientific communities (such as information systems and product lifecycle management) which narrows comparability. Finally, but not the final limitation is caused by the qualitative research strategy in the empirical part which implies restricted generalizability.

These limitations lead over to an outlook: On the one hand, with the emergence of the *servitization in manufacturing*, the role of services may be increasingly incorporated in the context of a product-service-systems lifecycle management (Cavalieri and Pezzotta 2012). On the other hand, *cloud-based design and manufacturing* (Wu et al. 2013) as a novel computational paradigm also represents a fertile scholarly field for the lifecycle management of industrial products.

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Part B – Articles of the Dissertation

Article #1 – Contribution A

Bibliographical details

Holler, Manuel, Uebernickel, Falk, and Brenner, Walter. 2016. “Challenges in Product Lifecycle Management - Evidence from the Automotive Supply Industry,” *Proceedings of the 27th Australasian Conference on Information Systems (ACIS 2016)*, Wollongong, Australia.

Abstract

Against the backdrop of a steady shift in value added from the automotive original equipment manufacturers to the automotive suppliers, product lifecycle management in the automotive supply industry gains importance. Prior literature has acknowledged product lifecycle management as paradigm for manufacturing industries, yet little is known about the specific characteristics and boundary conditions in this emerging industry branch. Grounded on extensive empirical evidence from a typical and revelatory case study at a global leader for mechatronic assemblies, this exploratory paper identifies, illustrates, and discusses challenges in product lifecycle management in the automotive supply industry. With the limitation of an exploratory and interpretive single-case study approach, we supply scholars and practitioners with grounded, stakeholder-related insights.

Challenges in Product Lifecycle Management - Evidence from the Automotive Supply Industry

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Abstract

Against the backdrop of a steady shift in value added from the automotive original equipment manufacturers to the automotive suppliers, product lifecycle management in the automotive supply industry gains importance. Prior literature has acknowledged product lifecycle management as paradigm for manufacturing industries, yet little is known about the specific characteristics and boundary conditions in this emerging industry branch. Grounded on extensive empirical evidence from a typical and revelatory case study at a global leader for mechatronic assemblies, this exploratory paper identifies, illustrates, and discusses challenges in product lifecycle management in the automotive supply industry. With the limitation of an exploratory and interpretive single-case study approach, we supply scholars and practitioners with grounded, stakeholder-related insights.

Keywords Product lifecycle management, PLM, automotive supply industry, case study.

1 Introduction

Much has been written about automotive original equipment manufacturers (OEMs). Having the well-known “big brands” in mind, the automotive industry is often diminished to those flagship enterprises. A look behind the scenes reveals a not less powerful and absorbing ecosystem: The automotive supply industry. Some figures demonstrate the branch’s magnitude: Market research company “Statista” quotes the worldwide revenue outlook for the automotive supply industry to 1,700 billion Euro in 2020, compared to 640 billion Euro in 2001 (Statista 2015). Thereby, a large share of innovation makes its transition from the OEMs to the suppliers. Over the last decades the worldwide proportion of value added by suppliers grew from 56 percent in 1985 to 82 percent in 2015 (Statista 2015). Evermore key technologies for the next wave of automotive innovation are developed outside the OEMs’ R&D labs which focus increasingly on their system and assembly competence (VDA 2012).

Within this challenging environment of quality improvement, reduction of cost and time to market, an effective and efficient management of the suppliers’ products – expressed in other words “product lifecycle management” – seems more timely and relevant than ever. As an established field of research and practice, a number of conceptualizations for product lifecycle management (PLM) have been suggested (Saaksvuori and Immonen 2002; Ameri and Dutta 2005; Grieves 2006; Eigner and Stelzer 2008; Terzi et al. 2010; Stark 2015), yet the authors understand product lifecycle management as a comprehensive strategy of managing a company’s products all the way across their lifecycles. Within the profound digitalization in manufacturing industries (Yoo 2010; Fichman et al. 2014), thought leaders propose novel ideas such as closed-loop product lifecycle management (Kiritsis 2011), digital twin concepts (Boschert and Rosen 2016), or cloud-based approaches (Lehmhus et al. 2015).

Yet, a glimpse at the daily business of manufacturing companies unveils challenges in product lifecycle management at various levels. In this sense, it is crucial to precisely understand the current situation as prerequisite to provide adequate solutions. Although product lifecycle management systems represent one of the essential information systems in industrial enterprises, research on product lifecycle management is not a common subject in the domain of information systems (Fichman et al. 2013; David and Rowe 2015). Despite some adjacent works, it is not clear which specific challenges automotive suppliers face. Hence, grounded on extensive empirical evidence from a typical and revelatory case study at a global leader for mechatronic assemblies, embedded in one of Europe’s largest industrial consortia, we explore these obstacles. For this objective, we word the subsequent research question:

[RQ] “What are challenges in product lifecycle management in the automotive supply industry?”

The remainder of this paper is arranged in the following way: In chapter two, we introduce fundamental concepts and provide an overview on related work. In chapter three, we present the applied case study research methodology with data collection and data analysis. In chapter four, we list and illustrate the identified challenges and discuss them in chapter five. In a final step, we close with a summary, implications for scholars and practitioners, and research limitations.

2 Theoretical Foundations

2.1 Product Lifecycle

Existing literature occupies two main perspectives regarding the lifecycle of industrial products: The sales-oriented and the engineering-oriented perspective (Sundin 2009; Cao and Folan 2012). The sales-oriented view distinguishes the stages market development, market growth, market maturity, and market decline (Cao and Folan 2012). In contrast, in the engineering-oriented view an established conceptualization of the product lifecycle is the differentiation into beginning-of-life (BOL), middle-of-life (MOL), and end-of-life (EOL) (Cao and Folan 2012). Thereby, BOL encompasses product conceptualization, definition, and realization. MOL comprises product usage, service, and maintenance. EOL may be shaped by various scenarios from refurbishing to disposal (Terzi et al. 2010; Stark 2015). Beside this evenly distributed engineering-oriented view, a more frontloaded conceptualization with the stages requirements elicitation, product planning, development, process planning, production, operations, and recycling is in wide use (Eigner and Stelzer 2008; Eigner and Roubanov 2014).

2.2 Product Lifecycle Management

2.2.1 Development and Conceptualizations of PLM

The evolution of product lifecycle management from its early days to its present form occurred in several waves over the last decades (Ameri and Dutta 2005; Cao and Folan 2012). In the 1980s, the first isolated computer-aided technologies with focus on product development such as computer-aided design (CAD) came up. As a result, product data management (PDM) systems were developed to administer those technologies to support the design chain. In parallel, enterprise resource planning (ERP) systems were designed to assist the supply chain (Ameri and Dutta 2005). In the 1990s, the concept of PDM evolved to product lifecycle management (PLM) through horizontal integration (upstream and downstream processes) and vertical integration (customers and suppliers) (Eigner and Stelzer 2008). In the 2000s, empowered by new capabilities of intelligent products, the latest manifestation closed-loop PLM targets seamless information and knowledge flows through all phases across the product lifecycle (Kiritsis 2011). In sum, no common perspective on product lifecycle management exists. An impressive number of conceptualizations have been suggested, Table 1 provides an overview.

Conceptualization	Source
<i>"(...) product lifecycle management is a systematic, controlled concept for managing and developing products and product-related information (...)"</i>	Saaksvuori and Immonen (2002, p.3)
<i>"(...) product lifecycle management is a business solution which aims to streamline the flow of information about the product and related processes throughout the product's lifecycle such that the right information in the right context at the right time can be made available (...)"</i>	Ameri and Dutta (2005, p.577)
<i>"(...) product lifecycle management is an integrated, information-driven approach comprised of people, processes/practices, and technology to all aspects of a product's life, from its design through manufacture, deployment and maintenance - culminating in the product's removal from service and final disposal (...)"</i>	Grieves (2006, p.39)
<i>"(...) product lifecycle management encompasses all activities and disciplines that describe the product and its production, operations, and disposal over the product lifecycle, engineering disciplines, and supply chain (...)"</i>	Eigner and Stelzer (2008, p.37)
<i>"(...) product lifecycle management is playing a "holistic" role, bringing together products, services, activities, processes, people, skills, ICT systems, data, knowledge, techniques, practices, procedures, and standards (...)"</i>	Terzi et al. (2010, p.364)
<i>"(...) product lifecycle management is the business activity of managing, in the most effective way, a company's products all the way across their lifecycles (...)"</i>	Stark (2015, p.1)

Table 1. Selected conceptualizations on product lifecycle management

2.2.2 Elements and IT Architecture of PLM

In line with the heterogeneous conceptualizations, a unified perspective what product lifecycle management exactly comprises, does not exist. Following Eigner and Stelzer (2008), five main elements are included: (1) Product data management (e.g., engineering design structures), (2) production development (e.g., manufacturing and assembly processes), (3) customer needs management (e.g., requirements management), (4) material sourcing (e.g., strategic supplier assessment), and (5) management functions (e.g., support for reporting and decision making). Thereby, engineering collaboration (e.g., collaboration tools and integrations) connects the different internal and external stakeholders. Inherently, product lifecycle management should not be regarded as an "out-of-the-box" tool, but rather as an intelligent combination of different systems (Terzi et al. 2010).

From an IT architecture perspective, four layer models are prevalent (Eigner and Stelzer 2008, Eigner and Roubanov 2014). Layer 1 represents the author systems (mechanical computer-aided design (M-CAD), electrical/electronic computer-aided design (E/E-CAD), computer-aided engineering (CAE), and computer-aided software engineering (CASE)). Layer 2 (team data management (TDM)) acts as administrative layer which handles data close to the author systems in native data formats. Layer 3 (PLM backbone) enables the actual engineering functions in neutral data formats. Finally, layer 4 projects the enterprise resource planning (ERP) layer. Recent ideas lean towards a multi-disciplinary repository as smart information collector for both design chain and supply chain with individual applications for each product lifecycle phase (Eigner and Roubanov 2014).

2.3 Related Work

As holistic approach, product lifecycle management touches several academic disciplines. Accordingly, related work can be found in various domains. Beside the field of product lifecycle management as established research area itself, product development and manufacturing, information systems, management, and computer science literature may be qualified to provide a knowledge base. Adjacent research works for the issue at hand include: Burr et al. (2003) explored challenges for computer-aided technologies and engineering data management at an international automotive OEM. Tang and Qian (2008) focused on supplier integration in product lifecycle management targeting automotive applications. With his investigation of critical issues and challenges for product lifecycle management implementation, Hewett (2010) presented another example. Furthermore, Pulkkinen et al. (2013) addressed the state of the practice and challenges in globally networked manufacturing companies.

To summarize: First, product lifecycle management has been investigated rather from conceptual than from empirical points of view. Second, the specific characteristics and boundary conditions of the automotive supply industry have been disregarded so far. Third, in the domain of information systems, research works on product lifecycle management are underrepresented. In the following, we address this research gap with a case study approach.

3 Research Methodology

3.1 Methodological Foundations

The objective of this research is to investigate challenges in product lifecycle management with focus on the automotive supply industry. Despite the availability of similar studies, we selected an exploratory research strategy by three main rationales: First, manufacturing industries are highly specific in nature (Olhager 2003), findings from studies in related industries may not match well. Second, extant studies commonly regard product lifecycle management as technical system (David and Rowe 2016), and do not take the manifestation as socio-technical system into account. Third, with product lifecycle management as inherently information technology-dependent concept, research works from the past may be outdated. Following the type of the posed research question, the control over behavioral events, and the focus on a contemporary phenomenon, a case study approach (Benbasat et al. 1987; Eisenhardt 1989; Yin 2009) was chosen. According to Yin (2009, p.13), a case study represents an “empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident” which is applicable to our research venture. Following Yin (2009), we selected a single-case study (epistemological perspective: interpretive) which is an established approach if the case is (1) typical and (2) revelatory.

During March 2015 and May 2016, we had the opportunity to gain an intensive insight in a “tier one” automotive supply enterprise (“CarSupply”) developing, manufacturing, and supplying mechanical and mechatronic assemblies for automotive OEMs. In addition to this unique opportunity for access, we consider this case as typical: First, the investigated case organization exhibits a strong tradition in mechanical engineering, continuously extending its portfolio to mechatronic assemblies. Second, natively characterized by a rather medium size and local footprint, the case organization furthermore features a strong and global expansion. Third, the case organization has implemented an industry-standard four layer IT architecture for product lifecycle management. As qualitative research is often criticized (Lincoln and Guba 1989; Klein and Myers 1999; Myers 2013; Sarker et al. 2013), we pursue a transparent and rigorous approach.

As case study research strongly relies on the case context (Eisenhardt 1989; Yin 2009), characteristics of CarSupply are outlined in detail: Ranked among the top three in its market segment, CarSupply aims to differentiate products by innovation and quality from competitors. For this purpose, CarSupply develops products as well as the required production machinery. From a financial viewpoint, CarSupply features revenues larger than 2,000 million Euro and comprises more than 5,000 employees (2015). The case organization exhibits a global footprint with development and manufacturing locations in Europe, the United States, and Asia. CarSupply is embedded in an interwoven ecosystem, supplying dozens of OEMs and being supplied by hundreds of suppliers. At a higher level, case organization is embedded in one of Europe’s largest industrial consortia. At a lower level, case organization is organized in four different operating units. In their daily business, product lifecycle management represents an important approach to manage their vehicle projects. From an IT perspective, CarSupply operates a PDM/PLM system from a top 5 vendor and an ERP system from a top 3 vendor which are integrated (CIMdata 2016). Thereby, a wide range of integrated tools (mainly requirements management, computer-aided design and simulation tools) serve as author systems.

3.2 Data Collection

According to the principle of triangulation (Yin 2009), multiple sources of evidence and methodologies were applied for data collection. Yet, semi-structured interviews (Eisenhardt 1989; Yin 2009) built the foundation. Overall, 21 interviews in three European development and manufacturing locations in relevant managing, operational, and supporting departments were accomplished on a face-to-face and remote basis. In line with the comprehensive scope of product lifecycle management, we included conversational partners from all relevant lifecycle stages. Thereby, the sample was compiled in an iterative manner (Lincoln and Guba 1989). In a first step, we interviewed informants with a broad overview. In the subsequent steps, with the objective to learn more about the discovered issues, we identified additional, more specialized informants. This “snowball approach” (Lewis-Beck et al. 2004; Patton 2014) was applied until additional data resulted in only minimal new information. For the data collection, we utilized a questionnaire with open questions designed along recommendations by Schultze and Avital (2011). The questionnaire included sections related to the study purpose, background of the interviewee, strategic, processual, organizational, cultural, and information technology-related aspects of CarSupply’s product lifecycle management, and conclusion. During the research process, the questionnaire was iteratively refined. The interviews lasted between 31 and 123 minutes with an average of 53 minutes. In order to ensure a rigorous processing, all interviews were recorded, anonymized, and transcribed. Table 2 provides an overview on accomplished interviews.

In addition to the interviews, further sources of evidence (Yin 2009) were considered. Studying archival records (e.g., documentations and management presentations) and artifacts (e.g., software applications) illuminated the issue additionally. All collected data was transferred in a central case study database.

Department	Sub-department	Interviewee
Managing departments	Innovation and technology management	Head of innovation and technology management
	Sales and marketing	Head of sales and marketing
	Process and quality management	Head of process management
	Process and quality management	Project staff process management (a)
	Process and quality management	Project staff process management (b)
Operational departments	Product engineering	Head of mechatronics development
	Product engineering	Project engineer engineering design
	Product engineering	Project engineer simulation
	Manufacturing engineering	Head of manufacturing engineering
	Manufacturing engineering	Head of technical editing
	Manufacturing engineering	Project lead manufacturing engineering
	Manufacturing engineering	Project lead equipment procurement (a)
	Manufacturing engineering	Project lead equipment procurement (b)
	Procurement	Project staff parts procurement
	Logistics	Head of logistics
	Production	Head of production
Supporting departments	IT support	Chief information officer
	IT support	Group head of PLM and CAx projects
	IT support	Head of IT engineering
	IT support	Head of PLM application projects
	IT support	Head of CAx application support

Table 2. Overview on accomplished interviews at CarSupply

3.3 Data Analysis and Quality Assessment

Following the exploratory character of our research, we adapted grounded theory techniques (Strauss and Corbin 1990; Strauss and Corbin 1997) for data analysis. More specifically, the rationale for selecting a grounded theory approach which is well-established in information systems is put forth along three lines (Urquhart and Fernandez 2006; Jones and Noble 2007): First, inductive approaches without applying existing concepts or theories from the body of knowledge are useful for developing insights if the phenomenon of interest is novel and data-grounded, unbiased research is desired. Second, grounded theory approaches generate insights with relevance for both scholars and practitioners, and thus contribute to reducing the theory-practice gap. Third, grounded theory approaches provide a comprehensive set of techniques without referring to a specific discipline and are able to complement weaknesses of case study research in terms of data analysis.

In detail, open, axial, and selective coding procedures (Strauss and Corbin 1990; Strauss and Corbin 1997) were employed. First, during the initial open coding stage, the transcribed interviews were put into codes, categories, and subcategories beginning early and iterating during the whole research process. Second, in the subsequent axial coding stage, systematic connections between categories and subcategories were established. Third, in the final selective coding stage, core categories were selected and categories and subcategories were rearranged (Strauss and Corbin 1990; Strauss and Corbin 1997). During the coding procedures, computer-assisted qualitative data analysis software (CAQDAS) NVIVO 10 was utilized as advised by Alam (2005) and Sinkovics et al. (2005) to assure transparent and efficient data analysis. Thereby, two theoretically sensitive investigators – guided by the underlying research question and the fundamentals of product lifecycle management, but as open and impartial as possible – constantly compared the emerging codes and categories to harmonize different perspectives and to occupy a consistent view. Particularly, conceptual maps were used to support the emergence of the relationships in a graphic manner. In total, 513 open codes acted as empirical evidence. For each identified challenge in the selective coding stage, the code frequency ranged from 23 to 84 codes.

Regarding the quality assessment of grounded theory approaches, Glaser and Strauss (1967) annotate that (1) grounded theory is a method for building, not verifying and that (2) insights have been verified in a certain manner if grounded in data. To ensure quality of our research, we stuck to the guidelines for grounded theory studies in information systems as suggested by Urquhart et al. (2010). Furthermore, to cope with the interpretive character of our research, we took the concepts credibility, corroboration, and generalizability (Lincoln and Guba 1989; Klein and Myers 1999; Myers 2013) into account.

4 Results

In the case study, challenges in product lifecycle management in the automotive supply industry were identified. Table 3 provides an overview. We seek to present the most impactful aspects with a subsequent in-depth discussion. Accordingly, nine identified challenges are explained in detail and illustrated by the aid of interviewee quotations.

No.	Challenge
#1	Multiple occurrence of media breaks along the lifecycle
#2	Insufficient integration of mechanical, E/E, and software development
#3	Complex data management and collaboration with OEMs and suppliers
#4	Isolated engineering change management
#5	Heterogeneous and contrarious requirements for tool portfolio
#6	Lacking coverage of the complete lifecycle
#7	Assurance of data security and protection of intellectual property
#8	Deficient management and user commitment
#9	Missing link between product lifecycle and knowledge management

Table 3. Challenges in product lifecycle management in the automotive supply industry

4.1 Multiple Occurrence of Media Breaks along the Lifecycle

As result of the historically grown and distributed system landscapes, automotive suppliers are confronted with the multiple occurrence of media breaks along the product lifecycle. Product data are exported from system (a) and imported in system (b) which interrupts consistency (“silos”). In early lifecycle stages, a seamless transition from requirements management to engineering, simulation, and process planning rarely exists in current product lifecycle management environments. Furthermore, in later lifecycle stages, the transition from the design chain (PDM) to the supply chain (ERP) is frequently afflicted with media disruptions.

“Our current product lifecycle management system is a patchwork rug: We have interfaces to ERP, to a file-based equipment database, to a project management tool, to a requirements management tool, to computer-aided design applications. Our departments live in a way on “islands of bliss”. The product engineering department is happy, the manufacturing engineering department is happy as well, difficulties always appear at the interfaces.” (Head of mechatronics development)

4.2 Insufficient Integration of Mechanical, E/E, and Software Development

With their traditional mechanics-oriented modus operandi, automotive suppliers face the challenge that mechanical, electric/electronic, and software development is not integrated sufficiently. Electronics and software have become the new enabler of automotive innovation with high shares of realized product functions. Whereas author systems for electrical/electronic design and software engineering were introduced and updated over time, management systems were not adapted to the required systems lifecycle management approach for mechatronic products. In this context, model-based engineering, the description by models, not by documents, is not widespread across all operational areas.

"The location for electronics and software development is a great distance off our headquarters where mechanical development is located. We started with embedded systems about five years ago and this metaphor represents very well the situation that these streams are often seen as two worlds. Although some final software versions are integrated in our central PLM application, we generally have separate IT landscapes." (Head of mechatronics development)

4.3 Complex Data Management and Collaboration with OEMs and Suppliers

Being situated in an intermediate position between OEMs and subordinate suppliers, complex data management and collaboration with those stakeholders represent an increasing obstacle for automotive suppliers. Value chains in the automotive industry become more decentralized and distributed, accordingly data and information exchange at an inter-organizational level gains importance. Despite constant efforts on harmonization and standardization between OEMs, tier one, and tier two suppliers, challenges reasoned in different processes and systems are a common issue. Frequently, not the product itself is the bottleneck, but the considerably more complex production machinery to manufacture it.

"Parallel to the machine delivery, we get 30 gigabyte of data with 30,000 CAD files from our equipment supplier. A manual integration of that data into our current PLM application would costs about two man months. Overall, our installed base encompasses more than 1,000 machines. This fact becomes even more difficult as those machines have a lifecycle with modifications, too. Internally, we call this "Ping Pong" with the equipment supplier." (Head of technical editing)

4.4 Isolated Engineering Change Management

Although development and manufacturing for high-volume quantities is a most widely standardized process, engineering changes with minor and major implications regularly impede automotive suppliers in their daily business. Drawing upon the logic of exponential growth of change and error correction costs with every passed through lifecycle stage, engineering change management represents an essential component of product lifecycle management. Conditioned by high product complexity involving different engineering disciplines and globally spread stakeholders, assessing, managing, and communicating engineering changes constitutes a major obstacle.

"Engineering changes are ok, they cannot be avoided, caused by customers, suppliers, or internal necessities. Most of our efforts focus on the optimization of regular activities, but we do not pay much attention to the handling of unscheduled events. Currently, we have two engineering change processes implemented in our PLM system which offer basic functionalities. In my opinion, engineering change management lacks in creating transparency and enabling communication." (Head of manufacturing engineering)

4.5 Heterogeneous and Contrarious Requirements for Tool Portfolio

From a tool perspective, automotive suppliers are challenged by boundary conditions such as working principles and software standards. On the one hand, working with dozens of OEMs imposing different requirements results in a redundant system landscape. On the other hand, also strategically important supplier monopolists raise similar requirements. Finally, the IT strategy department of the affiliated group pursues enhancements in terms of harmonization and simplification of the tool portfolio in their business areas and business units. Although every stakeholder has its rationale, in sum heterogeneous and contrarious requirements for the automotive suppliers' tool portfolio result.

"Currently, the IT engineering department administrates seven different CAD tools ("the tool zoo"). In my opinion, a large share of daily CAD tasks can be attended with one standardized application. One challenge is especially "the company in the company" which has its own specialties. Beyond our subsidiary, in our automotive business area [company1] has [tool1], [company2] has [tool2], and so forth. Although many discussions are ongoing, almost no synergies are leveraged." (Group head of PLM and CAX projects)

4.6 Lacking Coverage of the Complete Lifecycle

Other than indicated by the notion, existing product lifecycle management approaches in the automotive supply industry lack in covering the complete product lifecycle. Rooted in computer-based support for product development, the focus lies on the beginning-of-life stage, middle-of-life and end-of-life phases are comparably neglected. On closer examination, automotive suppliers have very limited information about the actual usage of their products once they are sold to their customers (closed-loop PLM) – conditioned by lacking technological capabilities, but also missing access to their products.

"What does our customer really need? From our manufacturer perspective, we cannot occupy the customer viewpoint. Currently, we cover this through selected reference customers and experiences from the past. But there are scarcely data that effectively show how the customer usage looks like. Our product lifecycle management stretches from requirements management to production planning. It would be very useful to see how our product are used, however we have no access to the OEMs' data." (Head of innovation and technology management)

4.7 Assurance of Data Security and Protection of Intellectual Property

With all enterprise data, information, and knowledge integrated in product lifecycle management systems, automotive suppliers are confronted with the assurance of data security and protection of intellectual property. Against the backdrop of the pervasiveness of cyber- and non-cyber-attacks across all industries, manufacturing industries are one of the most critical branches. Accordingly, data security and rights management represent core elements of product lifecycle management. Thereby, requirements for protection are imposed by customers, suppliers, and own impetus.

"Data security is a big issue in our IT engineering department. Some weeks ago, we had an IT security audit by one of our main OEMs. Their requirements rise constantly. Examples are the need for a safeguarded door locking to computer workspaces and OEM-specific employees to handle OEM-specific engineering data. But also internally, the efforts to protect our product data strongly ascend. An important factor is that we relocate our development centers closer to the emerging and – from a data security perspective – more critical end markets." (Head of IT engineering)

4.8 Deficient Management and User Commitment

Deficient management and user commitment in product lifecycle management is a common issue across departments in the automotive supply industry. Product lifecycle management is often equaled with a central repository for product data. Although the significance of human factors has been emphasized, understanding the relevance of product lifecycle management as a holistic strategy deeply entrenched into the enterprise culture and strengthened by all employees is not established across-the-board.

"Being responsible for product lifecycle management in terms of trainings and education, I learned that users experience PLM – sometimes intensified by legacy IT – more as a burden than as an assistance in their daily business. From my viewpoint, I recommend to invest – for example by the aid of trainings – in a mind-set change to manifest product lifecycle management as holistic enterprise strategy, relevant to and supported by every colleague." (Project staff process management (a))

4.9 Missing Link between Product Lifecycle and Knowledge Management

Although efforts on both product lifecycle management and knowledge management are made, automotive suppliers are challenged by missing links in-between. Researchers and practitioners agree that the ability to manage knowledge is becoming decisive in today's information age. Especially in manufacturing industries expertise has become one of the most essential assets. Yet, no sufficient alignment between the tangible product data and intangible product-related knowledge is created.

"I mostly use product data for purposes of manufacturing concept development. Sometimes it is hard to find the currently valid version and as soon as found it can be difficult to work solely with the data available because a lot of communication and know-how in the engineering process is conducted "silently". Beside the convenience factor, such product-related knowledge is lost if the employee is on holiday or even leaves the company." (Head of manufacturing engineering)

5 Discussion

The subsequent discussion is organized as follows: In a first step, we discuss general findings. In a second step, automotive supply industry-specific results are debated. In a third step, we contemplate on necessary activities to solving the identified challenges.

Regarding the first part, we structure our discussion along the established product lifecycle management framework (Eigner and Stelzer 2008; Eigner and Roubanov 2014), spanned by three dimensions. A priori, it can be observed that automotive suppliers are confronted with obstacles across all dimensions. Along the product lifecycle axis, challenges #1 ("multiple occurrence of media breaks along the lifecycle") and #6 ("lacking coverage of the complete lifecycle") are evident. Along the supply chain axis, challenge #3 ("complex data management and collaboration with OEMs and suppliers") is apparent. Along the engineering disciplines axis, challenge #2 ("insufficient integration of mechanical, E/E, and software development") is obvious. Furthermore, challenge #4 ("isolated engineering change management") may have implications on all three dimensions. Beyond, we can find information technology-related challenges (#5 "heterogeneous and contrarious requirements for tool portfolio" and #7 "assurance of data security and protection of intellectual property"). Interestingly, several challenges can be assigned to organizational culture (#8 "deficient management and user commitment" and #9 "missing link between product lifecycle and knowledge management"). This finding goes in line with David and Rowe (2015) who emphasize that research on product lifecycle management is currently dominated by technical issues and propose to understand the human and managerial dimensions.

Regarding the second part, some identified challenges are familiar from related studies (Burr et al. 2003; Tang and Qian 2008; Hewett 2010; Pulkkinen et al. 2013), whereas other unveiled obstacles are very specific for the case automotive supply industry. At a first glance, challenges #3 ("complex data management and collaboration with OEMs and suppliers") and #5 ("heterogeneous and contrarious requirements for tool portfolio") are counted among these, yet on closer inspection considerably more influences exist. To illustrate these influences, Table 4 provides a stakeholder analysis of challenges in product lifecycle management. Thereby, the identified challenges are analyzed by parties concerned. For this purpose, we adapted the manufacturing ecosystem framework by Meier et al. (2010). We can observe that many stakeholders such as OEMs and subordinate suppliers, but also the affiliated group play an essential role. In contrast, solely few challenges exist that automotive suppliers are able to address by their own efforts without involving their ecosystem stakeholders. Referring back to the underlying research question of this paper, the findings reinforce that product lifecycle management in the automotive supply industry is highly specific and constrained by several boundary conditions.

No.	Challenge	OEM	Tier One	Tier n	Group
#1	Multiple occurrence of media breaks along the lifecycle		•		
#2	Insufficient integration of mechanical, E/E, and software development		•		
#3	Complex data management and collaboration with OEMs and suppliers	•	•	•	
#4	Isolated engineering change management	•	•	•	
#5	Heterogeneous and contrarious requirements for tool portfolio	•		•	•
#6	Lacking coverage of the complete lifecycle	•	•		
#7	Assurance of data security and protection of intellectual property	•	•	•	•
#8	Deficient management and user commitment		•		
#9	Missing link between product lifecycle and knowledge management		•		

Table 4. Stakeholder analysis of challenges in product lifecycle management

Regarding the third part, it must be initially stated that modifications in such complex environments like the design and supply chain of globally operating automotive suppliers ever represent a major change which needs to be designed, evaluated, and implemented diligently. As many technological, processual, and organizational steps have to be climbed, transformations in product lifecycle management may be realized in steps as proposed by Batenburg et al. (2006). With respect to the interwoven stakeholders in the automotive industry, product lifecycle management requires joint optimization by all involved actors: From a technological viewpoint, standardization efforts as attempted in different initiatives (Rachuri et al. 2008) may act as starting point. From a non-technological perspective, organizational change management (David and Rowe 2015) represents an essential activity as well.

6 Conclusion

Over the last decades, product lifecycle management has unfolded as established approach to handle issues related to the lifecycle of industrial products. This exploratory paper reports on challenges in product lifecycle management with focus on the rising automotive supply industry. Against the backdrop of the profound digitalization in manufacturing industries, our research was initiated by lack in understanding the current, specific situation as prerequisite to provide adequate solutions. Anchored in extensive empirical evidence from a typical and revelatory case study at a global leader for mechatronic assemblies, we identified, illustrated, and discussed nine obstacles.

For scholars, our work contributes to the academic discussion on product lifecycle management in four ways: First, in all conscience, this study is the first to investigate challenges focusing on the specific characteristics of the automotive supply industry. Through unique, in-depth access, the single-case study provides essential insights on stakeholder-related aspects which notwithstanding have certain general character. More formally, Urquhart et al. (2010) distinguish grounded theory studies by (1) degree of conceptualization and (2) theory scope. Utilizing this framework, our (1) degree of conceptualization is description and our (2) theory scope is bounded context. Second, by applying the concept product lifecycle management we confirm the relevance of its social component. Hence, we reinforce the further developed understanding as socio-technical system (Bostrom and Heinen 1977; David and Rowe 2015). Third, our research work may be regarded as empirically derived research agenda. Thus, we supply scholars with ideas and directions for future work. Fourth, information systems is an interdisciplinary research domain (Webster and Watson 2002; Hevner et al. 2004) and may look into other domains. With this paper, we strive to link the field of product lifecycle management with information systems. For practitioners in manufacturing industries, the obtained insights serve as solid foundation for future decisions on product lifecycle management. As source of technical, economic, social, and environmental value (Terzi et al. 2010), our findings offer decision makers from managing, operational, and supporting departments guidance on quintessential and business critical topics.

Yet, the study at hand has restrictions. The advantages of a single-case study go hand in hand with its limitations. First, although we immersed in a typical automotive supply company, our findings are not representative. Second, despite investigator triangulation, our data analysis is interpretive in nature. Third, this study stands out due to its exploratory character which cannot ensure exhaustiveness.

The work raised potential directions for further research. In the narrower sense, validating the identified challenges using a mixed method or quantitative research design will provide more insights. To capture a broader perspective, multiple-case studies may be conducted. In addition, studying the specifics of product lifecycle management in other manufacturing industries such as the aerospace branch seems valuable. In a broader sense, it is obvious to service the identified challenges with solutions. For these activities, the work at hand can act as point of origin.

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Article #2 – Contribution B

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Abstract

In the light of pervasive digitalization, traditional physical products get augmented with digital components that create the potential of making the whole product lifecycle visible for product developers. As numerous opportunities sketch out how feedback such as sensor data might be leveraged for future products, a comprehensive model to describe, particularly a classification model to organize and structure these opportunities seems analytically useful. Hence, this paper pursues a scenario-based approach and proposes a taxonomy for feedback-driven product development scenarios in manufacturing industries. Grounded on (1) empirical data from case studies and focus groups and (2) a systematic literature review, we follow an established taxonomy development method employing the general systems theory as meta-characteristic. With the limitation of a (1) qualitative, interpretive empirical research design and a (2) representative literature review, we contribute to the body of knowledge by shedding light on feedback-driven product development from a classification perspective which may act as structuring and creativity fostering tool.

Digital Product Innovation in Manufacturing Industries - Towards a Taxonomy for Feedback-driven Product Development Scenarios

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Abstract

In the light of pervasive digitalization, traditional physical products get augmented with digital components that create the potential of making the whole product lifecycle visible for product developers. As numerous opportunities sketch out how feedback such as sensor data might be leveraged for future products, a comprehensive model to describe, particularly a classification model to organize and structure these opportunities seems analytically useful. Hence, this paper pursues a scenario-based approach and proposes a taxonomy for feedback-driven product development scenarios in manufacturing industries. Grounded on (1) empirical data from case studies and focus groups and (2) a systematic literature review, we follow an established taxonomy development method employing the general systems theory as meta-characteristic. With the limitation of a (1) qualitative, interpretive empirical research design and a (2) representative literature review, we contribute to the body of knowledge by shedding light on feedback-driven product development from a classification perspective which may act as structuring and creativity fostering tool.

1. Introduction

Managing the lifecycle of industrial products has been perceived as challenging issues in both academia and industry for several decades [1,2,3]. Within the setting of manufacturing, an established conceptualization of this product lifecycle is the division into beginning-of-life (BOL), middle-of-life (MOL), and end-of-life (EOL). Thereby, BOL encompasses product conceptualization, definition, and realization. MOL comprises product usage, service, and maintenance. EOL may be shaped by various pathways ranging from refurbishing to disposal [2,3,4]. From a chronological viewpoint, these phases are commonly not distributed equally. Dependent on the product type, the duration of the MOL phase can exceed the duration of the BOL phase by far [2,3,4]. On closer examination, industrial enterprises have very limited information about the actual usage of their products once they are

sold to their customers [2,4,5]. Although it is widely acknowledged that information about product usage is highly beneficial for the development of future products [2,4,6,7], manufacturers scarcely get feedback from the field – with the exception of selective snapshots from customer service or even complaints from customers. Conditioned by lacking technological capabilities, product usage has received little attention from product development departments in the past.

However, in the light of pervasive digitalization, traditional physical products get augmented with digital components [8,9,10] that create the potential of making the whole product lifecycle visible for product developers [2,4,7]. Traditional industrial products ranging from heavy engineer-to-order machinery to automotive make-to-stock-planning modules get infused with digital technologies such as sensors, networks, and processors [8,9,10]. Recent market research from strategy consultancy Oliver Wyman attempts to quantify this development and forecasts the number of connected objects across all industries to 75 billion in 2020 [11]. Hence, there may be billions of opportunities for product developers to obtain large-scale quantified and reliable insights from products in use.

Numerous opportunities sketch out how feedback such as sensor data might be leveraged for future products. A comprehensive model to describe, particularly a classification model to organize and structure these abundant and diverse opportunities seems analytically useful for product developers and decision makers discovering the benefits of digitized products. Yet, extant models are not capable of adequately describing the landscape of feedback-driven product development. Hence, this paper pursues a scenario-based approach and builds a classification model. Therefore, we (1) draw upon empirically derived scenarios from case studies and focus groups in four distinct manufacturing industries and (2) classify these objects of interest in a taxonomy for feedback-driven product development scenarios, guided by the method proposed by Nickerson et al. [12]. Accordingly, we frame the guiding research question for this paper as follows:

[RQ] “What are dimensions and characteristics that describe feedback-driven product development scenarios in manufacturing industries?”

The remainder of this paper is organized in the following way: In section 2, we provide an overview on the theoretical background, i.e. digital product innovation, product development, and related work. In section 3, the applied taxonomy development method with both empirical-to-conceptual and conceptual-to-empirical approach is introduced. In section 4, we present the taxonomy and illustrate it by the aid of an exemplary scenario in section 5. Finally, we conclude with a summary, implications for scholars and practitioners, and research limitations in section 6.

2. Theoretical background

2.1. Digital product innovation

As result of the pervasive infiltration of information technology across all industries, the nature of innovation has changed significantly over the last decades [13], and manufacturing industries represent no exception. As a matter of principle, the impact of digital technologies on innovation may appear in two manifestations [13]. First, digital technologies may affect the innovation process. Second, digital technologies may influence the innovation process outcome [13]. In the former case, a digital tool, in the latter case, a digital component, acts as trigger or enabler [13].

Table 1. Selected concepts and conceptualizations related to “digitized products”

Concept	Conceptualization
Digitized products	“(…) digitization makes physical products programmable, addressable, sensible, communicable, memorable, traceable, and associable (…)” [9:725,10]
Cyber-physical systems	“(…) are integrations of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa (…)” [15:1,16]
Intelligent products	“(…) contain sensing, memory, data processing, reasoning, and communication capabilities (…)” [4:480,17]
Smart objects	“(…) possess a unique identity, are capable of communicating effectively with their environment, can retain data about themselves, deploy a language, and are capable of making decisions (…)” [18:284,19]
Smart, connected products	“(…) consist of physical components, smart components (sensors, microprocessors, data storage, controls, software, operating system), and connectivity components (ports, antenna, protocols) (…)” [20:67]
Internet of things	“(…) everyday objects can be equipped with identifying, sensing, networking, and processing capabilities that will allow them to communicate with one another and with other devices and services over the Internet (…)” [21:261,22]

As this paper explores the role of digital components embedded in physical products, our research is positioned in the field of digital product

innovation which must be diligently distinguished from digital process innovation [9]. Yoo et al. conceptualize digital product innovation as “carrying out of new combinations of digital and physical components to produce novel products” [9:725], which goes in line with the Schumpeterian perspective on innovation. These new combinations of digital and physical materiality [14] can be described by the layered-modular architecture (contents layer, service layer, network layer, and device layer) in a comprehensive way [9]. Table 1 provides a survey on selected concepts and conceptualizations related to “digitized products” rooted in different scientific domains. Honoring concepts from the engineering and computer science domain at this juncture and utilizing their contributions at a subsequent stage, this paper employs the nomenclature of digitized products as it is the most comprehensive, scholarly mature, and in information systems dominant concept [9], used by several authors [e.g.,23,24].

2.2. Product development

In a generic sense, product development describes the process of bringing new products to market [25,26]. From an historical viewpoint, product development was influenced by different research streams [1]. Understood entirely as research and development project in the 1960s, marketing, organization, strategy, and operations research served as dominant logic for product development over the next decades [1]. Since the 1990s, product development can be regarded as an IT-enabled innovation process [1]. Furthermore, product development encompasses a strong integrative aspect involving all relevant stakeholders [25,26]. According to a recent conceptualization by Eigner and Roubanov, “product development encompasses all activities and disciplines that describe the product and its production, operations, and disposal over the product lifecycle, engineering disciplines, and supply chain with the result of a comprehensive product definition” [27:7]. Thereby, product development can be regarded as an integral part of product lifecycle management – a strategy of managing a company’s products across their lifecycles [2,3]. In the domain of information systems, product development is an emerging field [1,13], “information systems can serve as reference discipline” [1:1]. Research on the relationship of digital product innovation and product development is still in its infancy. Yoo et al. [9] note two main implications: With embedded digital capabilities, products offer (1) novel functions and enhanced price/performance ratios that however (2) fundamentally transform development processes and challenge existing product architectures and organizing logics.

2.3. Related work

Upon the interdisciplinary nature of the subject, related work can be found in various research domains. In a broader sense, the field of closed-loop product lifecycle management deals with seamless and multi-directional information flows through all lifecycle phases [4,28]. More specifically, regarding the information flow between individual lifecycle phases, several articles [e.g.,29,30] concentrate on narrow issues along the chain from identification, collection, storage, and analysis of product usage data. However, previous studies investigate the exploitation rather from maintenance points of view than from design perspectives [31,32]. Furthermore, the emerging field of big data & analytics [e.g.,33,34] seems qualified to provide valuable contributions, which increasingly discusses issues related to product lifecycle management [35]. Beyond, in the domain of computer science, the field feedback-driven software engineering [e.g.,36] is nascent. In the narrower sense, certain classification models related to digital product innovation exist. For example, Herterich et al. [37] developed a taxonomy for service systems enabled by digital product innovation. With a taxonomic framework for context aware computing for the Internet of things, Perera et al. [38] provide another example. However, these taxonomies have different purposes and foci than product development. Herterich et al. [37] address industrial service systems with the theory of affordances as lens, Perera et al. [38] take a strong technical perspective and neglect business benefits. Up to the authors' knowledge, there exists no research to describe feedback-driven product development from a classification perspective. In the following, we address this gap with a scenario-based, taxonomic approach.

3. Research methodology

3.1. Methodological foundations

According to March and Smith, “a model can be viewed simply as a description, that is, as a representation of how things are” [39:256], which is the purpose of our research endeavor. Well-established models to help scholars and practitioners understand and analyze complex domains are classification models which class objects of interest [12,40,41]. As the classification of objects is a fundamental task in various research domains, several paradigms, terminologies, and development methods exist. Going back to foundational literature on classification [42,43,44], extant studies distinguish – beside more general notions such as classification or framework – particularly typologies (theoretically derived) and taxonomies (empirically derived).

For this paper, we employ the method proposed by Nickerson et al. [12] by several reasons. First, it integrates inductive and deductive techniques. Second, it is well-accepted in the information systems domain where we position our research in and strive to contribute to. Finally, this approach is situated in the field of design science research [45,46] with the main goal to create a new useful artifact. Following Nickerson et al. [12], we define a taxonomy as a set of dimensions each consisting of mutually exclusive and collectively exhaustive characteristics such that each object of interest has exactly one characteristic for each dimension. In the case at hand, the objects of interest are scenarios which represent narrative descriptions of activity sequences [47,48]. We selected a scenario-based approach as “scenarios are ideal for exploring and defining the behavior of systems involving people in complex business procedures” [49:21]. Scenario-based research endeavors on product development have been realized successfully [50]. In line with Carroll [47,48], our understanding of a scenario is a specific, qualitative description how data from the MOL stage (“product usage”) may be leveraged for BOL purposes (“product development”) to enhance future products. For the taxonomy, scenarios were derived from (1) case studies and focus groups and (2) complemented by extant work.

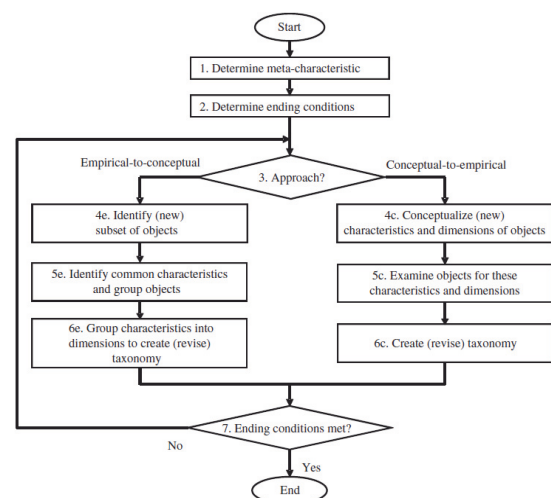


Figure 1. Method for taxonomy development in information systems by Nickerson et al. [12]

Figure 1 illustrates this method for taxonomy development in information systems. As Nickerson et al. [12] emphasize the relevance of taxonomies on the one hand, but identify methodological weaknesses on the other hand, we pursue a rigorous and transparent approach. Initially, we diligently selected the meta-characteristic which represents most comprehensive characteristic of the taxonomy [12]. In line with the proposed purpose (“a tool to foster transparency and

creativity”) and the proposed users (“product developers and decision makers in traditional manufacturing industries discovering the benefits of digitized products”), we grounded our meta-characteristic in the general systems theory. The general systems theory is the “transdisciplinary study of the abstract organization of phenomena, independent of their substance, type, or spatial or temporal scale of existence” [51:2]. Thereby, the concept “system” plays an essential role which can be characterized by (1) emergent properties, (2) layered structure, and (3) processes of communication and control [52]. We consider product development as a system with those characteristics. Product developers and decision makers need to be informed which system inputs they have to process in which way, and what may be potential system outputs. Subsequently, we defined objective and subjective ending conditions. A fundamental objective ending condition is that the taxonomy consists of dimensions each with mutually exclusive and collectively exhaustive characteristics [12]. Beyond, we included subjective ending conditions: Our final taxonomy should be concise, robust, comprehensive, explanatory, extendible, and comprehensive [12]. In the empirical-to-conceptual approach, dimensions and characteristics are derived inductively from the objects as logical sequence of the meta-characteristic [12]. In contrast, in the conceptual-to-empirical approach, dimensions and characteristics are developed without the objects and then synchronized [12]. The taxonomy development process is iterative until all imposed ending conditions are met.

3.2. Empirical-to-conceptual approach

For the empirical-to-conceptual approach, we applied case study research following Yin [53] and Eisenhardt [54], complemented by focus groups following Morgan [55]. A case study represents an “empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident” [53:13], which seems an appropriate research method in consideration of our research endeavor. With qualitative research, we targeted to (1) identify scenarios for a subsequent classification and (2) explore potential dimensions and characteristics that may describe feedback-driven product development.

Guided by our research question, we selected a purposeful case sampling strategy [56,57]. First, to ensure comparison, maximize variation, and obtain rich, diverse insights, we considered the spectrum of manufacturing industries ranging from engineer-to-order through to make-to-stock-planning enterprises [58] (maximum variation sampling [57]). Second, we took typical manufacturing companies into account

which have recognized the potential of digitized products (typical case sampling [57]). Table 2 provides an overview on the involved case organizations and sources of evidence. Case organization MachineCorp (revenue <1,000 MN €) is a special engineering company manufacturing special machinery for luxuries. Case organization ForkLift (revenue >2,001 MN €) is a materials handling original equipment manufacturer (OEM) developing trucks of high quality and durability. Case organization CarSupply (revenue 1,001–2,000 MN €) is a first tier automotive supplier providing mechatronic chassis systems to automotive OEMs. Case organization INGeneering (revenue >30,001 MN €) is one the largest diversified industrial consortia in Europe which unites various business areas under its roof.

Table 2. Overview on case organizations and sources of evidence

Case organ.	Sources of evidence
MachineCorp (Special engineering)	<i>Semi-structured interviews</i> [A] Head of engineering design [B] Head of control engineering [C] Project lead control engineering [D] Head of manufacturing engineering [E] Head of technical IT
ForkLift (Materials handling (OEM))	<i>Semi-structured interviews</i> [F] Project lead strategic product platforms [G] Project lead advance development [H] Project lead advance development [I] Senior engineer advance development [J] Head of product lifecycle management [K] Head of master data management
CarSupply (Automotive (first tier supplier))	<i>Semi-structured interviews</i> [L] Head of innovation and technology [M] Senior engineer product design [N] Senior engineer product simulation [O] Chief information officer
INGeneering (Diversified industrial consortium)	<i>Focus groups</i> Digitalization forum with focus on digitized industrial equipment: Eight focus group workshops with both technology- and management-oriented executives

With the purpose to collect potential scenarios that can be classified in a taxonomy, semi-structured interviews [53,54] acted as main source of evidence. For the interviewee sampling, we applied (purposeful) theoretical sampling [56,57] to approximate our study objectives in an iterative way rather than executing a pre-built scheme. In a first step, we interviewed informants with a broad overview. In the subsequent steps, with the goal to learn more about the discovered issues, we identified additional, more specialized informants. This “snowball approach” was applied until additional data resulted in only minimal new information and scenarios became repetitive. Accordingly, interviewees came from a variety of relevant functions (e.g., product design, product simulation) and different ranks (e.g., head of engineering design, project lead advance development). The interviews were realized from June 2015 to January 2016 with

two guiding elements. First, a questionnaire was developed along recommendations by Schultze and Avital [59] which encompassed the following sections: Introduction, interviewee's and company's background, trends in product development, strategies, processes, and information systems related to feedback-driven product development, scenario identification, and conclusion. Second, we employed paper-based scenario templates to support the scenario identification. Thereby, the scenario templates [47,48,49] were organized as follows: Scenarios are identified by a number and a short title. Involved stakeholders and a standard process can be described. The main section of the scenario template is structured along the system input-processing-output framework. Lastly, the scenario template encompasses space for comments and sources. First, we supplied the interviewees with exemplary scenarios from literature and asked to ideate similar applications in their own business environment. Interviews (minimum: 33 minutes, average: 64 minutes, maximum: 95 minutes) were recorded, anonymized, transcribed, and analyzed with computer-assisted qualitative data analysis software NVIVO 10 [60,61].

Furthermore, we had the opportunity to collect evidence from a digitalization forum at INGeneering with focus on digitized industrial equipment in the style of focus groups [55,62]. In eight workshop sessions (introduction, participants' and company's background, exemplary scenario presentation, individual ideation, group discussion, results presentation, and conclusion) of 90 minutes each in June 2015 with technology- and management-oriented executives, scenarios were identified. After the data collection, populated scenario templates were transferred in digital form and collected in a scenario database.

3.3. Conceptual-to-empirical approach

For the conceptual-to-empirical approach, we performed a systematic literature review following the established approach by vom Brocke et al. [63]. Furthermore, we enriched our review with methodological contributions from additional sources [64,65]. With the review, we aimed to (1) get an overview on related work, (2) identify existing scenarios, and (3) explore potential dimensions and characteristics for the taxonomy.

Referring to Cooper's framework [64], we position our review as follows: We focus on research outcomes. Our goal is the identification of central issues. The review results are presented neutrally. The coverage has representative character. We target to inform general scholars and practitioners. Upon the interdisciplinary and distributed nature of the review subject, the conceptualization of the topic was challenging. Hence, after a pre-screening of standard

references a visual concept map with synonyms, superordinate, infraordinate, and related terms to involve all facets of the topic was developed. With the purpose to include high-quality contributions, we searched peer-reviewed journals and conferences through major scholarly databases. We aim to ground our taxonomy in extant work which we find in information systems, engineering, and management literature. For the key word search we applied the search string “(“product development” OR “product engineering”) AND (“usage” OR “operational” OR “middle-of-life” OR “lifecycle” OR “feedback” OR “closed-loop”) AND (“data” OR “information”)” in the publication title and key words to go beyond domain-specific nomenclature and to focus on the actual phenomenon under investigation. To target the most current contributions, a fifteen year time frame from April 2001 to April 2016 was taken into consideration. Table 3 demonstrates the literature search and results (*publication title search only to reduce database search results <1,000 items).

Table 3. Literature search and results

Database	Results	Net hits
AIS Electronic Library	0	0
EBSCOhost	11	3
Emerald	3	1
PAIS Index	65	13
Science Direct*	579	12
Web of Science*	9	4
Interim results (database search, inclusion/exclusion)	667	33
Final results (duplicates, inclusion/exclusion, forward/backward, recommendations)	61	

The key word search amounted to 667 articles which were examined in a three-step approach reading title, abstract, and full text. In line with the review purpose, inclusion/exclusion criteria we elaborated: Articles are included if the publication (1) contains a scenario or (2) has a potential dimension and characteristics. Furthermore, we conducted a forward/backward search process (21 additional articles) and included recommendations by senior scholars and skilled practitioners (7 additional articles). Finally, the total count of publications for in-depth investigation resulted in 61 papers. Utilizing the standardized templates, existing scenarios were extracted from the papers and gathered in the case study database with overlapping and duplicate scenarios removed. The scenario identification from both case studies and focus groups and literature review resulted in 20 concrete, independent, and industry-overarching feedback-driven product development scenarios. In addition, these papers provided potential frameworks to anchor the taxonomy dimensions in the body of knowledge.

3.4. Taxonomy development and evaluation

With regard to the development process, we strictly followed Nickerson's example for mobile applications in graphical, tabular form [12]. Considering the introduced methodological foundations, scenarios were initially partitioned in manageable subsets. We decided to use the empirical-to-conceptual approach first because we have several objects of interest available. Grounded on a first subset, we identified initial dimensions and characteristics relating to the meta-characteristic. For the next iteration, we decided to use the conceptual-to-empirical approach in order to occupy another perspective. Also inspired by frameworks from literature, we conceptualized suitable dimensions and characteristics referring to the meta-characteristic and identified instances (scenarios). Both approaches were continued and alternated with subsequent examination of ending conditions after each iteration. Dependent on the fit, dimensions were added or removed and characteristics merged, split, or complemented until ending conditions were fulfilled. Six iterations were conducted. From an inductive viewpoint, source and method triangulation resulting in a substantial, saturated set of scenarios made a contribution towards collectively exhaustive characteristics. From a deductive viewpoint, anchoring characteristics in spanning frameworks from literature made a contribution towards collectively exhaustive characteristics. Specificity of scenarios and iterative modification of characteristics contributed towards mutual exclusivity.

With regard to evaluation strategies, Sonnenberg and vom Brocke [66] propose to conduct the artifact evaluation throughout the whole process. Upon the nature of our artifact, we selected the observational method case study [45] as suitable and studied it in an appropriate business environment with the evaluation technique of expert interviews [66]. The interviews were conducted with product developers and decision makers from the case organization MachineCorp, ForkLift, and CarSupply with two professionals each continuously during the design science research activities. During EVAL1, the problem statement and research gap was discussed. Subsequently, during EVAL2, questions referring to the design specifications and the selected methodology were asked. Finally, during EVAL3, the current version of the designed artifact was evaluated in an artificial setting. Thereby, audio was recorded and analyzed. Overall, participants appreciated the addressed problem, the selected scenarios-based model building approach, and the current version of the taxonomy. However, minor issues were addressed: First, we eliminated several dimensions and focused instead on those that are specific for the case of product development. Second, we

emphasized the outcome dimension as interviewees were especially interested in potential applications of the feedback. In sum, the build-evaluate-pattern [66] enabled us to refine and sharpen our taxonomy.

4. Results

In the empirical-to-conceptual approach and the conceptual-to-empirical approach, a taxonomy for feedback-driven product development scenarios in manufacturing industries was developed. Table 4 illustrates the taxonomy. In line with the selected meta-characteristic, D1 to D3 refer to input, D4 to D5 refer to processing, and D6 to D9 refer to output dimensions. In the following, each dimension and characteristics including sources are elucidated.

D1 - Approach to data collection: During the case studies and literature review [28,29,30], it became evident that product developers can approach the feedback collection in two fundamental ways (D1). The reactive approach (C1.1) aims to collect errors of existing products which already occurred and strives to eliminate those failures for future products in a retrospective manner. In contrast, the proactive approach (C1.2) rather pursues a large-scale data collection and targets to avoid possible dissatisfactions by predicting the presumable product usage with subsequent tailored product design. Existing approaches in the special engineering, materials handling, and automotive supply business rather work ex post through qualitative, interpretive customer (service) feedback. With the dissemination of digitized products, increasingly quantified ex post and ex ante approaches become feasible.

D2 - Product data source (level of abstraction): With feedback from the field as essential precondition, D2 relates to the product data source in terms of level of abstraction to measure the scope of collected feedback. This fundamental dimension emerged from the scenarios as well as extant literature [29,30]. In this dimension, the characteristics product instance (C2.1) and product class (C2.2) were identified. A product instance refers to a single product item whereas a product class contains several product items with the same or similar properties [29,30]. Whereas in the case of similar product usage (e.g., standardized automotive applications) it may be reasonable to gather feedback solely from representative product classes, it may be necessary to include all product instances of the installed base in other cases (e.g., highly individual engineer-to-order context).

D3 - Product data source (format of appearance): In line with existing studies [29,30], scenario identification and discussion with experts demonstrated the necessity of another dimension to describe the product data source in terms of format of appearance (D3).

Dimension		Characteristics				
Input	D1 - Approach to data collection	C1.1 - Reactive approach (ex post)			C1.2 - Proactive approach (ex ante)	
	D2 - Product data source (level of abstraction)	C2.1 - Product instance			C2.2 - Product class	
	D3 - Product data source (format of appearance)	C3.1 - Structured data		C3.2 - Semi-structured data		C3.3 - Unstructured data
Processing	D4 - Complexity of feedback processing	C4.1 - Low complexity		C4.2 - Medium complexity		C4.3 - High complexity
	D5 - Degree of feedback processing autonomy	C5.1 - Manual feedback processing		C5.2 - Partially automated feedback processing		C5.3 - Automated feedback processing
Output	D6 - Degree of product novelty	C6.1 - New product development			C6.2 - Product improvement	
	D7 - Addressed product development stage	C7.1 - Product conceptualization		C7.2 - Product definition		C7.3 - Product realization
	D8 - Enabled business benefit	C8.1 - Specification of requirements	C8.2 - Customer-centric product portfolio planning		C8.3 - Design for usage	C8.4 - Shortening of physical prototyping
	D9 - Enabled increase in value (neutral)	C9.1 - Technical	C9.2 - Economic	C9.3 - Environmental	C9.4 - Social	C9.5 - Combinations

Table 4. Towards a taxonomy for feedback-driven product development scenarios

In this dimension, the format of appearance structured data (C3.1), semi-structured data (C3.2), and unstructured data (C3.3) may be distinguished. Whereas structured data typically encompass measures or meta-data such as sensor data, unstructured data usually consist of text, pictures, audio, and video [29,30]. In most scenarios, interviewees drew on structured measures such as sensor data in all variant forms (e.g., mechanical, kinematic, thermal, and fluid), but also saw potentials for value-adding insights from unstructured data in some scenarios.

D4 - Complexity of feedback processing: Identified scenarios were described by a wide spectrum of feedback acquisition, modeling, reasoning, and distribution techniques as classified in [38]. Hence, D4 summarizes this complexity of feedback processing. From very basic procedures (e.g., tracking of operating hours) (C4.1) to complex data analyses (e.g., naturalistic driving studies) (C4.3), identified scenarios exhibited strongly diverse processing complexity. It is the purpose to demonstrate the importance of this dimension in the context of feedback-driven product development, rather than to present technical details which are not specific and can be found in existing work [38].

D5 - Degree of feedback processing autonomy: Various working modes of integrating the feedback into the product development activities are conceivable. Indicated by the case studies and grounded in extant work [7], D5 describes the degree of feedback processing autonomy. Feedback can be incorporated completely manually (C5.1), partially automated (C5.2), or completely automated (C5.3). Although manually accomplished activities by the design and simulation engineers clearly outweigh in most empirically derived scenarios, product development professionals forecasted a higher level of automation in the design process. In literature, this

paradigm shift from manual to automated feedback integration is labeled as “cloud-based automated design and additive manufacturing” [7:32079].

D6 - Degree of product novelty: In terms of possible applications of the gathered and processed feedback from digitized products, empirical evidence demonstrated a wide spectrum of possible purposes. In line with Pahl and Beitz [67], D6 refers to the degree of product novelty. Feedback can be harnessed to support new product development (C6.1) or product improvement (C6.2). In the case of new product development, feedback is applied to solve new problems and tasks under consideration of new solution principles [67]. In contrast, feedback can also be leveraged for the further development of existing devices utilizing the extant solution principles [67]. Product development professionals assessed the strongest impact on optimizing similar products from generation to generation, but also appreciated feedback for entering new terrains.

D7 - Addressed product development stage: During the interviews with different roles from various engineering departments, it became apparent that feedback is applicable in various product development phases. Accordingly, D7 distinguishes the addressed product development stages into product conceptualization (C7.1), product definition (C7.2), and product realization (C7.3), which goes in line with the approved product lifecycle stage model [2,3,4]. However, scenarios were not distributed equally, most scenarios referred to the early product conceptualization stage. Industry experts appreciated feedback especially for these early stages as the product definition with the determination of lifecycle implications and costs typically occurs in the very beginning of the product lifecycle [27].

D8 - Enabled business benefit: A pivotal dimension which was inductively derived from the scenarios, is the enabled business benefit for the manufacturers through feedback from the field. In

line with the established product development framework [27], D8 distinguishes four feedback benefits: First, feedback enables the specification of requirements (C8.1). Second, from a holistic perspective, feedback supports the creation of a customer-centric product portfolio (C8.2). Third, by the aid of feedback, products can be designed for usage overcoming assumption- and experience-based development processes (C8.3). Finally, feedback has the potential to shorten and replace physical prototyping and field testing (C8.4). In terms of enabled business benefits, the scenarios' focus lied on early lifecycle stages.

D9 - Enabled increase in value (neutral): With reference to the manufacturer-independent increase in value, identified scenarios demonstrated various manifestations (D9). In line with the classification by Kiritsis et al. [68], we distinguish technical (C9.1), economic (C9.2), environmental (C9.3), social (C9.4), and combined (C9.5) benefits. Although some empirically derived scenarios clearly address one main increase in value (e.g., economic benefit through optimized selection of purchase components), most scenarios featured combinations (e.g., optimized dimensioning of components resulting in technical, environmental, and social benefits).

5. Discussion

With the purpose to illustrate the relevance and usefulness, we discuss the developed taxonomy by the aid of an exemplary scenario. We selected the scenario "Finite element method dimensioning with real loads from the field" which has been in the spotlight in our data collection, but also in practitioners' literature [69] recently. In a nutshell, this scenario describes an activity sequence where environmental and usage loads such as forces and torsional moments are collected from the installed base in order to provide more realistic input for finite element method (FEM) simulations (e.g., structural or thermal analyses). Although these FEM simulations are very accurate from a modeling and computation viewpoint, these approaches suffer from insecure assumptions in terms of input loads. Table 5 illustrates the scenario with the correspondent dimensions and characteristics.

As a matter of principle, the scenario attempts to optimize prospect products predicting the presumable product usage through large-scale data collection with subsequent tailored product design, accordingly the approach to data collection (D1) is proactive. In order to ensure exhaustiveness, product data (D2) from all product instances need to be collected. With discrete sensor data being gathered, their format of appearance (D3) can be characterized as structured. This feedback serves as input for the numerical approximation of differential equations, hence, the

scenario's feedback processing complexity (D4) can be described as rather high. To this day, the degree of feedback autonomy has partially automated processing character (D5) as both automated (e.g., data collection and storage) and manual tasks (e.g., CAx design and simulation) are required. The scenario targets the development of future products with a rather small degree of product novelty (D6), namely product improvement of existing products. Furthermore, feedback is utilized in the product development stage (D7) of product definition determining geometries and properties of the component. The obtained business benefit (D8) is optimized design for usage. Finally, the enabled increase in value (D9) is a combination of technical, environmental, and social values.

Table 5. Scenario "Finite element method dimensioning with real loads from the field"

	Dimension	Characteristic
Input	D1 - Approach to data collection	C1.2 - Proactive approach (ex ante)
	D2 - Product data source (level of abstraction)	C2.1 - Product instance
	D3 - Product data source (format of appearance)	C3.1 - Structured data
Processing	D4 - Complexity of feedback processing	C4.3 - High complexity
	D5 - Degree of feedback processing autonomy	C5.2 - Partially automated feedback processing
Output	D6 - Degree of product novelty	C6.2 - Product improvement
	D7 - Addressed product development stage	C7.2 - Product definition
	D8 - Enabled business benefit	C8.3 - Design for usage
	D9 - Enabled increase in value (neutral)	C9.5 - Combinations

6. Conclusion

In the course of this paper, the development process of a taxonomy for feedback-driven product development scenarios in manufacturing industries was discussed. Our research was initiated by limited understanding how product usage data can be harnessed for product development although digital technologies created the potential of making the whole product lifecycle visible. Anchored in (1) empirical data and (2) a systematic literature review, our research followed the method for taxonomy development as suggested by Nickerson et al. [12]. Prior literature has acknowledged product usage data notably for maintenance purposes [31,32]. Results reinforce the existence of fruitful potentials for product development objectives as well. Furthermore, results demonstrate the multi-faceted manifestations of feedback-driven product development. Despite these new opportunities, critical issues such as ethic and legal aspects are important to mention which were intensively discussed within the interviews.

To our knowledge, this study is the first to investigate the role of digital product innovation for product development from a classification model perspective. The developed taxonomy bridges industry specifics and is evaluated in an artificial setting [66]. Following Gregor [70] who puts a taxonomy on a level with a “theory for analysis”, our work can be regarded as a “type one theory” enabling analysis and description without a prediction component. In addition, we provide a methodological example how to combine scenario- and classification-based approaches which may be helpful for other scholars investigating similar phenomena. Beyond, information systems is an inherently interdisciplinary field and thus requires to look into other areas [45,65]. With this paper, we link the domain of information systems with product development.

Apriori, we would like to stimulate product developers and decision makers for a more holistic lifecycle thinking. Manufacturers should assess and exploit new opportunities emerging from digital product innovation. The developed taxonomy may act as guiding and structuring, but also creativity fostering element in the vast, but diffuse opportunities that arise from new technological advances. First, the taxonomy helps to understand the different types of feedback-driven product development. Manufacturers can bring transparency in the numerous ideas from their R&D departments they are confronted with. Second, the taxonomy also supports the playful ideation of so far unknown configurations. Known scenarios can be modified by varying characteristics and new scenarios can be generated by recombining characteristics. Hence, our classification model serves as a foundation to make the right decisions in the competitive market environment of manufacturing industries.

However, there are some important concerns to our research. First, referring to the empirical-to-conceptual approach, our research design was qualitative and interpretive. Second, referring to the conceptual-to-empirical approach, our literature review needs to be characterized as non-exhaustive. Given the early stage of research, we cannot guarantee exhaustiveness.

Following the understanding of design as search process [45,46], the taxonomy may be validated in a more naturalistic setting (EVAL4) with consequent iterative adaption of dimensions and characteristics. Additionally, examining feedback-driven product development from technological, economic, and legal viewpoints seem promising avenues for further research. Furthermore, digitized products may be studied in other contexts such as feedback-driven service development. For these tasks, the paper at hand provides first insights and represents a steady starting point.

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Article #3 – Contribution C

Bibliographical details

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Abstract

The automotive industry represents one of the most relevant industrial sectors of the global economy. In response to a plethora of challenges, e-collaboration for product development has become a nexus of competitive advantage in the automotive world. Since new dynamics in organizational forms on the one hand and advancements in engineering information systems on the other hand have led to increased complexity, a classification model to organize and structure the manifold manifestations seems analytically useful. Hence, the paper at hand (1) proposes, (2) describes, and (3) validates archetypes of e-collaboration for product development in the automotive industry. Anchored in (1) a structured literature review and (2) rich empirical evidence from a multiple-case study in the automotive ecosystem, we organize our research study along a well-established, two-stage research method on archetypes adopting a socio-technical systems perspective. Key findings include the archetypes (1) mechanical development-dominant, (2) software development-dominant, (3) systems engineering-oriented, and (4) non-development-focused e-collaborations for product development as basic patterns. Thereby, “importance of mechanical development” and “importance of software development” act as essential classification dimensions. Keeping the inherent limitations of the qualitative research tradition in mind, this paper offers theoretical, methodological, managerial, and cross-disciplinary contributions.

DEFINING ARCHETYPES OF E-COLLABORATION FOR PRODUCT DEVELOPMENT IN THE AUTOMOTIVE INDUSTRY

Research paper

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Abstract

The automotive industry represents one of the most relevant industrial sectors of the global economy. In response to a plethora of challenges, e-collaboration for product development has become a nexus of competitive advantage in the automotive world. Since new dynamics in organizational forms on the one hand and advancements in engineering information systems on the other hand have led to increased complexity, a classification model to organize and structure the manifold manifestations seems analytically useful. Hence, the paper at hand (1) proposes, (2) describes, and (3) validates archetypes of e-collaboration for product development in the automotive industry. Anchored in (1) a structured literature review and (2) rich empirical evidence from a multiple-case study in the automotive ecosystem, we organize our research study along a well-established, two-stage research method on archetypes adopting a socio-technical systems perspective. Key findings include the archetypes (1) mechanical development-dominant, (2) software development-dominant, (3) systems engineering-oriented, and (4) non-development-focused e-collaborations for product development as basic patterns. Thereby, “importance of mechanical development” and “importance of software development” act as essential classification dimensions. Keeping the inherent limitations of the qualitative research tradition in mind, this paper offers theoretical, methodological, managerial, and cross-disciplinary contributions.

Keywords: Archetypes, Types, Classification, e-Collaboration, Product development, Product lifecycle management, Automotive industry.

1 Introduction

With a forecasted market size of 6,700 billion US-Dollar in 2030 (McKinsey & Company, 2016), the automotive industry represents one of the most relevant industrial sectors of the global economy. Fueled by digital technologies (Yoo et al., 2010; Yoo et al., 2012; Fichman et al., 2014), this economic branch is exposed to a plethora of challenges: On the one hand, non-traditional product innovations such as autonomous vehicles and business model innovations such as mobility on demand emerge. On the other hand, traditional forces on cost- and time-to-market reduction and quality enhancement remain (Ebel and Hofer, 2016). In this demanding milieu, the ability to launch innovative products in an effective and efficient manner is more pivotal than ever for today’s automotive product development departments (Clark and Fujimoto, 1991; Brown and Eisenhardt, 1995; Nambisan, 2013).

In response to this competitive pressure, stakeholders in the automotive industry increasingly organize in more open, global, and collaborative forms such as customer-supplier networks, strategic alliances, and joint ventures (Chesbrough, 2003; von Hippel, 2005; Büyüközkan and Arsenyan, 2012) to enable value co-creation (Vargo et al., 2008; Lusch and Nambisan, 2015). Comprehensively conceptualized as “collaboration among individuals engaged in a common task using electronic technologies” (Kock

et al., 2001, p.1), e-collaboration occupies an essential role in these decentralized product development and innovation activities. In the highly interwoven automotive ecosystems, different stakeholders ranging from original equipment manufacturers (OEMs), suppliers, and research centers of any kind collaborate in many different forms utilizing a variety of information systems (Howells, 2008; Büyüközkan and Arsenyan, 2012; Kalluri and Kodali, 2014).

Reinforced by this (1) heterogeneity of organizational forms and the (2) complexity and diversity of systems, scholars as well as practitioners are challenged by the manifold manifestations of e-collaboration for product development (Howells, 2008; Terzi et al., 2010; Büyüközkan and Arsenyan, 2012). Thus, against the backdrop of understanding the phenomenon, a classification model to organize and structure these e-collaborations seems analytically useful. Although product development and e-collaboration in knowledge-intensive industries are established areas of research, little efforts have been made from a classification perspective. Moreover, a review of literature unveiled that despite this urgent need (1) automotive peculiarities, (2) the socio-technical nature, and (3) the real-world character of e-collaboration for product development are understudied. With e-collaboration understood as socio-technical system (Bostrom und Heinen, 1977; Rutkowski et al., 2002; Alter, 2008), the information systems domain seems well eligible to address this research gap.

Hence, we follow recent calls for research (Howells, 2008; Büyüközkan and Arsenyan, 2012; Nambisan, 2013; David and Rowe, 2015) and propose archetypes of e-collaboration for product development in the automotive industry. Rooted in (1) a structured literature review (vom Brocke et al., 2009) and (2) rich empirical evidence from a multiple-case study (Yin, 2003) in the automotive ecosystem, we organize our research study along the well-established research method by Greenwood and Hinings (1993). More precisely, this paper intends to tackle the following research questions:

[RQ1] *“What are potential archetypes of e-collaboration for product development in the automotive industry?”*

[RQ2] *“What are socio-technical characteristics of the proposed archetypes of e-collaboration for product development in the automotive industry?”*

[RQ3] *“How can the proposed archetypes of e-collaboration for product development in the automotive industry be leveraged for the classification of real-world cases?”*

In order to address these research questions, the study at hand is organized as follows: Section two provides an overview on the theoretical background (i.e. product lifecycle management and e-collaboration) and reviews related work. Section three introduces the applied research methodology in terms of structured literature review and case study research. Section four (1) presents the archetypes, (2) describes them with characteristics, and (3) maps them with the accomplished case studies. Section five critically discusses the findings. Lastly, section six closes the study with a summary, contributions, limitations, and avenues for further research.

2 Theoretical Background

2.1 Product lifecycle management and product development

Inspired by the biological lifecycle of organisms, lifecycle theory culminated in two climaxes (Sundin, 2009; Cao and Folan, 2012). In the 1960s, the holistic, sales-oriented perspective emerged. The sales-oriented view distinguishes the stages market development, market growth, market maturity, and market decline (Cao and Folan, 2012). Addressing the criticism that the market as unit of analysis may be too imprecise, the more fine-grained and product-individual, engineering-oriented perspective appeared in the 1970s. The engineering-oriented view proposes the segmentation into beginning-of-life (BOL), middle-of-life (MOL), and end-of-life (EOL) phases (Cao and Folan, 2012). Thereby, BOL includes product conceptualization, definition, and realization. MOL contains product usage, service, and maintenance. EOL comprises a spectrum of options from refurbishing to disposal (Terzi et al., 2010; Stark, 2015). Against this backdrop, product lifecycle management can be regarded as a comprehensive business strategy of managing a company’s products all the way across their lifecycles, supported by a broad range of underlying information systems (Terzi et al., 2010; Stark, 2015).

Building on this logic, product development can be assigned to the initial stages of the product lifecycle. Broadly speaking, product development comprises “all tasks beginning with the perception of a market opportunity and ending in the production, sales, and delivery” (Ulrich and Eppinger, 2008, p.2). More precisely, paraphrasing Eigner and Roubanov (2014, p.7), product development includes “all activities and disciplines that describe the product and its production, operations, and disposal over the product lifecycle, engineering disciplines, and supply chain”. As central business process, management (e.g., Clark and Fujimoto, 1991; Brown and Eisenhardt, 1995) as well as engineering disciplines (e.g., Andreasen and Hein, 1987; Pahl and Beitz, 2007) have made fruitful contributions (Kalluri and Kodali, 2014). For this paper, two aspects should be emphasized: First, after a stepwise evolution with influences from R&D management, marketing, organization, strategy, and operations research within the last half a century, product development is nowadays conceived as IT-enabled innovation process (Nambisan, 2003). Second, in their literature review, Büyüközkan and Arsenyan (2012) highlight the collaborative, integrative, and strategic nature of product development.

2.2 e-Collaboration information systems for product development

When it comes to describing computer-supported collaboration among individuals, groups, and organizations, a vast amount of concepts can be encountered in literature. Among others, the notions computer-supported cooperative work (e.g., Kock et al., 2001), engineering collaboration (e.g., Molina et al., 2005), and e-collaboration for product development (e.g., Lefebvre et al., 2006) become evident. For the study at hand, we selected the nomenclature of e-collaboration as it fulfils several criteria: First, as powerful and fundamental concept, the umbrella term enables us to grasp the manifold manifestations of product development as demonstrated by Lefebvre et al. (2006). Second, understood as socio-technical system (Bostrom und Heinen, 1977), we are able to take both social and technical aspects into account which goes in line with our research objective. Finally, the concept is well-established in the information systems domain (Kock et al., 2001), where we ground our research in and aim to contribute to. Thereby, e-collaboration encompasses aspects of communication, cooperation, and coordination (Leimeister, 2014). In sum, e-collaboration for product development enables team members to jointly work on product-related information and to be seamlessly integrated in the development (Lefebvre et al., 2006).

Each stage of the product development process is empowered by a wide range of engineering information systems and e-collaboration tools (e.g., computer-aided design, engineering, and software engineering) (Molina et al., 2005; Li and Qiu, 2006; Eigner and Roubanov, 2014). Indicated by the diverse concepts, there exists no general consensus on tools for e-collaboration for product development. In line with Eigner and Roubanov (2014), product developers commonly operate and collaborate in five main areas: Product data management, production development, customer needs management, material sourcing, and management support. It should be accentuated that collaborative product development environments are intelligent combinations of specialized systems and may not be viewed as one singular tool (Molina et al., 2005; Li and Qiu, 2006). From an IT architecture perspective, four-layer models representing author systems, team data management, product lifecycle management backbone, and enterprise resource planning are prevalent. Thereby, e-collaboration is realized by specific collaboration tools and integrations respectively interfaces (Eigner and Roubanov, 2014). To optimize product characteristics at an early stage and to reduce resource-intensive physical prototypes, the subject model-based, virtual product development gains relevance (Eigner and Roubanov, 2014).

2.3 Related work

Upon the interdisciplinary character of the phenomenon of interest, we draw on prior research in relevant disparate research communities such as information systems, new product development, and computer science. A structured literature review (section “3.2 Literature review”) unveiled that studies addressing the interface of e-collaboration and product development in manufacturing industries, particularly studies related to classification, seem to be scarce and limited. Examples include: Bell and

Kozlowski (2002) developed a typology of virtual teams on the basis of conceptual research with the goal to derive implications for leadership. Thereby, virtual teams are initially distinguished from conventional teams (dimensions: spatial distance and communication) and then, types of virtual teams are differentiated (dimensions: member roles, boundaries, temporal distribution, and lifecycle). Gassmann and von Zedtwitz (2003) classed distinct forms of virtual team organizations for R&D projects anchored in empirical data. At that, the dimensions (1) type of innovation, (2) systemic nature of the project, (3) mode of knowledge involved, and (4) degree of resource bundling serve as basis for differentiation. Ostergaard and Summers (2009) developed a systematic classification of collaborative design activities grounded in an interdisciplinary literature review. Thereby, the design activities are classified by the dimensions (1) team composition, (2) communication, (3) distribution, (4) design approach, (5) information, and (6) nature of the problem with the superordinate objective to develop appropriate collaboration tools.

Synthesizing the extant body of literature (Kock et al., 2001; Orlikowski and Iacono, 2001; Büyüközkan and Arsenyan, 2012; Kalluri and Kodali, 2014): First, the characteristics and specificities of the automotive industry including stakeholder organization and supporting engineering information systems have not been taken into account in an adequate way. Second, the socio-technical nature of e-collaboration has been comparatively neglected, studying either pure technical or mere social aspects. Finally, extant studies frequently target narrow issues, often in a controlled setting, which seems applicable to the profoundly industry embedded phenomenon to a limited extent solely. Hereinafter, we address this research gap by a qualitative classification approach.

3 Research Methodology

3.1 Methodological foundations

The purpose of this paper is to classify the abundant forms of e-collaboration for product development in the automotive industry. In particular, we refer to the automotive business-to-business context with inter-organizational forms of e-collaboration as unit of analysis. Well-established models – “representations of how things are” (March and Smith, 1995, p.256) – to assist scholars and practitioners understand and analyze complex domains are classification models which organize objects of interest (Bailey, 1994; Nickerson et al., 2013). As common activity in sciences of any kind, even in our daily lives, the process of classification exhibits polymorphic facets. In the discourse on classification in social sciences, routinely (theoretically derived) typologies and (empirically derived) taxonomies are distinguished (Carper and Snizek, 1980; Doty and Glick, 1994). A useful approach to study organization design and change in a fundamental way with emerging interest are archetypical models which depict archetypes (Greenwood and Hinings, 1993).

In a simplified sense, archetypes may be regarded as basic patterns of organizing (Greenwood and Hinings, 1993). Following this, archetypical models are frequently regarded as antecedents of more advanced classifications. More precisely, archetypes are conceptualized as “a set of structures and systems that reflects a single interpretative scheme” (Greenwood and Hinings, 1993, p.1052). In line with Greenwood and Hinings (1993), we lay emphasis on two aspects: First, the analysis of overall patterns seems more suitable for understanding organizational structures and systems than the analysis of closely circumscribed properties. Second, these overall patterns are dependent of the underlying beliefs and values, hence, exhibit a strong interpretive character. In historical terms, archetypes are rooted in psychology literature. At a later time, the archetype concept has gained peculiar attention in strategy literature (Mintzberg, 1973; Miller and Friesen, 1978).

The selection of a research approach of this type is put forth along two lines: On the one hand, the derivation of overall patterns seems a proper method in consideration of our research objective of an initial classification. On the other hand, the proposition and validation of archetypes has been applied successfully for a variety of similar issues in contiguous scientific disciplines, such as open innovation (von Zedtwitz and Gassmann, 2002) or business model innovation (Bocken et al., 2014). Reviewing literature, several (arche-) typical models can be detected (e.g., Geiger et al., 2012; Haas et al., 2014).

However, there is no coincidence in terms of applied terminology (types, archetypes) and used methodologies (conceptual, empirical, combined methods). For the sake of scientific rigor and transparency, this study follows the well-established method introduced by Greenwood and Hinings (1993) and applied by Willner et al. (2016). In line with Greenwood and Hinings (1993), our research process encompasses two main stages:

[Stage 1] *Conceptualizing archetypes grounded on literature review and empirical evidence*

[Stage 2] *Empirically validating and iteratively refining the conceptualized archetypes*

Having formulated the proposition (Yin, 2003) that archetypes exist, we conceptualize archetypes grounded on literature review and empirical evidence in stage 1. Thereby, a structured literature review following vom Brocke et al. (2009) lays the groundwork. From an empirical viewpoint, exploratory case studies according to Yin (2003) and exploratory focus groups in line with Morgan (1988) are conducted to sensitize the conceptualization process. We neither follow a pure conceptual nor a pure empirical approach, but pursue a two-sided approach, as emphasized by Nickerson et al. (2013). In stage 2, we empirically validate and iteratively refine the conceptualized archetypes by classification of cases in an additional round of case studies and focus groups.

3.2 Literature review

Objectives and methods In order to ground our conceptual work in the body of knowledge, we performed a structured literature review following the established approach by vom Brocke et al. (2009). In addition, contributions from Cooper (1988) and Webster and Watson (2002) backed the review process from a methodological point of view. The purpose of this review is to (1) obtain an overview on related work (section “2.3 Related work”) and to (2) explore extant classifications and conceivable dimensions for the subsequent archetype conceptualization process.

Data collection Referring to Cooper’s framework (1988), our review exhibits the following boundary conditions: We focus on research outcomes. Our goal is the identification of central issues. The review findings are presented neutrally. The coverage has representative character. We target to inform general and specialized scholars as well as practitioners. Owing to the interdisciplinary nature of the review subject, the conceptualization of the topic was demanding. Hence, we carefully screened standard references and intensively discussed with senior scholars and professionals to carve out a graphic concept map. This concept map composed of synonyms, superordinate, infraordinate, and related terms ultimately resulted in the search string “(“classification” OR “taxonomy” OR “typology” OR “archetype”) AND (“product development” OR “product engineering” OR “R&D”) AND (“*collaborat*”)” which was applied for the literature key word search in major scientific databases. In brief, the rationale for the selection of this search string is based on our research objective, comprising (1) classification-related, (2) product development-related, and (3) collaboration-related constituents with manageable variation. Where available, database fields title, abstract, and key words were searched. With the objective to incorporate the most recent articles, we considered a publishing time frame from November 2001 to November 2016. In aggregate form, Table 1 illustrates the conducted literature search and results.

Publisher	Database	Net hits	Results
Association for Information Systems	AIS Electronic Library	0	0
EBSCO Information Services	EBSCOhost	228	10
Elsevier	Science Direct	15	1
Emerald	Emerald	238	3
ProQuest	ABI/INFORM Collection	215	9
Springer	SpringerLink	0	0
Thomson Reuters	Web of Science	206	12
Interim results (inclusion/exclusion)		Σ 902	Σ 35
- Duplicate removal			- 3
- Forward/backward search			+ 12
- Recommendations			+ 4
Final results			Σ 48

Table 1. *Literature search and results*

Data analysis To include all potentially relevant contributions and not to exclude pertinent ones in advance, a comprehensive initial search resulting in a large number of articles was conducted. Given this broad search, it was necessary to exclude a large amount of non-relevant publications during data analysis. The literature key word search initially equaled to 902 articles which were examined in a two-level approach reviewing title and abstract. On the basis of the review purpose and overarching research objective, inclusion/exclusion criteria were elaborated: Articles are included if the publication contains (1) content at the intersection of e-collaboration and product development in manufacturing industries, (2) a concrete classification, or (3) conceivable dimensions for the subsequent archetype conceptualization process. In contrast, we particularly excluded publications that (1) focalize on highly technical and mathematical issues, (2) lack in sufficient (explicit or implicit) statements, or (3) do not meet rigorous scientific requirements such as panel discussions and practice commentaries. From the remaining 35 articles we removed duplicates (3 articles), executed a forward/backward search process (12 articles), and integrated recommendations by senior scholars and skilled practitioners (4 articles). In total, the overall count of publications for in-depth full-text investigation equaled to 48 papers.

3.3 Case study research

Objectives and methods In order to ground our conceptual work in empirical data rich in content and for the purpose of triangulation (Yin, 2003), a pluralistic policy regarding data sources and collection methods was applied. More precisely, case study research following Yin (2003), Eisenhardt (1989), and Benbasat et al. (1987) complemented by focus group research following Morgan (1988), Nielsen (1997), and Tremblay et al. (2010) served as methodological guidance. A case study represents an “empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident” (Yin, 2003, p.13), which fits to the real-world phenomenon under investigation. The purpose of the qualitative research is to (1) explore potential dimensions and characteristics that may describe e-collaboration for product development for the subsequent archetype conceptualization process and to (2) identify concrete cases of e-collaboration (objects of interest) for classification and validation.

Data collection Primarily, semi-structured interviews and focus groups served as sources of evidence (Yin, 2003). As proposed by Lincoln and Guba (1989) and Coyne (1997), we applied purposeful theoretical sampling for the case organizations, focus group participants, and conversational partners. Thereby, one of the main organizational theories – stakeholder theory (Freeman, 1984; Donaldson and Preston, 1995) – acted as sensitizing device. The stakeholder model proposes that a firm has stakeholders such as investors, political groups, customers, communities, employees, trade associations, suppliers, and governments. Transferred to the research milieu of e-collaboration for automotive product development, the stakeholder model primarily includes OEMs, suppliers, research institutes, and start-ups of any kind (Sturgeon et al., 2008; Sturgeon et al., 2009). Although relationships increasingly evolve from hierarchical supply pyramids to interwoven networks, OEMs still represent the focal point as customer interface. In consideration of our research focus, we excluded non-development-related e-collaboration between stakeholders such as political groups and governments. Through a consortium research approach (Österle and Otto, 2010), we had the opportunity to study case organizations in an intensive way from an inside perspective. In addition, we had the chance to incorporate cases from automotive innovation hubs like Singapore and Silicon Valley (Ebel and Hofer, 2016).

In order to achieve an initial lucid picture, interview partners and workshop participants which held senior managerial and technical responsibilities from relevant R&D departments were selected. With the objective to understand the emerging issues better, snowball sampling (Lincoln and Guba, 1989; Coyne, 1997) was used to identify more specialized informants. These sampling strategies were applied until saturation and additional data unveiled only minimal further information. The utilized interview questionnaire was designed along recommendations by Schultze and Avital (2011), the employed guideline for the focus groups was developed along principles by Tremblay et al. (2010). Both guidelines were harnessed to explore the following e-collaboration topics: Background of the interviewee and case organization, strategic, processual, organizational, cultural, social, and

information technology-related aspects. Auxiliaries were iteratively adapted over the course of the research process. In order to ensure a rigorous processing, all audio was recorded, anonymized, and transcribed. Interviews and focus groups were enriched by supplementary data (Yin, 2003) such as participation in company meetings, company presentations, and publicly available data. Qualitative and quantitative data were collected in a case study database (Yin, 2003) for subsequent analysis. Table 2 provides an overview on involved case organizations and sources of evidence.

Case organization	Description	Characteristics (HQ ¹ , EE ²)	Sources of evidence
OEM _{Alpha}	Traditional OEM (luxury segment)	Germany, 100,000+	2 interviews, supplementary data
OEM _{Beta}	Traditional OEM (mid-range segment)	Germany, 100,000+	2 interviews, supplementary data
OEM _{Gamma}	Non-traditional OEM (luxury segment)	United States, 1,500+	1 interview, supplementary data
Supplier _{Alpha}	Tier-one supplier (mechatronic modules)	Germany, 7,000+	4 interviews, 3 focus groups, suppl. data
Supplier _{Beta}	Tier-one supplier (mechanical modules)	Germany, 3,000+	2 interviews, 2 focus groups, suppl. data
Research institute _{Alpha}	Research institute (complete vehicle)	Singapore, 100+	1 interview, supplementary data
Research institute _{Beta}	Research institute (digital innovation)	Switzerland, 50+	2 workshops, supplementary data
Start-up _{Alpha}	Start-up (vehicle design and concepts)	Switzerland, 30+	1 interview, supplementary data
Start-up _{Beta}	Start-up (autonomous driving)	Switzerland, 10+	2 interviews, supplementary data
Car sharing _{Alpha}	Mobility provider (OEM-dependent)	Germany, 500+	1 interview, supplementary data
Car sharing _{Beta}	Mobility provider (independent)	Switzerland, 150+	1 interview, supplementary data

¹ HQ = Country of headquarters // ² EE = Number of employees (approximate numbers of fiscal year 2015)

Table 2. Case organizations and sources of evidence

Data analysis Congruent with the exploratory research strategy, we made use of grounded theory techniques (Strauss and Corbin, 1990; Strauss and Corbin, 1997) for data analysis. More precisely, open, axial, and selective coding procedures were performed. In the course of the open coding phase (1) the transcribed interviews were broken into codes, categories, and subcategories. During the axial coding phase (2) systematic connections between categories and subcategories were developed. Over the selective coding phase (3) core categories were chosen and categories and subcategories were reorganized (Strauss and Corbin, 1990; Strauss and Corbin, 1997). Thereby, the data analysis started as early as the first data were collected as recommended by Miles and Huberman (1994). For the coding processes, computer-assisted qualitative data analysis software (CAQDAS) NVIVO 10 was harnessed as advised by Alam (2005) and Sinkovics et al. (2005). During this systematic aggregation, several dominant themes emerged, among them “importance of mechanical development” with 322 open codes and “importance of software development” with 217 open codes.

In addition to comprehensive *ex post* validation activities (section “4.3 Empirical validation of archetypes”), ample *ex ante* efforts regarding quality assurance (Yin, 2003) were undertaken. First, we aimed to increase internal validity by comparing different sources and accomplishing cross-checks. Second, we strived to enhance external validity by involving diverse cases in terms of product portfolio and organization size. Finally, constantly seeking for scientific rigor across the whole study operations, we targeted reliability. Particularly, for investigator triangulation (Miles and Huberman, 1994), two researchers coded the data independently and discussed differences. Upon the diversity of data sources, we selected the basic measure “percent agreement” (Lombard et al., 2002) to calculate the intercoder reliability (intercoder agreement). The resulting coefficient of 78 percent seems acceptable within the frame of our exploratory research strategy (Lombard et al., 2002).

4 Archetypes of e-Collaboration for Product Development

4.1 Conceptualizing template structure and dimensions

In order to answer research question I (“What are potential archetypes of e-collaboration for product development in the automotive industry?”), we conceptualize (1) an archetype template and (2) the associated archetypes grounded on the previously introduced foundations. With the goal to make these conceptualization steps transparent and comprehensible, we stick to the guidelines for conceptual papers by Hirschheim (2008) in aspects such as presentation and structure and data analysis/interpretation/argumentation.

Apriori, we propose a two-dimensional archetype template where the archetypes are conceptualized. Such a parsimonious representation fits very well with our research objective of an initial classification and has been proven as suitable in similar research contexts (e.g., Kaufmann et al., 2000; von Zedtwitz and Gassmann, 2002; Willner et al., 2016). Regarding the dimensions of this archetype template, it became evident in various ways (Nickerson et al., 2013) that the dimensions “importance of mechanical development” and “importance of software development” are essential for classifying e-collaborations for product development in the automotive industry. The key rationale for the selection of these dimensions is put forth along the following line: On the one hand, mechanical development has represented the center in cost- and time-to-market-driven environments in the past. On the other hand, software development will become the focal area in innovation- and information technology-driven market environments in the future. In the template, the horizontal axis represents the “importance of mechanical development” and the vertical axis represents the “importance of software development”, both dichotomized from low to high. Whereas a spectrum of quantitative metrics may be applicable, we decided not to apply a number-based scheme as we follow the tradition of qualitative research. Figure 1 depicts both template and herein situated archetypes.

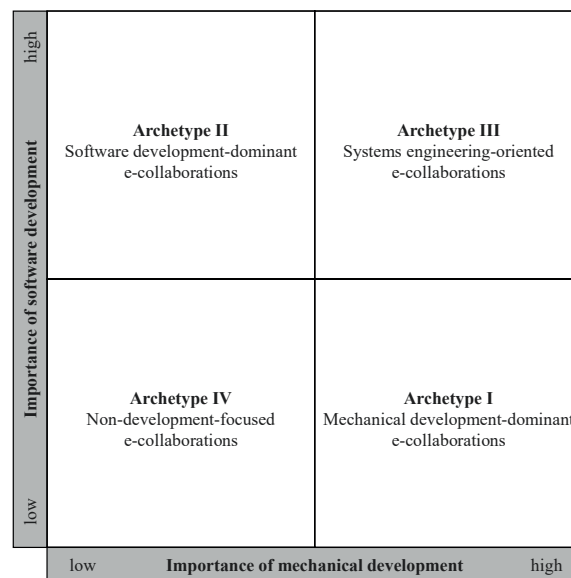


Figure 1. Towards archetypes of e-collaboration for product development

Evidence for this reasoning can be unkenneled in both approaches (Nickerson et al., 2013): First, in the literature review this argumentation is supported by Clark and Fujimoto (1991) and Ulrich and Eppinger (2008) from the mechanical development perspective and by Nambisan (2013) and Porter and Heppelmann (2014, 2015) from the software development perspective. For example, Porter and Heppelmann (2015, p.100) argue that “at the most basic level, product development shifts from largely mechanical engineering to true interdisciplinary systems engineering.” Second, in the case study research the line of argument for the dimension “importance of mechanical development” is underpinned by 322 open codes, the line of argument for the dimension “importance of software development” is substantiated by 217 open codes. In order to illustrate these codes, we provide “thick” and context-rich data within the limited space available: “Currently, we reorganize our supplier management and develop a group-wide supplier strategy. In the assessment process, you see this spectrum of rather traditional suppliers relying on the efficient development of physical components and rather new players leaning onto software-driven innovations – with anything in-between these extremes.” (Senior executive supplier management of OEM_{Beta}). In the introduced template, four archetypes were conceptualized which are subsequently elucidated in detail.

4.2 Conceptualizing and characterizing the archetypes

AI: Mechanical development-dominant e-collaborations Mechanical development-dominant e-collaborations are designated by a high importance of mechanical development and a low importance of software development. Illustrative examples for this archetype may be traditional OEM and tier-one supplier relationships which collaboratively design and manufacture pure physical components such as car body structures, powertrain components, or drivetrain assemblies.

AII: Software development-dominant e-collaborations Software development-dominant e-collaborations are characterized by a low importance of mechanical development and a high importance of software development. Exemplary instances for this archetype may be OEM and engineering office relationships jointly blueprinting and implementing control systems for car body, powertrain, or media applications for future vehicles.

AIII: Systems engineering-oriented e-collaborations Systems engineering-oriented e-collaborations are denoted by both – a high importance of mechanical development and software development. Exemplifying samples for this archetype may be relationships of large OEMs working together with equally powerful tier-one suppliers on highly complex mechatronic systems composed of mechanical components, electric/electronic elements, and software constituents such as digitally controllable, electro-mechanic power transmissions.

AIV: Non-development-focused e-collaborations Non-development-focused e-collaborations are described by a low importance of mechanical development and a low importance of software development. Clarifying cases for this archetype may be relationships between OEMs and market research institutes focusing on innovation management before technical realization with a generally low involvement in product development activities.

Characterization methodology With the objective to answer research question 2 (“What are socio-technical characteristics of the proposed archetypes of e-collaboration for product development in the automotive industry?”), Table 3 provides empirically derived and in literature grounded characteristics. In addition, these characteristics help to demarcate the individual archetypes more clearly as the archetype boundaries are fluent in a qualitatively described representation. In line with Greenwood and Hinings (1993), we selected set of suitable dimensions to specify the patterns. Following the understanding of e-collaboration as socio-technical system (Kock et al., 2001; Rutkowski et al., 2002), we employ the social-technical systems theory (Bostrom and Heinen, 1977; Alter, 2008) as theoretical lens. In this sense, e-collaboration encompasses a social subsystem (dimensions “people” and “structure”) and a technical subsystem (dimensions “technology” and “task”) which are closely interrelated (Bostrom and Heinen, 1977). The characteristics were derived from case study research and – engaging in existing theory – triangulated with literature (dimension “selected, supporting literature”).

Characterization results Examining the characteristics of each archetype in terms people and structure, considerably different actors (ranging from automotive engineers to interdisciplinary roles) and divergent values, norms, and behaviors (ranging from “straight forward” to “systems-of-systems”) become evident. Investigating the characteristics relating to technology and task, distinctly heterogeneous information technology (from mechanical computer-aided design tools to integrated development environments) and objectives (from cost-, time-, and quality-driven development to realization of system functions) become obvious. We did not include generally accepted characteristics of synchronous and asynchronous e-collaboration (Leimeister, 2014) as these can be found across all archetypes, but rather focus on characteristic features for the case of product development. Regarding the archetype “Non-development-focused e-collaborations”, the dependency of the product lifecycle (early versus late stages) is conspicuous. An essential differentiation criterion seems related to materiality (Leonardi and Barley, 2008), distinguishing between digital and physical materiality. Empirically derived characteristics can be strengthened by discipline-specific literature such as Pahl and Beitz (2007) for “Mechanical development-dominant e-collaborations” or Porter and Heppelmann (2014) for “Systems engineering-oriented e-collaborations”. In sum, the characteristics detail the proposed patterns and help delineating the archetypes from one another.

Dimensions		AI: Mechanical development-dominant e-collaborations	AII: Software development-dominant e-collaborations	AIII: Systems engineering-oriented e-collaborations	AIV: Non-development-focused e-collaborations
Social subsystem	People	Automotive engineers, mechanical engineers, manufacturing experts	Electrical engineers, computer scientists, data scientists	Interdisciplinary roles, R&D focus	Interdisciplinary roles, no R&D focus
	Structure	“Straight forward” (physical materiality)	“Agile, iterative” (digital materiality)	“Systems-of-systems” (digital and physical materiality)	Early lifecycle stages: innovation-driven culture Late lifecycle stages: efficiency-driven culture
Technical subsystem	Technology	Mechanical computer-aided design, computer-aided-engineering and manufacturing tools, product data management systems	Electric/electronic computer-aided design, computer-aided software engineering tools, software management systems	Environments integrating mechanical, electric/electronic, and software development and validation	Early lifecycle stages: office and project management tools Late lifecycle stages: enterprise resource planning tools
	Task	Cost-, time-, and quality-driven development and adaptation of products	Realization of innovative product functions	Realization of system functions incorporating adjacent systems	Early lifecycle stages: providing input for PD Late lifecycle stages: processing output of PD
Selected, supporting literature		Pahl and Beitz (2007); Ulrich and Eppinger (2008)	Broy (2006); Schäuffele and Zurawka (2013)	Porter and Heppelmann (2014); Porter and Heppelmann (2015)	Chesbrough (2003); von Hippel (2005)

Table 3. Socio-technical characteristics of archetypes of e-collaboration for product development

4.3 Empirical validation of archetypes

Validation methodology With the purpose to address research question 3 (“How can the proposed archetypes of e-collaboration for product development in the automotive industry be leveraged for the classification of real-world cases?”), a second round of case studies and focus groups was accomplished. Discussing the findings with interview partners and workshop participants which were (1) not involved in the initial evidence collection, yet (2) from the theoretically sampled case organizations (Table 2) contributed unbiased and broad perspectives for validation alike. Moreover, beyond the introduced organizations, one additional case (Engineering consultancy_{Alpha}, headquarters: Italy, employees: 4,000+) was added to bring in additional fresh insights. Both interviews and workshops were organized as follows: Introduction, participants’ and company’s background, archetype template and archetypes presentation, individual ideation, discussion, and conclusion. Beside the framework and archetypes, particularly the horizontal and vertical position of the e-collaborations of the present case organization were discussed and iteratively refined. Thereby, the advantages of interviews and focus groups in terms of flexibility and interactivity (Morgan, 1988; Yin, 2003) enabled us to scrutinize potential differences and reinforce consistencies among the estimations. This procedure contributed to an acceptable consensus regarding the horizontal and vertical positions despite the qualitative approach. In sum, a considerable amount of objects of interest was classified. Figure 2 depicts the empirical validation of archetypes of e-collaboration for product development.

Validation results Principally, the archetype approach was reinforced. The archetypical model in its current form was considered as descriptive for the automotive ecosystem. For example, Supplier coordination manager at OEM_{Alpha} annotated: “For our product lifecycle management harmonization project, we are collecting best practices from our suppliers. What we actually can see: The collaboration forms manifest in different schemes, different worlds.” Despite the inherently positive attitude, two major modifications were integrated in the course of the validation activities. First, the structure was adapted from an early four-quadrant representation in a 2x2 matrix to the current triangle representation, considered as more close to reality. In this context, Head of IT Engineering at Supplier_{Alpha} brought in: “The present dominance of mechanical or software development surfaces more clearly in such a representation. Horizontal and vertical shares of 0-100 and 0-33 percent resulting in triangles seem more adequate to express dominance than shares of 0-50 and 0-50 percent eventuating in quadrants.” Second, the horizontal and vertical position as well as the extent of the archetypes was modified. In that regard, Senior Consultant at Engineering consultancy_{Alpha} reasoned: “The spread of the archetype areas should not be equal for each archetype as systems engineering-

oriented e-collaborations already originate with minor shares of mechanical and software development. Respectively, non-development-focused e-collaborations should occupy only little space with negligible relevance in development activities.”

Essential quality criteria of classification models include that dimensions comprise (1) mutually exclusive and (2) collectively exhaustive characteristics (Bailey, 1994; Nickerson et al., 2013). Regarding the first criterion, each e-collaboration could be located in one archetype in an unambiguous way. Regarding the second criterion, the archetypical model was able to classify all e-collaborations in an entire way. Finally, we remark that the archetype template should be regarded as an initial illustrative model assisting the comprehension of the phenomenon e-collaboration.

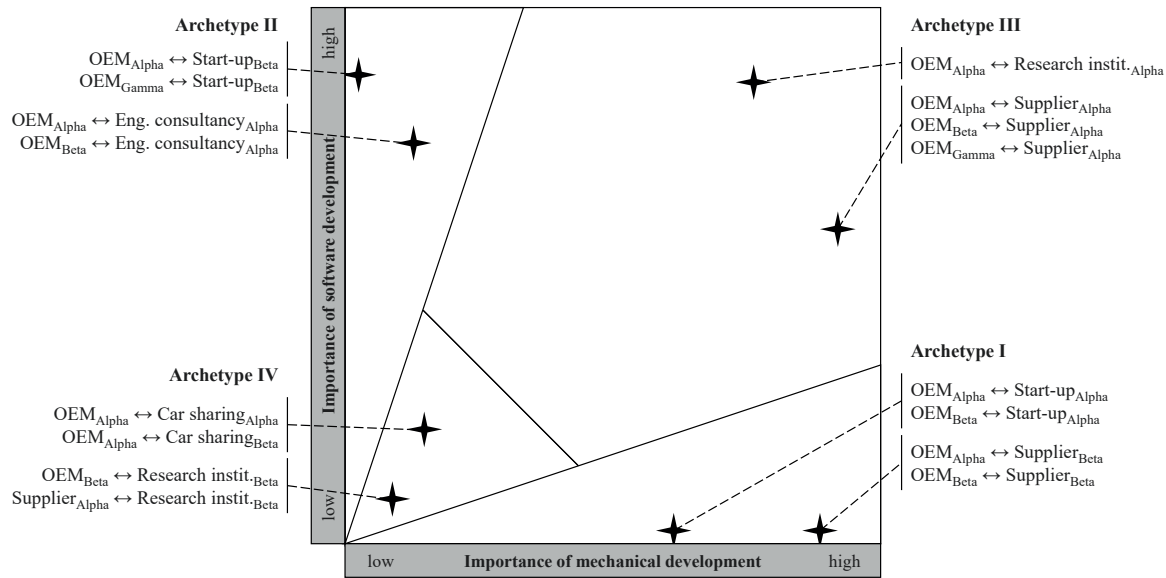


Figure 2. Empirical validation of archetypes of e-collaboration for product development

AI: Mechanical development-dominant e-collaborations In the field study, four cases of e-collaboration emerging in two clusters (cluster OEM_{Alpha} ↔ Start-up_{Alpha} and OEM_{Beta} ↔ Start-up_{Alpha}; cluster OEM_{Alpha} ↔ Supplier_{Beta} and OEM_{Beta} ↔ Supplier_{Beta}) matched with archetype I. Start-up_{Alpha} focuses on vehicle product design and novel vehicle concepts. Being specialized on early development stages from conceptual design through to first physical prototypes, Start-up_{Alpha} collaborates with major European automotive OEMs. Supplier_{Beta} represents a tier-one automotive supply enterprise developing and manufacturing mechanical components and assemblies for combustion engines together with automotive OEMs in a global setting. All instances feature similar social (e.g., traditional automotive engineers) and technical (e.g., plain product data management systems) characteristics, yet minor differences in terms of collaboration complexity become visible as well.

AII: Software development-dominant e-collaborations In the empirical investigation, four cases of e-collaboration appearing in two clusters (cluster OEM_{Alpha} ↔ Start-up_{Beta} and OEM_{Gamma} ↔ Start-up_{Beta}; cluster OEM_{Alpha} ↔ Engineering consultancy_{Alpha} and OEM_{Beta} ↔ Engineering consultancy_{Alpha}) were in accordance with archetype II. Start-up_{Beta} develops software platforms for autonomous vehicle fleets including smartphone and infrastructure applications in close collaboration with traditional and non-traditional OEMs worldwide. Key competences of Engineering consultancy_{Alpha} include the development and validation of electronic control modules for a variety of automotive interior and exterior uses in conjunction with their customer OEMs. Despite different collaboration scopes, all studied forms show social (e.g., technology specialists) and technical (e.g., software management systems) characteristics at a comparable level.

AIII: Systems engineering-oriented e-collaborations In the validation stage, four cases of e-collaboration nascent in two clusters (cluster OEM_{Alpha} ↔ Supplier_{Alpha}, OEM_{Beta} ↔ Supplier_{Alpha}, and OEM_{Gamma} ↔ Supplier_{Alpha}; cluster OEM_{Alpha} ↔ Research institute_{Alpha}) corresponded with archetype

III. Similar to $\text{Supplier}_{\text{Beta}}$, $\text{Supplier}_{\text{Alpha}}$ also represents a tier-one automotive supply enterprise developing and manufacturing mechatronic assemblies for steering systems together with major traditional and non-traditional automotive OEMs at global-scale. $\text{Research institute}_{\text{Alpha}}$ aims to enhance roadways, vehicles, and public transportation in Singapore as pointer for Asian megacities. For this vision, both stakeholders $\text{Research institute}_{\text{Alpha}}$ and $\text{OEM}_{\text{Alpha}}$ have collaboratively developed a function prototype for e-vehicles. Considering different system complexities (subsystem versus complete vehicle), comparable social (e.g., interdisciplinary nature of team members) and technical (e.g., integrated development environments) properties become ostensible.

AIV: Non-development-focused e-collaborations Lastly, in the validation phase, four cases of e-collaboration occurring in two clusters ($\text{cluster OEM}_{\text{Alpha}} \leftrightarrow \text{Car sharing}_{\text{Alpha}}$ and $\text{OEM}_{\text{Alpha}} \leftrightarrow \text{Car sharing}_{\text{Beta}}$; $\text{cluster OEM}_{\text{Beta}} \leftrightarrow \text{Research institute}_{\text{Beta}}$ and $\text{Supplier}_{\text{Alpha}} \leftrightarrow \text{Research institute}_{\text{Beta}}$) met archetype IV. Both $\text{Car sharing}_{\text{Alpha}}$ and $\text{Car sharing}_{\text{Beta}}$ supply mobility services for private as well as business customers. With different levels of proximity and involvement, both stakeholders collaborate with $\text{OEM}_{\text{Alpha}}$ regarding customer requirements for future mobility solutions. $\text{Research institute}_{\text{Beta}}$ supports manufacturing businesses (OEM_{Beta} and $\text{Supplier}_{\text{Alpha}}$) in the digital transformation and provides concepts for digital innovation for the industrial product and service business close-partnered. All e-collaborations are intensively involved in upstream (e.g., market studies) and downstream processes (e.g., marketing), but have no direct involvement in the actual development activities. The extent of social and technical properties is wide, yet common pattern can be detected.

5 Discussion

New dynamics in the automotive stakeholder ecosystem on the one hand and advancements in engineering information systems and e-collaboration tools on the other hand have led to an increased complexity of e-collaboration for product development in the global auto world. Prior research has not considered the (1) specificities of the automotive industry, (2) ties and dependencies of both social and technical subsystems, and (3) real-world mechanisms sufficiently. Adopting a socio-technical systems perspective, we conceptualized, described, and validated four archetypes. Three aspects seem particularly worthy of discussion: (1) Embedding findings in prior research, (2) debating effects owing to the archetype approach, and (3) discussing implications regarding the information systems domain.

First, the prejudice of “software development-intensive” and “mechanical development-intensive” product development relationships is widespread in the academic and practice-oriented discussion on manufacturing industries (Chu et al., 2006; Eigner and Roubanov, 2014). Grounded on a rigorous and transparent qualitative research process, we can corroborate this assumption and strengthen our initial proposition (Yin, 2003). However, findings demonstrate the subtle differences and characteristics of the classified e-collaborations within these rather approximate archetypes. Furthermore, findings indicate that the archetypes “Non-development-focused e-collaborations” and “Systems engineering-oriented e-collaborations” represent additional patterns beyond the two assumed ones. Although we solely can rely on evidence from the automotive industry, the results may be transferable to other manufacturing industries which develop innovative and knowledge-intensive products incorporating mechanical and software elements. In that regard, further research can establish clarity.

Second, archetypes are particularly suited to investigate organization design and change over time (Greenwood and Hinings, 1993). As electric/electronic elements and software constituents have become an emerging source of innovation for today’s product development departments with proportions up to 70 percent of implemented product functions (Eigner and Roubanov, 2014), the archetypes “Software development-dominant e-collaborations” and “Systems engineering-oriented e-collaborations” can be expected to gain relevance. On the one hand, with new stakeholders in the automotive innovation hubs predominantly working on software-intensive systems, new e-collaborations may be situated in the upper section of the template. On the other hand, traditional stakeholders – which increasingly evolve from the development of mechanical components to mechatronic systems – may also adopt their e-collaborations towards the upper section. Taking these aspects into account, a general vertical shift of e-collaboration for product development in the

automotive industry is likely to occur. Yet, it should not be disregarded that findings also show the relevance of specific, non-software-development-involved forms of e-collaboration.

Finally, the information system discipline strives to assist managers to understand the potential of information technology with the objective to exploit its advantages at the best possible rate (Agarwal and Lucas, 2005; Chen et al., 2010). As this paper aims to contribute to this discipline, it seems valuable to discuss the role of the archetypes in the light of the design, implementation, and operations of e-collaboration. In this sense, the archetype template and archetypes support the understanding of current and the development of potential future e-collaborations. Managers can assess their actual situation and subsequently discuss and sharpen their strategic position. Referring to the selected socio-technical theoretical lens, findings demonstrate the tight connection and relevance of both social and technology-related aspects to successfully design e-collaboration. Accordingly, beside the evident technology-related implications such as information systems introduction, particularly social consequences and transformation processes such collaboration culture need to be derived. To further study the fit with the environment, contingency (“if-then”) or configuration (“cause-effect”) theory approaches (Meyer et al., 1993) seem well qualified.

6 Conclusion

The paper at hand presents the classification of e-collaboration for product development in the automotive industry. On the basis of (1) a structured literature review and (2) rich empirical evidence from a multiple-case study, four distinct archetypes were conceptualized, described, and validated: (1) Mechanical development-dominant, (2) software development-dominant, (3) systems engineering-oriented, and (4) non-development-focused e-collaborations for product development.

Our study offers four contributions: First – from a theoretical point of view – we identify archetypes and related characteristics and further empirically validate them. Hence, we contribute to a better understanding of the phenomenon e-collaboration in manufacturing industries. Considering the framework of Gregor (2006), classifications are equaled with “type one theories” affording analysis and description without prediction. Hence, we can specify our theoretical contribution as “theory for analysis”. Second – from a methodological perspective – we transfer and apply the archetype concept in the field of information systems. Thus, we are able to strengthen the contemporary relevance of this methodological approach. Third – from a managerial point of view – we provide a useful analytical artifact for benchmarking enabling understanding and designing e-collaboration. Lastly – from a cross-disciplinary perspective – with the information systems domain being a scientific discipline at the intersection of other domains, we interlink the new product development community with the information systems discipline.

We are sensible that our research study faces limitations: One potential weakness is reasoned in the qualitative approach. On the one hand, this entails a restriction in sources of evidence and – thus – generalizability. On the other hand, this implies the referred fluent transition of archetype boundaries. Another potential limitation may arise from the snapshot approach in the dynamic automotive market environment. New momenta in the stakeholder ecosystem and advancements in information systems may lead to novel archetypes of e-collaboration in the future. Lastly, but certainly not the last constraint is raised by the non-exhaustive literature review.

Our study opens the door for several conceivable research directions: On the one hand, the introduced work may benefit from additional qualitative and quantitative research to expand, specify, and revise the archetypes and their characteristics. In this context, potential metrics and indicators to quantify the dimensions may be of value. On the other hand, from a social point of view organizational transformation processes and from a technical point of view the integration of distributed development environments seem fruitful research areas. Furthermore, e-collaborations for product development may be studied in other industrial contexts (e.g., aerospace or plant construction and engineering) to assess the generalizability of the archetypes beyond the automotive industry. We hope that our work serves as a necessary foundation for the introduced avenues.

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Article #4 – Contribution D

Bibliographical details

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Abstract

The pervasive infiltration of digital technology into physical products brings both tremendous challenges and opportunities to original equipment manufacturers. With the goal to support the initial stages of the product lifecycle, this article introduces a method compendium for the development of digitized products. More precisely, the compendium suggests (1) customer- and user-centric innovation methods, (2) agile and prototyping methods, (3) system and architecture modelling methods, (4) feedback- and data-driven methods, and (5) service and business modelling methods. Methodically, we draw on secondary data from a longitudinal single-case study scrutinizing the development of digitized trucks at a leading materials handling and intralogistics organization. Bounded to the business-to-business context of industrial equipment manufacturing, we enrich product lifecycle management with methodological contributions valuable for academia and practice alike.

Towards a method compendium for the development of digitised products – findings from a case study

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Abstract: The pervasive infiltration of digital technology into physical products brings both tremendous challenges and opportunities to original equipment manufacturers. With the goal to support the initial stages of the product lifecycle, this article introduces a method compendium for the development of digitised products. More precisely, the compendium suggests: 1) customer- and user-centric innovation methods; 2) agile and prototyping methods; 3) system and architecture modelling methods; 4) feedback- and data-driven methods; 5) service and business modelling methods. Methodically, we draw on secondary data from a longitudinal single-case study scrutinising

the development of digitised trucks at a leading materials handling and intralogistics organisation. Bounded to the business-to-business context of industrial equipment manufacturing, we enrich product lifecycle management with methodological contributions valuable for academia and practice alike.

Keywords: product development; product design; product lifecycle management; method; methodology; method compendium; method set; digitised product; smart product; materials handling and intralogistics organisation; original equipment manufacturer; case study.

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1 Introduction

The pervasive infiltration of digital technology into physical products brings both tremendous challenges and opportunities to original equipment manufacturers. In particular, the rather traditional manufacturing industry is seen as a sector with a large economic potential unlocked by digital product innovation. Analysts expect the worldwide spending on digitised products in an industrial context to reach US\$500 billion delivering an annual value of US\$1,200 billion by 2020 (Floyer, 2013).

This trend of digital product innovation particularly impacts

- 1 the design of digitised products
- 2 the engineering and innovation processes.

First, the design of digitised products goes beyond the physical materiality of the product (Yoo et al., 2010). Physical products are increasingly understood as platforms to deliver value to customers (Barrett et al., 2015). Thus, special requirements from the product operations phase have to be taken into account when designing digitised products (Porter and Heppelmann, 2014). Second, traditional engineering and innovation processes have to be adapted (Fichman et al., 2014). As digital technology is gaining in importance, digitised products can be updated during the product operations stage resulting in more iterative processes and shorter innovation cycles (Porter and Heppelmann, 2014). Novel interdisciplinary engineering and innovation methods have to be developed to bridge between mechanical, electrical, software development, and new product and service engineering (Böhmman et al., 2014). Especially industrial manufacturing faces tremendous challenges within the imminent digital transformation due to its historically strong focus on physical products and traditional engineering processes.

In this sense, the article at hand provides a method compendium for the development of digitised products. Beyond a literature review on existing methods, we prevalently build up on an in-depth single-case study (Yin, 2003) conducted in the context of a leading materials handling and intralogistics organisation. Starting in the end of 2014, we accompanied the journey of the German original equipment manufacturer with the objective to leverage the potential of digitised trucks for the next product generation launched in 2020. Central results include a profound examination of how a real project addressing the transition from mere physical to digitised product development is accomplished. In particular, emerging options for action and outcomes of decisions taken are analysed. Grounded on these insights, we derive a set of generalised methods (i.e., a method compendium) addressing different levels of product development to support the early lifecycle stages of digitised products. For scholars, our work contributes to grasp the new role of product lifecycle management (Terzi et al., 2010) by better understanding the key mechanics of digital product innovation in the context of industrial manufacturing. For practitioners, the method compendium helps to surmount the manifold challenges of such intricate projects.

The residual article evolves as follows: Section 2 provides the necessary background in terms of digitised products and product-service-systems (PSS) and existing development methods. In Section 3, the research methodology referring to the empirical setting, data collection and analysis, and validation of findings is presented. Section 4 outlines the case study chronologically offering an overview on main phases and methods. In Section 5, the method compendium is carved out and discussed. Ultimately,

Section 6 concludes with contributions, limitations, and selected items for a research agenda.

2 Background

2.1 *Digitised products and product-service-systems*

Referring to the context of product lifecycle management, Pinqu   et al. (2015) conceptualise a *product* (tangible or intangible) as the outcome of interlinked activities. Such a tangible product – for example a forklift – is designed, manufactured in the beginning-of-life, distributed, used, supported in the middle-of-life, and eventually retired in the end-of-life stage (Terzi et al., 2010). When it comes to grasp the pervasive infiltration of digital technology into these tangible products, a generally accepted conceptualisation is lacking (Novales et al., 2016). Moreover, disparate research communities have generated a multitude of concepts, such as *digitised products* and *smart, connected products* for management literature and *cyber-physical systems* and *intelligent products* for engineering literature. In this article, the terminology of *digitised products* “containing sensing, memory, data processing, reasoning, and communication capabilities” [Yoo et al., (2010), p.725] will be used for the sake of an interdisciplinary and comprehensive perspective. Digitised products may be modelled as *layered modular architecture* consisting of contents, service, network, and device layer. Physical materiality is complemented by digital materiality which requires novel logics (Yoo et al., 2010). Particularly the generativity of digital technology as “capacity to produce unanticipated change through unfiltered contributions from broad and varied audiences” [Zittrain, (2008), p.70] requires an advanced innovation management. In essence, the impact of digitised products on product lifecycle management is profound, enabling a closed-loop product lifecycle management with seamless information and data exchange throughout the lifecycle (Kiritsis, 2011).

Driven by buyer pull and supplier push, product-related services overproportionately gained importance within the last decades offering benefits to both stakeholder groups (Cavalieri and Pezzotta, 2012). This emerging *servitisation in manufacturing* has increasingly given rise on *PSS* which can be understood as well-integrated combinations of products and services delivering value in use (Baines et al., 2007). Principally, such *PSS* can exhibit manifestations from 0 to 100%, offering a spectrum from pure-product to pure-service (Oliva and Kallenberg, 2003). Reverting again to the materials handling and intralogistics example, the combination of a onetime forklift sale paired with periodic maintenance services can be seen as an exemplary industrial product-service-system (Meier et al., 2010). The extensive infiltration of digital technology into these *PSS* evoked the offering of novel *digitised PSS*. Lerch and Gotsch (2015, p.47) conceptualise such *PSS* as “integrated bundles of physical products, intangible services, and digital architectures designed to fulfil individual customer needs via automated, independent operation.”

2.2 *Existing development methods*

Summarised under terms like *methods*, *methodologies*, or *techniques*, academia as well as industry has yielded a wide field of structured approaches for the design of the introduced

products and PSS. Within this article, we employ the nomenclature *method* understood as “description of a rule-based and systematic approach for accomplishing specific tasks to achieve a particular objective” [Lindemann, (2007), p.57] to consider the spectrum from micro (working methods) to macro (process models) methods alike. Pahl and Beitz (2007) emphasise the prescriptive, goal-oriented, and operative character of methods. Rationales for use are diverse, yet all merge in reducing complexity and risks of development endeavours (Graner and Mißler-Behr, 2012). Supporting tools help to conduct methods more efficiently and effectively. The scientific field of method engineering deals with method design (Brinkkemper, 1996).

Table 1 Selected methodological contributions from relevant engineering domains

<i>Category</i>	<i>Domain</i>	<i>Methodological contribution</i>
Domain-specific development approaches	Mechanical engineering	<ul style="list-style-type: none"> • Integrated product development (Andreasen and Hein, 1987). • Systematic approach to the design of products (VDI, 1993).
	E/E engineering	<ul style="list-style-type: none"> • Y-approach for hardware design (Gajski and Kuhn, 1983). • Systematic development of devices with microelectronics (VDI, 1994).
	Software engineering	<ul style="list-style-type: none"> • Waterfall/V-model for software development (Boehm, 1979). • Agile methods for software development (Martin, 2003).
	Service engineering	<ul style="list-style-type: none"> • New service development (Edvardsson and Olsson, 1996). • Methodical development of service products (Bullinger et al., 2003).
Integrated development approaches	Systems-engineering	<ul style="list-style-type: none"> • Systems-engineering and analysis (Blanchard and Fabrycky, 2010). • Systems-engineering processes and techniques (Bhise, 2013).
	Mechatronics engineering	<ul style="list-style-type: none"> • V-model for mechatronic development (VDI, 2004). • Three-cycle model for mechatronic development (Gausemeier et al., 2011).
	PSS engineering	<ul style="list-style-type: none"> • Lifecycle-oriented design of product-service-systems (Aurich et al., 2006). • Developing new product-service-systems (Morelli, 2006)
	Digitised products engineering	<ul style="list-style-type: none"> • Design and modelling of smart products (Ahram et al., 2011). • Engineering cyber-physical systems (Broy et al., 2012). • Engineering cyber-physical systems (Broy and Schmidt, 2014). • Developing smart, connected products (Porter and Heppelmann, 2015).

In general, the co-creation of value can be seen as overarching paradigm for development. The basic idea of this value co-creation is resource integration by different parties striving for a jointly appreciated outcome (Prahalad and Ramaswamy, 2004). Dependent on aspects such as co-creation motive (e.g., customer experience), form (e.g., co-design), and engaging actor (e.g., customer), this original concept has been applied in several contexts (Frow et al., 2015). Especially the manifestations co-innovation (Lee et al., 2012) and co-design (Maniak and Midler, 2008) can be seen as relevant.

In particular, several distinct engineering domains provide a range of extant approaches for the development of digitised products. Therefore, Table 1 introduces selected methodological contributions, extending the works of Berkovich et al. (2011) and Eigner and Roubanov (2014). We note that we rather focus on coverage than exhaustiveness. For one, regarding the rather established domains from mechanical engineering to PSS engineering, we primarily relied on discussion with experienced scholars and practitioners. For another, the specific contributions for novel digitised products engineering were identified by a structured literature review according to the guidelines by Webster and Watson (2002). Thereby, initially scientific databases were searched, followed by a forward and backward search to detect additional articles. For the concrete selection for Table 1, first, we built up on existing literature acknowledging the pre-selection by experienced scholars (Berkovich et al., 2011; Eigner and Roubanov, 2014). Second, we focused on highly published and cited papers in academia respectively well-established standards and industry norms in practice. Third, we strived for typical methods for each domain.

The contributions can be classified on the one hand in domain-specific (i.e., mechanical, electric/electronic (E/E), software, and service) and on the other hand in integrated (i.e., systems, mechatronics, PSS, and digitised products) engineering approaches. Several saliences become glaring, in brief: first, methods for tangible products are rather mature, whereas methods for intangible ones seem rather premature. Second, domain-specific methods are more sophisticated, whereas integrated approaches exhibit a more generic character. Third, regarding the focus of this article, very few authors (e.g., Ahram et al., 2011; Broy et al., 2012; Broy and Schmidt, 2014; Porter and Heppelmann, 2015) have attempted to carve out guidance for digitised products. In essence, the development of digitised products is a young discipline. Sound, integrative, and comprehensive guidance assisting their design is practically non-existent. In particular, the generative and non-material nature and its implications have been comparatively neglected. In what follows, we tackle this objective and provide initial guidance by compiling a method compendium on the basis of a case study.

3 Research methodology

3.1 Empirical setting

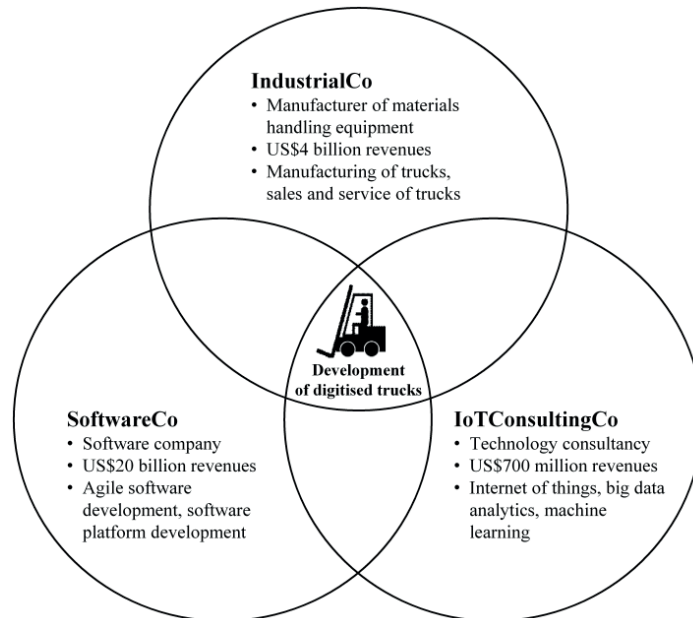
To investigate how the augmentation of industrial products with digital technology transforms product development and applied methodologies, we draw on a single-case study in the materials handling and intralogistics industry (Yin, 2003). With regard to our research goal, a case study as an “empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident” [Yin, (2003), p.13] represents a suitable

approach. Furthermore, case study research has proven as established method to scrutinise phenomena around product lifecycle management (e.g., Bokinge and Malmqvist, 2012).

Our case study comprises three organisations (‘the consortium’), shown in Figure 1:

- 1 *IndustrialCo* is a leading manufacturer of materials handling equipment mainly focusing on industrial trucks and warehouse equipment. It is split up into a manufacturing division and a sales and service division. In 2014, the case organisation generated revenues exceeding US\$4 billion with around 20,000 employees. *IndustrialCo* has access to a global dealer network that allows the organisation to gain insights regarding customer needs. The dealer organisations that are mostly part of *IndustrialCo* itself are a trustworthy partner for conducting co-innovation projects and jointly working on the development of the future trucks.
- 2 *SoftwareCo* is a leading global software company with US\$20 billion revenues and around 75,000 employees worldwide. A strategic goal of the organisation is to develop a software platform for the context of the *industrial internet of things and services*. The organisation has profound experience in agile software development methodologies.
- 3 *IoTConsultingCo* is a US\$700 million revenues technology consultancy involved in the study focusing on topics like *internet of things, big data analytics, and machine learning*.

Figure 1 Empirical setting in the materials handling and intralogistics industry



In his seminal work, Yin (2003) lists five settings where a single-case is appropriate. The case at hand meets three independent criteria:

- 1 being typical with *IndustrialCo* as traditional manufacturer coping with digital technologies
- 2 being revelatory with insightful views into commonly isolated research and development activities
- 3 being longitudinal with an examined product development project over several years.

Moreover, Keutel et al. (2014, p.259) stress the advantages of “rich, contextual insights into the dynamics of phenomena.” In sum, we chose the case because of

- 1 *IndustrialCo*'s current goal to develop the next forklift generation that serves as the technology platform for the future service business
- 2 access to this organisation over a period of 2.5 years.

3.2 *Data collection and analysis*

Summarising different perspectives from a multi-year project on digital product innovation at the introduced consortium, this article is based on secondary data (Heaton, 2004). The accomplishment as longitudinal case enabled us unrestricted and long-term access to diverse sources of evidence (Yin, 2003). Moreover, support from the *Head of Strategic Product Platforms of IndustrialCo* attained unique insights in uni-, bi-, and multi-lateral product development activities. In this way, during a time period of 30 months, 20 semi-structured interviews ($\Sigma \sim 25\text{h}$), direct ($\Sigma \sim 5\text{h}$) and indirect observations ($\Sigma \sim 20\text{h}$) in workshops were gathered. In addition, we collected project documentations and physical as well as digital artefacts in form of hardware and software prototypes (Yin, 2003). Harnessing these heterogeneous data sources made a contribution to validity. Moreover, using stringent collection approaches (e.g., interview guidelines) and processing methods (e.g., audio and video recording, memos) contributed to reliability. In sum, these diverse sources of evidence and collection methodologies contributed to study

- 1 the product development project in its entirety
- 2 the applied product development methods in particular.

Following this, qualitative data analysis methods (Strauss and Corbin, 1990; Miles and Huberman, 1994; Strauss and Corbin, 1997) were leveraged to reduce the textual data in a systematic, multi-level, and iterative approach. Transcribed interviews as well as notes from observations, documentations, and artefacts were collected in a cloud-based case study database to facilitate the analysis. For the case study description in Section 4, we used a *chronological coding scheme*. In contrast, for the method compendium in Section 5, we utilised an *inductive coding scheme* continuously synchronising with literature. In detail, we executed a three-step coding process composed of:

- 1 *open coding*
- 2 *axial coding*
- 3 *selective coding* (Strauss and Corbin, 1990, 1997).

The first *open coding period* was dominated by crushing the textual data, resulting in a large number of codes describing the fragments. In the second *axial coding period*, the textual data were orderly concentrated by carving out relationships and arranging codes around promising axes. The third *selective coding period* in closing was characterised by re-ordering and harmonising along emergent core categories ('clusters'). We harnessed computer-assisted qualitative data analysis software to facilitate and secure coding procedures (Sinkovics et al., 2005). In sum, the textual data provided 87 codes for cluster C1, 158 codes for cluster C2, 66 codes for cluster C3, 109 codes for cluster C4, and 53 codes for cluster C5 which are presented in detail in Section 5.

3.3 Validation of findings

Beyond ex-ante efforts, ex-post validation was conducted through a project wrap-up meeting in the style of a focus group (Morgan, 1988). In total, 16 participants from the consortium partners reviewed the project, which was recorded, analysed, and worked in the case study. In addition to this rather internal validation, we had the opportunity to cross-check our findings through temporary access to external cases pursuing the development of digitised products in related industry branches. In particular, this includes validation with *AutomotiveCo* (Swiss automotive supplier, digitised chassis products, US\$3+ billion revenues), *ElevatorCo* (German industrial equipment manufacturer, digitised elevators and escalators, US\$5+ billion revenues), and *MultinationalCo* (German industrial equipment manufacturer, diversified goods, US\$20+ billion revenues).

4 Case study at IndustrialCo

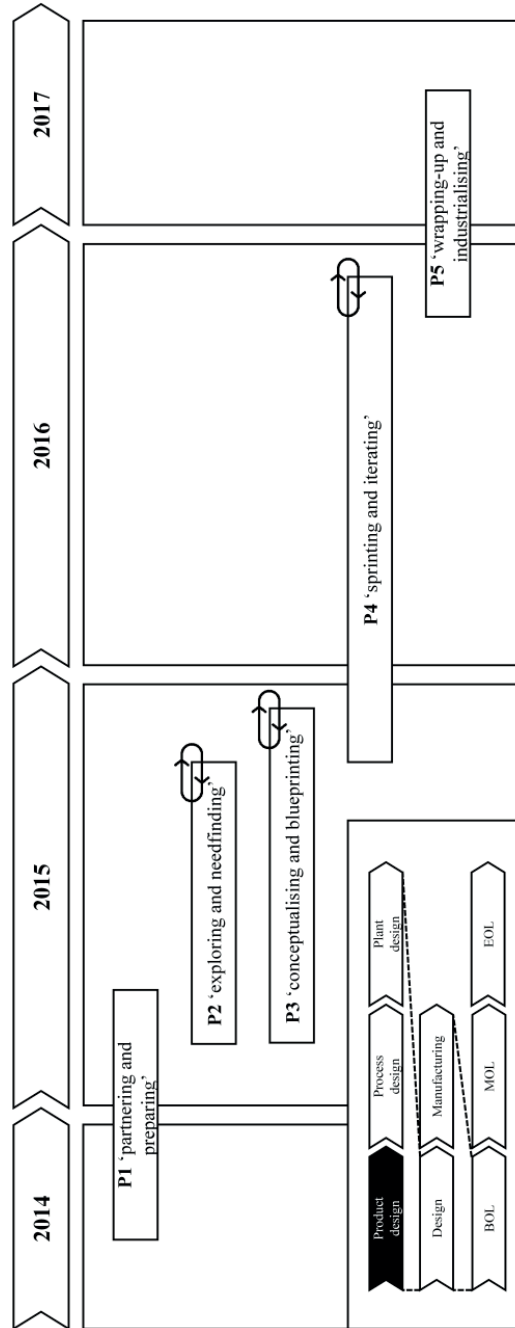
4.1 Motivation, objective, and overview

In search for exploiting the potentials of digitised products and PSS for itself and its customers, *IndustrialCo* has mounted a large-scale initiative to develop the next product generation of digitised trucks to be launched in 2020. To leverage necessary competencies at the best and to minimise nascent research and development hazards, *IndustrialCo* organised the product development as co-innovation project with *SoftwareCo* and *IoTConsultingCo* collaborating with both manufacturing and sales and service division of *IndustrialCo*.

Specifically, the project pursues two main objectives. First, the overarching purpose is to jointly design prototypical digitised trucks instantiating selected data-driven industrial services. These prototypes then serve for the generation of management attention and act as starting base for series development. Second, based on the collaboration within this co-innovation project, all stakeholders are interested in gaining experience in designing and leveraging technology affordances of digitised industrial equipment. Thereby, the project scope is far reaching, adopting a comprehensive lifecycle perspective considering prerequisite

- 1 requirements from beginning-of-life and middle-of-life stages
- 2 innovation capabilities regarding processes, methodologies, and information and communication technology.

Figure 2 Timeline of IndustrialCo's product development project



In this sense, Figure 2 provides the timeline of *IndustrialCo*'s product development project. Referring to the lifecycle model of Terzi et al. (2010), the project particularly concentrated on the initial critical phases setting the stage for success. In this section, we report findings from the case study. More precisely, we focalise on presenting an overview on main phases and applied methods contextualising their usage.

4.2 Phase 1 'partnering and preparing' [09/2014–03/2015]

The initial project phase P1 lay under the sign of partnering and preparing. In several preparatory meetings, the working mode and organisation of the partnership between *IndustrialCo*, *SoftwareCo*, and *IoTConsultingCo* was stipulated. An interdisciplinary project core team was composed where *IndustrialCo* brought in rather traditional research and development specialists and *SoftwareCo* and *IoTConsultingCo* more IT-related functions. Furthermore, the consortium decided to focus on a proof-of-concept for a specific series of trucks to generate a successful pilot and enable quick learnings rather than a comprehensive strategy for the whole product portfolio. As the project targets to prepare the next product generation with strict release dates, yet to approach the topic in an open-minded and unrestrained style for experimentation, the project was organised with minor stages and review gates and a highly iterative *modus operandi*. After this pre-phase, the project finally was kicked-off in the end of February 2015.

4.3 Phase 2 'exploring and needfinding' [02/2015–09/2015]

In the subsequent project phase P2 exploring and needfinding was central. To adopt a customer- and user-oriented development, requirements from a wide range of relevant stakeholders in *IndustrialCo*'s ecosystem were collected. First, internally professionals from technical customer service (e.g., *Head of Full Service Business*, *Director of After-Sales and Customer Service*), research and development (e.g., *Project Lead Strategic Product Platforms*, *Senior Engineer Advance Development*), and IT (e.g., *Head of Competence Center IoT Platform Architecture*, *Global Head of IT Operations*) were involved. Second, the global dealer network (Germany, France, and Poland) as well as experts from adjunct branches (e.g., harbour logistics) had opportunity to shape requirements from an external perspective. Mainly, open, explorative interviews and *design thinking* innovation workshops were conducted to identify and prioritise stakeholder needs. Beyond, site visits at customers and narratives from operations personnel complemented this set. Potential future applications were condensed in qualitative descriptions ('scenarios') which served as foundation for the requirements. First, the objective was to identify universally accepted building blocks valid for the next truck generation. Second, selected scenarios also served as input for the realisation of concrete prototypical digitised trucks later in the process. Third, the scenarios acted as foundation to offer more sophisticated digitised PSS at a later stage.

4.4 Phase 3 'conceptualising and blueprinting' [02/2015–11/2015]

Parallel to the project phase P2, phase P3 focalised on conceptualising and blueprinting. Pre-eminently, the layered modular architecture as core component for and critical element of the future forklift generation occupied the centre stage. Thereby, the

consortium occupied an end-to-end perspective from device layer ('close to physical trucks') to contents layer ('close to customers and users'). In this stage, particularly *SoftwareCo* and *IoTConsultingCo*, but also *IndustrialCo* which is growing an internal *Competence Center IoT Platform*, contributed their competencies. Again, viable architectural foundations for large-scale production as well as a prototypical architecture were searched. Based on reference models from standardisation organisations such as the *Industrial Internet Consortium* several variants were carved out and iterated. The consortium debated advantages and disadvantages by using extreme manifestations (lean vs. thick architectures) and modifying essential architectural components. This conceptual approach was supported by concrete prototyping of architectures using data from

- 1 embedded systems
- 2 newly installed open hardware on existing trucks.

As external sources, enterprise resource planning (ERP) and product data management (PDM) systems served as input. Especially the alignment with *IndustrialCo*'s existing IT architecture and the creation of a future-proof set-up represented major obstacles. Against the backdrop of the long lifecycles of industrial equipment and with the goal to realise more advanced digitised PSS in the future, especially aspects of compatibility and extendibility were intensively debated. After several iterations, a *Lambda architecture* supporting both

- 1 batch processing
- 2 real-time processing was determined as appropriate concept.

Analogue to technical aspects, economic considerations were made for financial feasibility. On the cost side, one-time and running costs for the architecture were estimated. On the revenue side, several business model innovation workshops were conducted to pay tribute to the new opportunities. For example, employing the *Business Model Canvas*, service-based revenue models like flexible pricing and performance-based contracting, but also more advanced analytical services such as sale of usage data were discussed.

4.5 Phase 4 'sprinting and iterating' [10/2015–11/2016]

After laying the foundations, the fourth project phase P4 focused on sprinting and iterating. To speed up the learning curve and delivery of outcomes, the consortium followed an iterative approach to design prototypical industrial equipment and related data-driven industrial services. Emphasising this agile character, the main period was baptised *ProtoLab*. En bloc, a total of three *SprintSessions* adapted from the *Scrum* method with a 'working by doing' philosophy was accomplished. Beside the core project team, the T-shaped sprint teams mainly comprised mechanical and electrical engineers, service staff, and further IT professionals. Knowledge transfer and impulse workshops provided the foundation. Furthermore, prototyping open hardware (e.g., *Arduino*) and software (e.g., *Kibana*) was applied. For manageable complexity within the brief time frame the consortium chose to realise two pivotal scenarios:

- 1 predictive maintenance
- 2 fleet management.

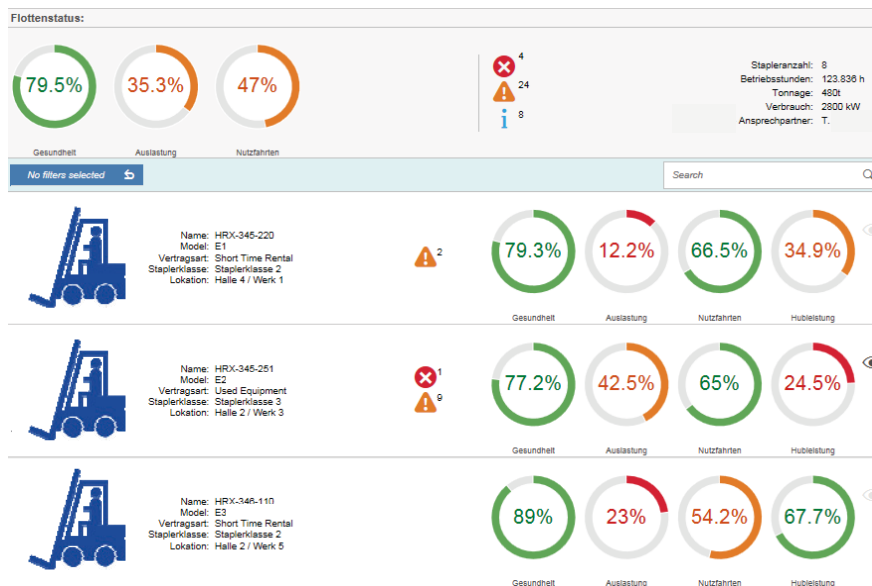
Predictive maintenance strives to steadily monitor and analyse the state of health of forklifts to anticipate breakdowns, and furthermore automatically trigger technical customer service and order spare parts. In contrast, *Fleet Management* seeks to oversee and schedule the truck utilisation for an optimal logistics performance at the customer site, and autonomously offer enhanced logistics solutions. For a solid data foundation, additional trucks were equipped with sensors to track their behaviour. Then, consisting of sub-stages *plan*, *build*, *launch*, and *feedback*, the sprint teams created prototypes with different levels of fidelity. Here, the development of specific data-driven algorithms played a major role. In a step-by-step delivery, prototypical digitised trucks instantiating data-driven industrial services emerged as central outcome of the product development project.

4.6 Phase 5 ‘wrapping-up and industrialising’ [10/2016–03/2017]

Finally, the last project phase P5 consisted of wrapping-up and industrialising. In an ultimate consortium workshop, the final prototypes were discussed and evaluated in a qualitative and quantitative manner. All stakeholders from *IndustrialCo*, *SoftwareCo*, and *IoTConsultingCo* agreed on the success of the project in terms of both initial goals

- 1 usability of the digitised truck prototypes
- 2 organisational learnings on digital product innovation.

Figure 3 Exemplary user interface ‘Fleet Management’ (German) (see online version for colours)



Yet, it also was acknowledged consistently that some topics could not be examined as profoundly as desired and further activities are necessary for *IndustrialCo* to bring hardware and software to market maturity. In the spring of 2017, the prototypes were communicated and marketed to top management. In this sense, *IndustrialCo* is pushing the completed proof-of-concept towards an industrialisation for series development and scaling for the whole product and service portfolio in the medium run. To visualise the product development project outlined beforehand, Figure 3 demonstrates an exemplary user interface *Fleet Management* developed in one of the *SprintSessions*.

At a vehicle-instance level, the digitised trucks acquainted sensing, computation, and communication capabilities. Based on health parameters such as quantity and quality of shocks and fleet parameters such as workload and lifting capacity from the product operations phase, several value-adding services in terms of tracking, benchmarking, and optimisation are realised for fleet managers.

5 Towards a method compendium

5.1 Overview on method compendium

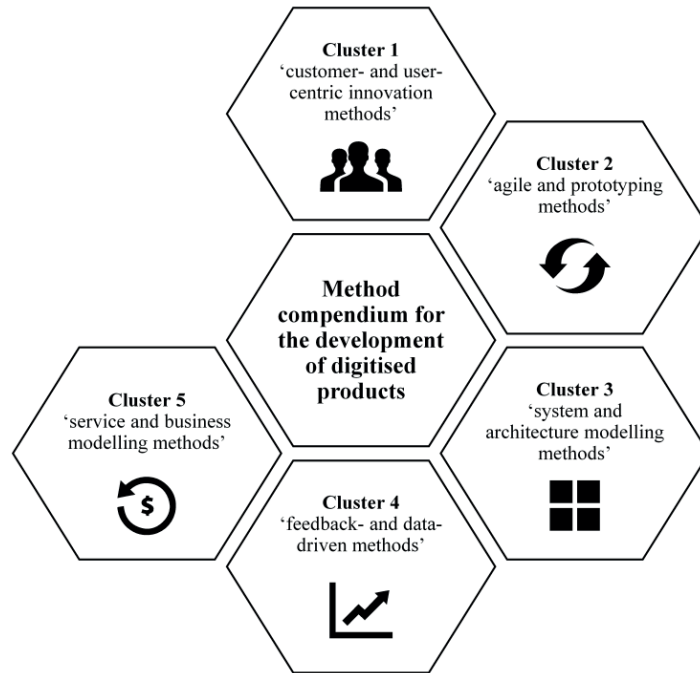
In this section, we provide a method compendium for the development of digitised products grounded on the previously accomplished case study and supplemented with literature. More precisely, we chose a compendium approach because

- 1 it enables us to integrate methods from different domains
- 2 methods are challenging objects of interest for more sophisticated classifications
- 3 sets of methods are prominent in product development literature (Lindemann, 2007; Pahl and Beitz, 2007).

Considering the introduced purpose of initial guidance, we rather aim for coverage of method clusters than for exhaustiveness of each cluster. Although the delineation is challenging, we particularly concentrate on methods beyond traditional engineering methods. In total, five method clusters C1 to C5 were identified, summarised as method compendium for the development of digitised products in Figure 4.

Upon the scope of the method clusters and moreover the heterogeneity of methods in general (Terzi et al., 2010; Graner and Mißler-Behr, 2012), further information is necessary for a successful method application. In what follows, we thus characterise these clusters applying the framework by Lindemann (2007) specifying

- 1 exemplary methods
- 2 purpose
- 3 approach
- 4 situation
- 5 tools.

Figure 4 Towards a method compendium for the development of digitised products

Compared to alternative frameworks which can be found in literature (e.g., Eversheim, 2003; Pahl and Beitz, 2007; Albers and Braun, 2011), the approach by Lindemann (2007) offers us

- 1 an adequate level of detail for our initial, exploratory work
- 2 the necessary information for the audience (i.e., professionals in innovation, research and development, and product development departments) of the article.

Beyond, to illustrate the method application and establish connection to the case study, we underpin each cluster with statements from the case study participants.

5.1.1 Cluster 1 'customer- and user-centric innovation methods'

A first cluster C1 is related to customer- and user-centric innovation methods. Exemplary instantiations at an operational level represent *design thinking* and *foresight thinking* (e.g., Dym et al., 2005; Brown, 2008). As customers and users ever represent the centre of value creation, these methods strive to consider their current and future needs in an adequate way by co-creation. This seems particularly relevant in consideration of the transition from a producer- to a customer- and user-dominant innovation paradigm. Moreover, digitised industrial products have a high generative capacity to allow for numerous use potentials of the products. To pave the way for designing such generative products, potential internal and external ecosystem stakeholders increasingly need to be

involved. In a simplified sense, all methods from this cluster adopt a human-centric viewpoint and seek to spot explicit and implicit needs. From a processual perspective, for example *design thinking* suggests the recurring stages inspiration, ideation, and implementation (Brown, 2008). Customer- and user-centric approaches seem applicable throughout the whole product development process, yet specifically for setting the requirements foundation in early stages of the lifecycle. Dependent on the progress, tools like questionnaires in the inspiration, visualisation boards in the ideation, and prototyping instruments in the implementation stage may be applied to support the method use (Brown, 2008). In the case study, cluster C1 is particularly reflected by continuous involvement of *IndustrialCo*'s sales and service division as well as its customers and users.

“[Developing digitised products] is not a task that one department can carry out. The whole company and our customers need to act in concert. The project would have benefited if we would have involved even more stakeholders.” (Head of Strategic Product Platforms, *IndustrialCo*, Evaluation workshop, November 2016).

5.1.2 Cluster 2 ‘agile and prototyping methods’

Agile and prototyping methods can be synthesised as a second cluster C2. Exemplary working methods adopt elements from the *Scrum* and *Lean Software Development* methodology (e.g., Martin, 2003; Dybå and Dingsøy, 2008). In brief, these methods aim at generating a balance between a structured, yet adaptable development process. The design of complex digitised products is confronted to aspects to which agile methods supply adequate solutions, such as barely predictable development processes and quick time-to-market with stepwise evolution of software-driven product functionality. Agile methods have in common to absent from linear and sequential to more lean and joint approaches embracing change (Dybå and Dingsøy, 2008). Thus, agile methods, for instance *Scrum*, comprise repeating sprints of planning, implementing, and reviewing with feedback loops as decisive elements. Citing principles from the Agile Manifesto (2001), individuals and interactions stand over processes and tools, working software over comprehensive documentation, customer collaboration over contract negotiation, and responding to change over following a plan. This method cluster seems suitable throughout the whole lifecycle, explicitly accepting change in late stages and delivering incremental product functionality. Assisting tools to accomplish the method use comprise a wide spectrum from basic aids like *Scrum* and *Kanban* boards to complex digital resources such as hardware and software. In the studied product development project, cluster C2 becomes nascent by the *SprintSessions* and the intense use of prototyping open hardware (e.g., *Arduino*) and software (e.g., *Kibana*).

“I liked the working mentality, like a small software start-up in a professional industrial environment. [Digital technologies] are always a playing field and projects gain from dynamic adaptation. Particularly by the *SprintSessions* we progressed more efficiently and effectively.” (Department Director IoT, *IoTConsultingCo*, Evaluation workshop, November 2016).

5.1.3 Cluster 3 ‘system and architecture modelling methods’

A third cluster C3 refers to system and architecture modelling methods. Exemplifying samples may be *systems-engineering*, but also novel approaches such as agent-based

modelling methods (e.g., Broy et al., 2012; Hehenberger et al., 2016). As the full potential of digitised products emerges from an intelligent integration of embedded systems with networks, it is necessary to design and validate this layered modular architecture. Regarding the approach, Hehenberger et al. (2016) propose a multi-disciplinary design process involving both

- 1 separate development of physical and computational components
- 2 their integration and interaction.

Thereby, a spectrum of functional and non-functional objectives such as security and privacy protection apply (Broy et al., 2012). Within an initial architecture setup, it seems obvious that architecture modelling methods apply especially in early, decisive stages of the product development process. However, with an extension of the architecture over time, modelling methods demonstrate relevance throughout the lifecycle. Various tools help to run the method use. At a conceptual level, formal languages like the *Systems Modelling Language* facilitate the modelling. At an implementation level, the realisation is aided by model-based IT instruments (Hehenberger et al., 2016). In the case study, cluster C3 is mirrored by the intense discussion on the layered modular architecture, triggered by *IndustrialCo* from a use perspective and by *SoftwareCo* and *IoTConsultingCo* from a design viewpoint.

“Today we do not know enough about the business we will enter in the future, but we can already prepare ourselves by modelling a powerful system architecture and collecting all available data.” (Architecture Developer, IoTConsultingCo, Partner workshop, October 2015).

5.1.4 Cluster 4 ‘feedback- and data-driven methods’

Feedback- and data-driven methods form a fourth cluster C4. Clarifying cases are basic rule-based or more advanced analytics, up to machine learning (e.g., Lehnhus et al., 2015; Herterich et al., 2016). In all manifestations, data from digitised products are fed into different functions in beginning-of-life and middle-of-life. The objective of these approaches is twofold. In the beginning-of-life, they enable real-world, data-driven, and large-scale validation of products out in the field and forecasting of future product generations (Lehnhus et al., 2015). In the middle-of-life, digitised products create novel data-driven analytical services (Herterich et al., 2016). Thereby, product instance tracking over lifetime is made possible. In a generic sense, data from the field need to be collected, processed, analysed, and finally leveraged in the distinct functions. Whereas the introduced applications in middle-of-life refer to any product generation, applications in beginning-of-life are particularly suitable for second and subsequent product generations. In addition to the presumed layered modular architecture, depending on the capabilities of digitised products and thus, quantity and complexity of data, diverse software analysis tools support these methods (Herterich et al., 2016). For example, finite element simulations can be enriched with data from the field to optimise components for proximate generations (Lehnhus et al., 2015). In the analysed project, cluster C4 becomes emergent with a view to the development of specific algorithms for *Predictive Maintenance* and *Fleet Management* targeting middle-of-life, but also usage-driven design addressing beginning-of-life.

“For research and development, sensor data from the operations phase can help to understand which truck components are adequate and which components are oversized. This helps to engineer better equipment that needs less service.” (Head of Full Service Business, IndustrialCo, Needfinding interview, June 2015).

5.1.5 Cluster 5 ‘service and business modelling methods’

Lastly, a fifth cluster C5 encapsulates service and business modelling methods. More precisely, *As-A-Service Design* and *Business Model Design* can be quoted as examples for this method cluster (e.g., Osterwalder and Pigneur, 2010; Velamuri et al., 2013). As digitised products enable the transition from mere transaction-based to more complex mechanisms of value creation, for example as-a-service delivery, the main objective of these methods is to make value delivery an integral part of product development. Moreover, digitised products increasingly offer new digitised services based on operational data which entail novel value propositions (Velamuri et al., 2013). Methodically, the design, evaluation, and continuous evolution represent main steps. For instance, according to the *Business Model Canvas*, the business model be shaped by customer-related (e.g., relationships, segments, and channels), company-related (e.g., partners, activities, and resources), and finance-related aspects (e.g., cost structure and revenue streams) while putting the value proposition in the centre (Osterwalder and Pigneur, 2010). The benefit of this cluster specifically applies in early, strategic phases. However, with an extension of functionality, the value proposition needs to be assessed and extended continuously. Thereby, frameworks like the *Business Model Canvas* or *Value Proposition Canvas* for low-fidelity and calculation software for high-fidelity modelling act as auxiliary tools (Osterwalder and Pigneur, 2010). In the case study, cluster C5 is reflected in the overarching motivation of *IndustrialCo* to offer new services and leverage novel business models based on digitised industrial equipment.

“The impulse talk and interactive workshop sessions on business model innovation were very inspiring and opened new perspectives compared to the conventional sale of trucks and industrial equipment.” (Product Developer, IndustrialCo, Partner workshop, October 2015).

5.2 Discussion of method compendium

With the goal to provide methodological assistance for the development of digitised products, we studied a product development project and derived a method compendium comprising five clusters. Turning now to the discussion, three aspects are illuminated:

- 1 general discussion
- 2 embedding in literature
- 3 application of the compendium.

A scientific assessment completes the discussion.

First, the studied project clearly demonstrated the demand for further novel engineering and innovation approaches. It became nascent that compared to rather traditional methods in product development (Graner and Mißler-Behr, 2012), additional socio-technical approaches are needed to address the peculiarities of digitised products. Thus, for example, to tribute to their generative capacity and digital materiality,

increasingly agile and prototyping methods need to be incorporated. Most identified clusters are well-established in other domains, such as agile and prototyping methods in the community of software engineering. Consequently, for the design of digitised products, it is necessary to revert on the transfer, adaptation, and combination of methods from other scientific domains. However, also some areas (e.g., Cluster 3 ‘system and architecture modelling methods’) emerged in which methods cannot be simply transferred, but need to be redeveloped. An interdisciplinary application on the opposite side entails challenges of synchronising and aligning discipline-specific methods. So, cycle times of days and weeks in software engineering contrast periods of months in mechanical engineering.

Second, juxtaposing the results with reviewed literature there is consensus. As Broy and Schmidt (2014, p.72) argue that the “required engineering process [for digitised products] is neither an extension of traditional engineering nor a straightforward application of software engineering. Instead, it must draw on insights from mechanical, electrical, computer, and software engineering.” Moreover, the identified methods seem well-eligible to realise the established design principles for digitised products, as highlighted by Porter and Heppelmann (2014, 2015). So, for instance, agile and prototyping methods contribute to implement the design principle of fast market introduction and evergreen design through software updates.

Third, in view of the increasing complexity of digitised products, methodic guidance seems more relevant than ever for the success of product development endeavours (Graner and Mißler-Behr, 2012). Therefore, we see this method compendium as complement to existing methods. On the one hand, for strategic product developers, the compendium acts as framework for orientation. On the other hand, illustrated working methods serve operative engineers as initial, pragmatic guidance. Yet, as any method usage in product development, the goal-oriented use of methods needs to be considered (Lindemann, 2007; Pahl and Beitz, 2007). In this sense, the compendium and herein situated methods need to be applied situation-dependently and not for the sake of method usage (Lindemann, 2007; Pahl and Beitz, 2007). Another aspect which emerged prominently in the case study is initial and continuing education for method users.

As a last point, Yin (2013) designates validity and generalisability as pivotal quality criteria in case study research. Regarding the first aspect, triangulation and seeking for alternative, plausible explanations strengthened validity of this study. Moreover, the intense immersion over a time frame of 2.5 years contributed to portray the case of *IndustrialCo* in a valid manner. Referring to the second facet, the findings are somehow bound to a specific type of product and industry: mobile investment goods of high financial value and longish lifecycles in a business-to-business context. Thus, generalising to other contexts may be done with care and in any way rather conceptually than statistically (Yin, 2013).

6 Conclusions

The present article deals with digitised products, concentrating predominantly on methods assisting the initial stages of the product lifecycle. Aggregating insights from a single-case study, we derived a method compendium. It can be synthesised that product

development needs to have recourse to different domains to support the design of digitised products at the best possible rate.

For the academic discourse on product development and product lifecycle management, we provide

- 1 rare insights from a real-world case
- 2 a concise set of methods as demanded by research.

For professionals in innovation, research and development, and product development departments, our work pragmatically helps to overcome the tremendous obstacles in exploiting digital product innovation.

Though we proceeded up to the best of our knowledge during the compilation of the method compendium, this study is not without limitations: a major restriction is attributable to the single-case study method, bearing limited generalisability and restricted completeness of methods included. Another point of criticism may be related to the cluster forming. Upon the qualitative approach, a clear attribution of methods to one cluster was not possible in some cases.

These restrictions lead over to future work: for one, additional product development cases and used methods need to be studied to strengthen, amplify, and generalise the method compendium. At that, investigating the effectivity of methods on product development success helps to prioritise their use. For another, designing a more macro-level process model seems promising. Ultimately, approaches for the remaining lifecycle stages are required to complement the lifecycle management of digitised products.

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Article #5 – Contribution E

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Abstract

In this paper, we explore the evolution of product lifecycle management information systems projects in manufacturing industries over time. There is critical need because initiated projects routinely fail in terms of time, budget, or quality to which the academic discourse has not given adequate consideration. Therefore, we build up on an in-depth case study within the project setting of a leading European automotive supplier kicked-off in January 2016. As central results, the paper provides insights (1) how product lifecycle management information systems projects develop over time, (2) what may be underlying causes, and (3) which implications on project management may be deduced. In view of the limitations by the applied case study research strategy, we illumine the specifics of these information systems projects for scholars. For project managers, an overview on essential developments and their implications supports the successful project execution.

The Evolution of IS Projects in Manufacturing Industries: The Case of Product Lifecycle Management

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Abstract

In this paper, we explore the evolution of product lifecycle management information systems projects in manufacturing industries over time. There is critical need because initiated projects routinely fail in terms of time, budget, or quality to which the academic discourse has not given adequate consideration. Therefore, we build up on an in-depth case study within the project setting of a leading European automotive supplier kicked-off in January 2016. As central results, the paper provides insights (1) how product lifecycle management information systems projects develop over time, (2) what may be underlying causes, and (3) which implications on project management may be deduced. In view of the limitations by the applied case study research strategy, we illumine the specifics of these information systems projects for scholars. For project managers, an overview on essential developments and their implications supports the successful project execution.

1. Introduction

The concept of product lifecycle management and its underlying information systems has been gaining importance in the scholarly (e.g., [1,2,3]) and practically relevant (e.g., [4,5,6]) body of literature. In essence, product lifecycle management can be conceptualized as a “*business strategy of managing a company’s products all the way across their lifecycles*” [6:1]. Recent figures by market investigation firm *Transparency Market Research* [7] quantify the size of the market for product lifecycle management information systems to around 75 billion US-Dollar in the year 2022, and thus emphasize their tremendous relevance in the industrial manufacturing milieu.

Introduced across a broad front around the turn of the millennium [8], manufacturing businesses are putting their first generation of product lifecycle management information systems to the test. Given

unparalleled necessities in the product realization process (*market pull*) and driven by powerful advancements of digital technologies (*technology push*), companies initiate large-scale and long-term projects to modernize their existing information systems [6,9,10]. Nevertheless, manufacturers are challenged by managing this transition and triggered projects regularly suffer from serious shortcomings in terms of predefined project objectives regarding time, costs, and quality in particular [6,9,10] and stakeholder satisfaction in general [11].

Even though these engineering applications represent focal information systems in industrial enterprises, product lifecycle management is not an entrenched field of research in the information systems domain [3,12]. In particular, fine-grained empirical evidence regarding product lifecycle management information systems projects is mainly missing [9,12]. For one, the temporal progress and its implications for project management have been remarkably disregarded by literature [9,10]. For another, most available works study initial implementations and neglect modernization projects which gain importance within the pervasiveness of product lifecycle management in today’s manufacturing business [9,10]. For scholars, such research sheds initial light on the specifics of product lifecycle management information systems projects as postulated by project management (e.g., [13]) and product lifecycle management (e.g., [9]) literature alike. For project managers, an overview on essential developments and their implications supports the successful realization of such complex projects.

Thus, this paper is interested to explore the evolution of product lifecycle management information systems projects over time. We condense the delineated motivation in the guiding research question as follows: “*How do product lifecycle management information systems projects in manufacturing industries evolve over time?*” We approach this study purpose on the empirical foundation of an exploratory single-case study following Yin [14]. As part of a larger empirical research endeavor on the phenomenon,

this article characterizes essential evolution directions in product lifecycle management information systems projects in the automotive industry acquainted by the well-established framework by Batenburg et al. [15].

At first, we provide an overview on the nature of product lifecycle management, corresponding information systems projects, and related work. Next, the case study research design, surrounding case context, and data basis is outlined. We then present and discuss results in form of evolution directions. Lastly, the conclusion points out contributions, limitations, and avenues for further research.

2. Theoretical background and related work

2.1. Product lifecycle management

Cardinally, the idea of a lifecycle-oriented way of looking at things originates from the biological lifecycle of living things [8]. Nowadays, the most prominent lifecycle model for complex industrial products postulates the stages beginning-of-life, middle-of-life, and end-of-life [2,6]. At that, the product – for example an automobile or a sub-component – is developed and produced in the beginning-of-life, distributed, utilized, maintained in the middle-of-life, and ultimately discarded in the end-of-life phase [2,6]. An emerging body of literature offers a spectrum of conceptualizations of product lifecycle management accentuating its different managerial (e.g., [2]) or technological (e.g., [16]) facets. In this sense, major conceptualizations are itemized chronologically in Table 1.

Table 1. Essential conceptualizations of product lifecycle management

Conceptualization	Source
<i>"[...] product lifecycle management is a systematic, controlled concept for managing and developing products and product-related information [...]"</i>	Saaksvuori and Immonen [4:3]
<i>"[...] product lifecycle management is a business solution which aims to streamline the flow of information about the product and related processes throughout the product's lifecycle such that the right information in the right context at the right time can be made available [...]"</i>	Ameri and Dutta [1:577]
<i>"[...] product lifecycle management is an integrated, information-driven approach comprised of people, processes/practices, and technology to all aspects of a product's life, from its design through manufacture, deployment and maintenance - culminating in the product's removal from service and final disposal [...]"</i>	Grieves [5:39]
<i>"[...] product lifecycle management encompasses all activities and disciplines that describe the product and its production, operations, and disposal over the product lifecycle, engineering disciplines, and supply chain [...]"</i>	Eigner and Stelzer [16:37]
<i>"[...] product lifecycle management is playing a "holistic" role, bringing together products, services, activities, processes, people, skills, ICT systems, data, knowledge, techniques, practices, procedures, and standards [...]"</i>	Terzi et al. [2:364]
<i>"[...] product lifecycle management is the business activity of managing, in the most effective way, a company's products all the way across their lifecycles [...]"</i>	Stark [6:1]

For this paper, we use the formulation by Stark [6] as this very current conceptualization reflects the modern, holistic understanding of product lifecycle management and is furthermore highly cited. The contemporary far-reaching scope accrued from computer-assisted product design in the 1970s and 1980s by stepwise integration of contiguous business processes and involved stakeholders [8,16,17]. Overall, product lifecycle management needs to be understood as an intertwining set of processes, methodologies, and information and communication technology that offers to enhance effectiveness and efficiency [2].

To this end, product lifecycle management platforms integrate abundant decentral information systems [2,16]. The intelligent interplay of individual customized applications such as computer-aided design and computer-aided engineering tools rather corresponds with the idea of a product lifecycle management platform than a single "ready to use" system [2,16]. At the present day, four layer IT architectures consisting of (1) author systems, (2) team data management, (3) engineering backbone, and (4) enterprise resource planning are dominant state-of-the-art [16,17]. In contrast, cloud-based design and manufacturing approaches [18,19] are still subject matter of research. In their seminal paper, Wu et al. [19:2] introduce this concept as *"service-oriented networked product development model in which service consumers are able to configure, select, and utilize customized product realization resources and services and reconfigure manufacturing systems through IaaS, PaaS, HaaS, and SaaS in response to rapidly changing customer needs"*.

2.2. Product lifecycle management IS projects

Contrary to more traditional management forms, projects exhibit a *"limited, temporary, innovative, unique, and multidisciplinary nature"* [20:6]. Implying further on Laudon and Laudon [21:46] who define information systems as a *"set of interrelated components that collect, process, store, and distribute information to support decision making and control in an organization"*, information systems projects focalize on these components [13,22]. In doing so, some authors emphasize the difference between IT and IS projects. Whereas the former is rather technically dominated, the latter is seen globally taking its environment more into account [22,23]. For this paper, we leverage the notion information systems project as we aim to view the phenomenon in its entirety. Accordingly, product lifecycle management information systems projects may be regarded as subset of information systems projects. However, attributes such as the expansive scope, complex

interdependencies, and heavy customization make product lifecycle management projects unique beyond ordinary information systems projects [9,24]. More precisely, Hewett [25:81] stresses “*cultural issues around the product engineer, a lack of standard engineering processes as a foundation for PLM, and the failings of the PLM technology itself*” as distinctive features. In sum, harnessing the typology by Shenhar and Dvir [26], these projects comprise both (1) high technological uncertainty and (2) broad system scope.

Hence, the activity of project management is the “*planning, organizing, directing, and controlling of company resources for a relatively short-term objective [...] to complete specific objectives and goals*” [27:4]. Scientists (e.g., *International Journal of Project Management* and *Project Management Journal*) as well as practitioners (e.g., *Project Management Institute* and *International Project Management Association*) have made fruitful contributions targeting to increase project success and minimize project failure [20,28,29]. For the case at hand, the field of project dynamics (e.g., [30]) attempts to grasp temporal aspects of projects. Contingent upon the process-oriented character [2,31], product lifecycle management information systems projects are commonly accomplished by a process-oriented approach. In that context, Eigner and Stelzer [16] provide an overview on project management approaches for scientific and consulting objectives which comprise the generic phases (1) strategy development, (2) process design, (3) process implementation, and (4) process controlling.

2.3. Related work

For one, the cross-disciplinary field of product lifecycle management has flourished in several science fields, such as new product development and computer science [3]. For another, the area of information systems project management grew in equal measure [32]. To identify key contributions at the intersection of both, we conducted a structured literature review adopting the well-established method by Webster and Watson [33]. In a first step – for the initial literature search [33] – we browsed peer-reviewed journals and academic conferences through main databases incorporating a time frame from April 2002 to April 2017. Thereby, covering major topical constituents with manageable variation, the search string “(“*product lifecycle management*” OR “*PLM*”) AND (“*information systems*” OR “*information technology*” OR “*IS*” OR “*IT*”) AND (“*project*”)” was applied in the publication title, abstract, and key words. We limited this initial bunch of articles to those that explicitly or implicitly address the formulated research

question. In a second step – for the identification of further articles [33] – a forward and backward search was accomplished. Furthermore, doubles were cleared and experts were surveyed for recommendations (books and dissertations) not included so far.

Overall, studies are rare: At a high level, Saaksvuori and Immonen [4] deal with general aspects of project management of product lifecycle management. Such a level of detail can also be found within the seminal work by Stark [6] who identifies common issues within product lifecycle management initiatives. More specifically, Hewett [25] primarily targets organizational challenges and critical issues of implementation projects. Fichman et al. [10] also immerse deeper into implementation focalizing on configurational thinking for value creation. As a last point, most time-wise aspects can be found in Bokinge and Malmqvist [9] who analyze an implementation project and reflect corresponding guidelines. Beyond these particular studies on product lifecycle management information systems projects, the rich body of literature on information systems projects (e.g., [29]) and enterprise resource planning projects (e.g., [34]) provides an insightful knowledge base.

3. Research methodology

3.1. Research design and case study context

The interest of this research is to explore how product lifecycle management information systems projects in manufacturing industries evolve over time. For this ambition, we selected an exploratory case study research design [14,35] which is based on two fundamental reasons: On the one hand, recognizing the type of research question (*how? question*), the control over behavioral events (*no control required*), and the phenomenological focus (*contemporary phenomenon*) [14], case study research enables us to study the complex industry-embedded phenomenon in an intense manner [36,37]. On the other hand, pivotal works on project management (e.g., [9,10]) have demonstrated its aptitude to investigate product lifecycle management information systems projects in an eligible manner. We align with Yin [14:13] and conceptualize a case study as “*empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident*”. More specifically, we employ a holistic and single-case study design with the product lifecycle management information systems project as unit of analysis. Despite the page limitations, we strive for a stringent presentation of our elaborated research design. This seems particularly vital in consideration of

the qualitative approach which is often charged with drawbacks [38].

Contextually, the automotive branch was selected because managing the product lifecycle is particularly demanding and critical in this domain. Since the beginning of 2015, we have been accompanying the project journey of the case organization *ManuCorp*. The automotive supplier from the European DACH region with more than 7,000 employees and close to three billion US-Dollar sales initiated an ample product lifecycle management project with (1) high technological uncertainty and (2) broad system scope [26]. We opt for a single-case study because of (1) the complex nature of product lifecycle management projects [9,24,25], (2) the case's revelatory character [14] through the possibility for long-term and unrestricted access, and (3) its typicality [14] as traditional fabrication business managing its modernization.

In order to cope with the context dependence of case study research [14], we outline substantial characteristics of the case setting at *ManuCorp*. Founded in the 1930s, the firm nowadays operates as a subsidiary of a leading multinational. Around the 1990s the company become part of its automotive business area within an M&A transaction. In the first two decades rather under a financial than strategic roof, *ManuCorp* and the multinational increasingly aim for synergies. In terms of core business, *ManuCorp* is specialized in designing and producing mechanical and mechatronic components and systems for major automotive players. For that, the company is organized on a global scale with R&D locations in Europe and sales and assembly centers in Asia and North America. Having installed a product data management and enterprise resource planning system in the late 1990s which was incrementally further developed, the prime rationale for the project was reasoned in the rapid growth of revenues and rising product complexity. Hence, product lifecycle management processes and information systems had to be re-evaluated and adapted. In this context, Figure 1 demonstrates the timeline of *ManuCorp*'s project including major project phases and accomplished activities. We studied the project as far as April 2017 as major adaptations have been completed and the project has reached linear progress.

Supported by a Swiss technology consultancy (*ConsultCorp*), the project is realized in a bottom-up and process-oriented fashion [2,31]. After a brief scoping phase in 2015, the actual project started in early 2016 and is planned to be finished by the end of 2017, comprising three main phases: In stage I, an analysis of the current processes and information systems, development of a basic concept, and cost-

benefit analysis represented the main elements. Subsequently, in stage II, the design of a target concept with detailed requirements including its extensive evaluation, and finally, in stage III, the concrete system implementation and roll-out acted as core constituents.

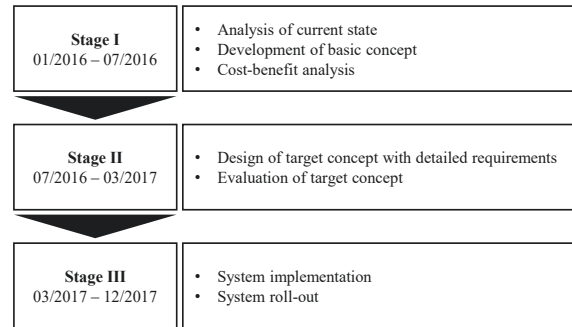


Figure 1. Timeline of *ManuCorp*'s product lifecycle management IS project

Whereas stage I is system-neutral, stage II and III is already system-specific. The project is set up with a core project team of ten members encompassing specialists with relevant managing, operating, and supporting departments involved, rather regularly in workshops or more temporary in milestone meetings.

3.2. Data collection and analysis

Integrating different viewpoints from research at *ManuCorp*, this paper is grounded on primary and secondary data [39]. For data collection and analysis, we leveraged a range of interlinked sources of evidence and techniques [14,35]. For evidence collection, semi-structured interviews [14] and focus groups [40] were harnessed to examine the progress of the product lifecycle management information systems project. With regard to the sampling strategy, informants held key responsibilities in the project (purposeful sampling, [41]). In detail, seven IT roles (e.g., Chief Information Officer), eleven technical roles (e.g., Head of Manufacturing Engineering), and five management roles (e.g., Head of Innovation Management) from *ManuCorp* as well as its parent company and *ConsultCorp* were considered to collect rich and diverse evidence. An iteratively refined interview questionnaire [42,43] and workshop guideline [40] instructed the data collection. As additional sources of evidence [14] we could access the complete project documentation and accomplish observations within the frame of regular visits of the project site. Beyond, we also exploited archival records [14] to augment and triangulate our data sets. Using these resources, we were able to study the project from both an (1) individual and (2) organizational

perspective [14]. To summarize, Table 2 outlines details of analyzed sources of evidence. For the sake of a compelling processing, conversations were taped up, transcribed, and consolidated in a database [44,45].

Table 2. Details of analyzed sources of evidence

Source of evidence	Specification
Interviews/ focus groups	Two resumptive interviews (February 2017)* and 21 intermediate interviews (May 2015 - February 2017)**, four intermediate focus groups (May 2015 - April 2017)*
Documentations	Complete project documentation compiled by <i>ConsultCorp</i> , e.g., project plans, roadmaps, specifications, deliverables, status and cost reportings*
Observations	Continuous project companionship (May 2015 - April 2017) with an average of two days per week at project site including participation in major meetings*
Archival records	Comprehensive documentation of product lifecycle management history of <i>ManuCorp</i> , e.g., process and system documentations, implemented modifications**

* Primary data, ** Secondary data

For evidence analysis, we utilized qualitative coding techniques [46,47,48]. We did so because such practices are adequate for the novel, uncharted phenomenon and our exploratory research strategy at hand [46,47,48]. Furthermore, this kind of analyses enabled us to generate insights valuable for scholars and managers alike [48]. Not least, the advantages of grounded analyses are increasingly recognized in the information systems domain [49]. From a processual perspective, we broke up the data in the (1) *open coding*, created initial relationships in the (2) *axial coding*, and reorganized them in the (3) *selective coding stage* [46,47]. To empower efficiency and effectiveness of coding sequences and to promote rigor, analysis software NVIVO 10 was availed.

Thereby, the well-established product lifecycle management framework [15] informed our coding processes. More precisely, the framework which is rooted in the IT business alignment [50] comprises the dimensions (1) *strategy and policy*, (2) *management and control*, (3) *organization and processes*, (4) *people and culture*, and (5) *information technology*. We selected this analysis framework because of three rationales: First, the framework represents the product lifecycle management project in an overarching manner which goes in line with the goal of this paper. Hence, it enables us to examine technical and non-technical as well as static and dynamic aspects. Second, the framework is anchored in theory and validated through empirical evidence [15] and thus, contributes to guy our study in existing research. Ultimately, the structure affords to go more into detail than rather rough project management frameworks, for example proposed by Kerzner [27].

4. Case study results

In the case study, we identified evidence for the evolution of product lifecycle management information systems projects in manufacturing industries. In aggregate form, Table 3 visualizes *ManuCorp*'s project dynamics from January 2016 to April 2017 along the introduced framework [15] and provides selected supporting literature for each evolution direction.

4.1. Strategy and policy

The temporal progress of the project entailed remarkable changes regarding the first analysis dimension, aspects of *strategy and policy*. Initiated to renew the extant product data management system to enable a more competitive product design, the project objective evolved to the implementation of product lifecycle management as concept: "*Within the first year, we recognized that a pure system replacement is not enough, instead we conceived the need to introduce novel topics and product lifecycle management as holistic management approach.*" (Head of IT Engineering, *ManuCorp*, February 2017). This shift from a pure ICT-centric understanding to an appreciation as business strategy was triggered by internal as well as external drivers: "*By visits of technology fairs and intensive exchange with our operating departments, we learned how product lifecycle management is understood today and what real user needs are.*" (Head of IT Engineering, *ManuCorp*, February 2017).

Furthermore, an augmented involvement of *ManuCorp*'s parent company seeking economies of scale shaped the scope in the course of the project duration. Thus, the role of the project made progress from the development of an autonomous strategy for *ManuCorp* to assessing possibilities for a scalable strategy for other business units of the parent company in the style of a lighthouse project: "*Beside my role as IT project lead at our business unit, I took on a role in our automotive business area where we strive to scale our project outcomes. For one, this has positive effects for our corporation, for another some decelerating and compromising effects through necessary alignment and additional requirements.*" (Chief Information Officer, *ManuCorp*, February 2017).

4.2. Management and control

The project's chronological sequence also had far-reaching impact on the second analysis dimension, issues of *management and control*. Driven by Chief Information Officer and Head of IT Engineering at the very start, increasingly top management attention

through Chief Executive Officer and Head of Operations swapped over as they recognized the strategic and critical role of product lifecycle management for *ManuCorp*'s future product and service business: "For a few months, we regularly host steering committees to inform the executive board and provide them the opportunity to shape strategic directions." (Core Project Team Member, *ManuCorp*, November 2016). Complementary to this novel control mode, a decentralization of project management became nascent as well. The number of involved people imposing requirements has been rising constantly since the project beginning: "More people want to be informed, want to influence decisions, and want to shape the project." (Consultant, *ConsultCorp*, November 2016). This resulted in a core team extension with further representatives.

Aspects that did not affect the project in a direct way, but rather shaped it indirectly, are influences through *ManuCorp*'s customer, supplier, and partner ecosystem. In addition to the initial narrowly drawn internal focus, the project quickly stretched towards further stakeholders beyond the enterprise boundaries. In the heavy interconnected ecosystem of the automotive industry, customers (original equipment manufacturers) on the demand side and suppliers (part and machine suppliers) on the supply side were factored in: "Increasingly we need to seek bilateral exchange with our partners, but also with standardization organizations for industry overarching requirements." (Core Project Team Member, *ManuCorp*, November 2016). These stakeholders impose new and modify extant requirements.

Table 3. Evolution of *ManuCorp*'s product lifecycle management IS project

Temporal progress	Strategy and policy	Management and control	Organization and processes	People and culture	Information technology
Initial product lifecycle management IS project (January 2016)	<i>Objective:</i> Renewal of product data management system <i>Scope:</i> Autonomous strategy for <i>ManuCorp</i>	<i>Steering:</i> Chief Information Officer and Head of IT Engineering with core project team	<i>Value chain:</i> Product development and manufacturing engineering processes	<i>Perception:</i> Niche project with supporting character <i>Awareness:</i> Little awareness on product lifecycle management	<i>IT architecture:</i> Incremental further development of IT architecture
	∇	∇	∇	∇	∇
Evolved product lifecycle management IS project (April 2017)	<i>Objective:</i> Implementation of product lifecycle management as concept <i>Scope:</i> Scalable strategy for parent company	<i>Steering:</i> Chief Executive Officer and Head of Operations with extended core project team, influences through ecosystem	<i>Value chain:</i> End-to-end value chain with direct integrations and indirect allowances, engineering disciplines integration	<i>Perception:</i> Central project attracting attention <i>Awareness:</i> Awareness on product lifecycle management as concept through learning process	<i>IT architecture:</i> Rethinking of IT architecture (macro level), introduction of novel product realization approaches (micro level)
Supporting literature (selected)	Terzi et al. [2]; Stark [6]; Abramovici and Göbel [51]	Fichman et al. [10]; Hewett [25]; Garetti et al. [52]	Terzi et al. [2]; Eigner and Stelzer [16]; Eigner and Roubanov [17]	David and Rowe [3]; Hewett [25]; Garetti et al. [52]	Eigner and Stelzer [16]; Eigner and Roubanov [17]; Bergsjö [53]

4.3. Organization and processes

By far, the most vigorous changes originated in the third analysis dimension referring to aspects of *organization and processes*. Primarily started to enhance key processes of product development and manufacturing engineering, *ManuCorp* increasingly discovered the necessity to involve flanking value chain processes. On the one hand, additional affected functions such as requirements engineering were directly integrated: "Initially, the project was triggered by long-term pain points from series development. Step-by-step we discovered the tight relationships and realized that we need a more global end-to-end perspective." (Core Project Team Member, *ManuCorp*, September 2016). On the other hand, more distant functions like procurement were considered in an indirect manner. As other modernization projects were ongoing in parallel, these functions were allowed by interfaces: "Ideally such a project would cover the whole lifecycle, but operatively projects are divided in more manageable subsets. We carefully selected which value chain elements are in scope, out of scope, or affected." (Consultant, *ConsultCorp*, November 2016).

A nameable evolution is related to engineering disciplines. Over time, the project scope opened from mechanical development processes for physical components to electrics, electronics, and software engineering processes for mechatronic systems. Originally launched to deal better with the complexity, variety, and quantity of the product realization process of mere physical components, *ManuCorp* realized the relevance of digital components (sensors, embedded systems, and actuators) for innovative product functions:

“Most dominantly, this radical further development manifested in the project title. The project was renamed from “product lifecycle management strategy” to “systems lifecycle management strategy.” (Head of IT Engineering, *ManuCorp*, February 2017). In essence, this shift and enlargement of scope doubled the number of involved engineers and their information systems.

4.4. People and culture

The temporal progress of the project also unveiled dynamics related to *people and culture*, the fourth analysis dimension. Kicked-off in 2015 as niche project with a rather supporting character, the product lifecycle management information systems project gradually evolved to a central project attracting attention throughout the whole firm. Moreover, upon the company-wide extent and impact, the product lifecycle management project became one of the essential digitization activities at *ManuCorp*: *“In general, the awareness for the project has been growing strongly. More people speak and discuss about the project. Now it is a common conversational topic on the corridors here.”* (Head of IT Engineering, *ManuCorp*, February 2017). In that regard, an inspirational talk on the technological possibilities for a broad public by a scholar in the summer of 2016 can be regarded as a fostering event. Even beyond the enterprise boundaries the project became well-known in the parent company which has led to an augmented interest as described in the preceding paragraph.

Beyond the perception of the project, the awareness of product lifecycle management itself by the organization showed a highly dynamic behavior. An intensive learning process became perceivable within the project accomplishment. Through intense engagement with the topic in regular workshops, project management staff, but also research and development- and product realization-related functions discovered the manifold and complex faces of product lifecycle management: *“In particular, the apprehension of product lifecycle management as concept, not as application or IT platform was one of our major learnings.”* (Head of IT Engineering, *ManuCorp*, February 2017). Overall, people- and culture-related aspects exhibited a substantial and profound evolution.

4.5. Information technology

The fifth analysis dimension copes with chronological issues in terms of *information technology*. At a macro level, in accordance with the early project scope, the project targeted a more

incremental further development of the existing IT architecture. In line with the evolving, increasingly disruptive project character, a more fundamental rethinking of the IT architecture found its way into the project: *“By now, we discuss completely new arrangements of the IT architecture layers and components including cloud computing approaches.”* (Project Manager IT Engineering, *ManuCorp*, November 2016). In general, upon the complexity more functionality is assigned to layers more close to the authors systems. Furthermore, another major challenge is the composition of a suitable IT architecture for the systems lifecycle management approach for developing mechatronic systems.

At the other information technology spectrum, at a micro level, the necessity to introduce novel product realization approaches like model-based systems engineering occurred over time. The technology to support product realization developed more distinctly than expected by *ManuCorp* at the project kick-off: *“Increasingly, we conduct educational workshops with the product lifecycle management state-of-the-art such as model-based systems engineering or closed-loop product lifecycle management enabled by intelligent products in the context of Industry 4.0.”* (Consultant, *ConsultCorp*, November 2016). In closing, the weightiness of these IT-related changes manifested in the recruitment of two additional IT engineering specialists starting their full-time activities in the spring of 2017. Whereas the first expert aims at creating an overarching architectural picture, the second specialist strives to support the introduction of more specific technologies.

5. Discussion

5.1. General discussion of case study results

First, we commence with a general discussion including a quality assessment and embedding in literature. Our underlying philosophical assumption is an interpretivist epistemology. In contrast to practices for positivist case studies [54], Walsham [55,56] as well as Klein and Myers [57] introduce guidelines for interpretive studies. Ranging from concept to publication, we exerted these principles relating to (1) carrying out fieldwork, (2) theory and data analysis, and (3) constructing and justifying a contribution [56] to the best of our knowledge. In addition, Guba and Lincoln [58] discuss criteria of *trustworthiness* for interpretive studies. We aimed to enhance credibility, dependability, and confirmability by intense engagement, opposite reasoning with further scholars and practitioners, and provision of raw data. With regard to transferability, we believe that with

ManuCorp there is a typical case similar to other manufacturing enterprises at hand. Yet, generalizing is limited in single-case studies and influenced by the parent company and the powerful automotive ecosystem should be mentioned at this juncture which brought in additional dynamics. With a view to potential biases of our direct involvement we note that our role had a rather supporting than directing character and we generally aimed for mindful research.

Next, debating content-wise on the findings, profound dynamics of product lifecycle information systems projects became visible. Moreover, in all dimensions of the analysis framework, major adaptations over the project progression came to the fore. Recalling the aim for stringent project management by *ManuCorp*, this appears indeed surprisingly. Correlating this central finding with existing literature from information systems project management (e.g., [13]) in general and the introduced product lifecycle management (e.g., [6,9]) in particular, these dynamics have been indicated by previous research, but not described in detail. Comparing the evolution directions in terms of their impact on posed project objectives, the value chain integration – in particular the integration of engineering disciplines – had the greatest influence. Accordingly, the impactful shift from product to systems lifecycle management for increasingly mechatronic and digitized products [59] may be paid the most attention. Examining more detailed the temporal sequence of the project, the scope steadily widened over time, yet the intensity varied wavelike. Started with strong intensity during the interviews and workshops for the current state identification, the following stages were characterized with low intensity for scoping and high intensity for completing novel scopes. Furthermore, whereas it seems obvious that companies which are implementing product lifecycle management for the first time are confronted with challenges, it remains conspicuous that businesses with more experience also undergo severe challenges. Ultimately, juxtaposing this product lifecycle management project with the introduced traditional information systems projects (e.g., [29]) and enterprise resource planning projects (e.g., [34]), some similarities such as the important role of (top) management can be detected. In contrast, the necessity for customization to meet the lacking engineering standards represents an example for differentiation which both go in line with literature [12,25].

5.2. Sensemaking of IS project evolutions

Second, having discussed the manifold facets of the project evolutions, sensemaking of the underlying reasons seems worthwhile. Investigating the reasons of

these profound dynamics, there is recurring evidence that product lifecycle management as concept with its far-reaching outreach is not fully understood although its character has been highlighted by research and practice for a considerable time: For example, Eigner and Stelzer [16] sketched the solution space comprising the dimensions (1) product lifecycle, (2) supply chain, and (3) engineering domains. Later on, Terzi et al. [2] nominated product lifecycle management as interlinked set of processes, methodologies, and information and communication technology. Moreover, David and Rowe [3] emphasized its managerial character. This misjudgment has led to serious deficits regarding agreed project goals for *ManuCorp* and may be a conceivable situation for other traditional fabrication businesses. Thus, the severe project dynamics may uncover the paradoxical nature of product lifecycle management information systems projects: Although the extent is principally known, the project endeavor starts with a compact scope, commonly triggered by a specific pain point. Then, the project dilatation emerges step-wise in parallel with an organizational learning process. Whereas some dimensions of product lifecycle management are well-known, others seem to be more underestimated. The case indicated that technical dimensions tendentially seem to be better understood than organizational dimensions which is also reported by previous studies (e.g., [25]). Overall, such pervasive dynamics seem not unexpected as such projects are initiated seldom. Thus, not much knowledge is available within the organization.

5.3. Implications on IS project management

Finally, in consequence this specific character has profound implications on the design of product lifecycle management information systems projects in manufacturing industries. Based on our findings, we argue that it is necessary and worthwhile to consider the dynamics in project management. Thus, existing methods and practices (e.g., [9]) need to be refined. Therefore, adopting a project lifecycle perspective, evolution-driven implications in particular refer to (1) project preparation and (2) project execution: First, we propose that project resources may be increasingly allocated from project operations to planning stages. We do so because quality management research (e.g., [27]) has shown that project change costs rise exceedingly with preceding project lifecycle. Moreover, with reference to the uncovered limited understanding of product lifecycle management, these resources may be particularly assigned to accelerate the organizational learning process. So, for example a maturity assessment and advanced training before

project initiation can support the specification and validation of the forthcoming project. Specifically, *ManuCorp* respectively its parent company targets a business area-overarching maturity assessment and a periodic forum on product lifecycle management topics. Second, complementary to these preparatory activities, we suggest that at an increasing rate elements from agile project management (e.g., [60]) may be incorporated. Upon the complex, evolving nature of product lifecycle management information systems projects, agile approaches seem well qualified as they are explicitly designed to react to change [60]. So, elements such as continuous feedback loops can assist a successful project operation. In detail, *ManuCorp* has partitioned the remaining project time in shorter cycles to gain in agility. This leads over to the established discussion of plan-based versus agile project management [60]. Our case study shows evidence that these projects can benefit from a consideration of both approaches offering immediate value and high assurance alike. Beyond these managerial implications, academic research should increasingly look after these emerging projects. In particular, the complex real-world character should be addressed.

6. Conclusion

The paper at hand strives to study the evolution of product lifecycle management information systems projects over time. We do so because the far-reaching complexity of such projects poses challenges on producers to which the academic discourse has not given sufficient consideration. Grounded on a case study approach, we retrospectively captured the evolution of product lifecycle management information systems projects utilizing an established analysis framework. Going back to the posed research question, we can conclude that these information systems projects show a highly dynamic character.

For research, we offer three main contributions: First, to the best of our judgement this manuscript is the first to examine the chronological sequence of such projects in an ample way. Thus, by elaborating temporal aspects, we shed initial light on the specifics of these projects as claimed by literature (e.g., [9,13]). Second, we provide a connecting factor for other scholars [33]. Grounded on the preliminary findings as starting point, we would like to animate researchers continuing and extending this aspiring research field towards theoretical contributions. Finally, as truly interdisciplinary academic domain [33,61], we connect the domain of information systems with the research community of project management and product lifecycle management.

For practice in today's demanding manufacturing industries, the case study provides a valuable overview of real-world insights and implications for project managers charged with similar tasks in the digital age. As the success of these information systems projects becomes a pivotal factor for the future prosperity of producers, this knowledge holds the potential to support IT executives overcoming the multi-dimensional challenges and increasing the success rate.

Nevertheless, we acknowledge that our approach is exposed to weaknesses, conceptually, empirically, and analytically: First, conceptually, the exploratory approach cannot provide completeness, the interpretive approach is formed by social construction. Second, empirically, the single-case study offers extensive description, yet is paralleled by limited generalizability. Ultimately, analytically, upon the heterogeneity of involved sources of evidence, the processing procedures encompassed some simplifications (e.g., summary report of meetings instead of full transcript) for the sake of operability.

As an outlook, accomplishing further case studies can endorse or disconfirm the identified dynamics and furthermore enhance the generalizability of the findings (cross-case analysis, Yin [14]). In addition, the identification of specific factors influencing project success or project failure can make an appreciated contribution as well. Selected of these issues will be the content of our future research works, yet we hope that this research also will fuel further scholars.

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Abstract

In today’s competitive economy the systematic development and management of industrial products has become a central issue for manufacturers. In this paper, the field of product lifecycle management is mapped to tribute to its colorful past and promising future. Therefore, a set of well-established bibliometric methods – i.e. (1) citation analysis, (2) co-citation analysis, (3) bibliographic coupling analysis, (4) co-author analysis, and (5) co-word analysis – provides a suitable methodological vehicle. Essential results comprise (1) the documents, authors, and journals with the most impact, (2) the intellectual structure, (3) the intellectual structure of emerging literature, (4) the social structure, and (5) the topics associated with the field. Grounded on these insights, potential avenues for further research are highlighted. Within the characteristic limitations of this kind of literature review, the paper offers content-wise, method-wise, and discipline-wise contributions.

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Mapping the Field of Product Lifecycle Management: A Bibliometric Study

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Abstract: *In today's competitive economy the systematic development and management of industrial products has become a central issue for manufacturers. In this paper, the field of product lifecycle management is mapped to tribute to its colorful past and promising future. Therefore, a set of well-established bibliometric methods – i.e. (1) citation analysis, (2) co-citation analysis, (3) bibliographic coupling analysis, (4) co-author analysis, and (5) co-word analysis – provides a suitable methodological vehicle. Essential results comprise (1) the documents, authors, and journals with the most impact, (2) the intellectual structure, (3) the intellectual structure of emerging literature, (4) the social structure, and (5) the topics associated with the field. Grounded on these insights, potential avenues for further research are highlighted. Within the characteristic limitations of this kind of literature review, the paper offers content-wise, method-wise, and discipline-wise contributions.*

Keywords: *Product lifecycle management, PLM, manufacturing industries, literature review, bibliometric study*

Introduction

In today's competitive economy the systematic development and management of industrial products has become a central issue for manufacturers (Terzi et al. 2010; David and Rowe 2015; Stark 2015). Conformable to the highly cited understanding of Stark (2015, p.1), product lifecycle management is defined as a “business activity of managing, in the most effective way, a company's products all the way across their lifecycles”. In this product lifecycle, activities of product design and manufacturing (i.e. beginning-of-life stage), tasks of distribution, use, and support (i.e. middle-of-life stage), and works of retiring and disposing (i.e. end-of-life stage) are accomplished (Terzi et al. 2010; Stark 2015). From an economic perspective, an estimated product lifecycle management market of around 65 billion US-Dollar in five years from now on (Global Industry Analysts Inc. 2016) underlines the vital role of the 21st century paradigm for product realization (Stark 2015).

With product lifecycle management coming to age on the one hand (David and Rowe 2015) and being predicted to have a glowing future by novel technologies such as the Internet of Things, Big Data analytics, and cloud computing on the other hand (Terzi et al. 2010), a review of the field seems both timely and relevant. Increasingly understood as socio-technical phenomenon (Bostrom and Heinen 1977; David and Rowe 2015), the information systems domain seems predestinated to attend this matter. Despite brilliant knowledge syntheses from the outset (e.g., Terzi et al. 2010; David and Rowe 2015), qualitative structured literature reviews are inherently restricted by scope and rigor (Zupic and Cater 2015). In contrast, quantitative bibliometric literature reviews to explore hidden structures and furthermore overcome these limitations (Zupic and Cater 2015) are practically non-existent. Moreover, a major challenge is rooted in the deeply distributed research and practice activities related to the lifecycle of industrial products that merged in the field of product lifecycle management (David and Rowe 2015; Pinquié et al. 2015). Summarizing this need for a mapping of the field (Bhatt et al. 2015; David and Rowe 2015), the guiding research question (RQ) for this paper is stated as follows: *“How is the field of product lifecycle management in manufacturing industries organized?”*

Therefore, this paper applies a set of well-established bibliometric methods according to the single-source reference of Zupic and Cater (2015). In particular, bibliometric data from the largest scholarly database for peer-reviewed literature are compiled, analyzed, visualized, and interpreted (Zupic and Cater 2015). Such an approach is chosen because the demand for diversity in the information systems domain has been expressed by Benbasat and Weber (1996) in general and by Fettke (2006) for literature reviews in particular.

The paper continues with the research background in terms of product lifecycle management and existing literature reviews. Next, the research methodology including an overview on bibliometric studies and the applied workflow is ushered. The subsequent two sections focus on presentation and discussion of the bibliometric study results, clustered by analysis type. The paper closes with a summary, contributions, limitations as well as potential directions for further research.

Research Background

Nature of Product Lifecycle Management

In essence, Cao and Folan (2012) describe the history of product lifecycle management as four-level evolution: Main development steps range from (1) essential product-centric IT tools (e.g., computer-aided design CAD) in the 1970s, to (2) more general product-centric IT applications (e.g., computer-aided quality CAQ) in the 1980s, to (3) product data management (PDM) in the 1990s, and nowadays (4) product lifecycle management (PLM) since the 2000s (Cao and Folan 2012). The birth of the field may be the establishment of the International Conference of Product Lifecycle Management and the International Journal of Product Lifecycle Management in 2003 respectively 2005 (Pinquié et al. 2015). Notwithstanding the field resorts to related research communities such as new product development, product-service-system engineering, or computer science up to today (Pinquié et al. 2015). Beyond the given conceptualization of Stark (2015) seminal definitions have been formulated by Saaksvuori and Immonen (2002), Ameri and Dutta (2005), Grieves (2006), Eigner and Stelzer (2008), and Terzi et al. (2010) over the years. In their comprehensive article, Corallo et al. (2013) emphasize the diversity of elements of product lifecycle management. Nevertheless they agree on (1) managerial features (e.g., integrated approach), (2) technological features (e.g., product information backbone), and (3) collaborative features (e.g., integrating people, process, and data) as distinctive elements (Corallo et al. 2013). In brief, from an originally technical understanding, product lifecycle management is increasingly grasped as management approach (Terzi et al. 2010; David and Rowe 2015). Accordingly, the field is becoming a major area of interest in the information systems domain (Nambisan 2003; Nambisan 2013; David and Rowe 2015).

Existing Literature Reviews

Looking for available literature reviews relating to product lifecycle management within the last decade (Webster and Watson 2002), fundamentally two distinct publication streams can be detected, qualitative and quantitative analyses: Firstly, concerning qualitative literature reviews, Terzi et al. (2010) created a pioneering piece recapitulating the preceding and future role of product lifecycle management. Furthermore, a set of shorter state-of-the-art contributions (Abramovici 2007; Garetti et al. 2007; Cheung and Schaefer 2009) with no structured literature search approach mainly published as book chapters becomes nascent. The work of Ming et al. (2005) on the state-of-the-art of product lifecycle management in collaborative contexts can be counted to the group of reviews on specific topics. The most recent contribution is made by David and Rowe (2015) who systematically review publications from different communities and derive avenues for further research. Secondly, regarding quantitative analyses, publications come considerably more rarely into sight. Solely Bhatt et al. (2015) conducted a quantitative study on publications from the International Conference of Product Lifecycle Management. Other quantity-oriented publications are solely partially tangent to the field, such as Kalluri and Kodali (2014) who review new product development research or Oliveira et al. (2015) who examine the field of product-service-systems.

Highly appreciating the attempts to map the complex field of product lifecycle management, extant research works are exposed to shortcomings: For instance, as most fitting qualitative contribution, David and Rowe (2015) merely map the field selectively and communicate their findings in French language. As most relevant quantitative contribution, Bhatt et al. (2015) exhibit a very narrow scope of literature and provide few implications for action. Briefly, a consistent mapping of the field is hardly existent (Bhatt et al. 2015; David and Rowe 2015). To shrink this research gap, the paper at hand reports on a conducted bibliometric study.

Research Methodology

Overview on Bibliometric Studies

Zupic and Cater (2015) differentiate three fundamental types of literature reviews: Qualitative studies, meta-studies, and bibliometric studies. For this paper, a bibliometric study was selected upon three rationales: Firstly, within the increasing number of publications, quantitative analyses can be seen as value-adding methods (Zupic and Cater 2015). Especially the holism and interdisciplinary character of the subject at hand (Terzi et al. 2010) put such methods forward. Secondly, concrete metrics assist to overcome potential biases of interpretive, qualitative reviews (Zupic and Cater 2015). Thirdly, the diversity in review methods in the information systems domain needs to be strengthened as Fettke (2009) unveils that zero percent of reviews published in the journal *Business & Information Systems Engineering* exhibit quantitative character.

In short, the purpose of bibliometric methods is to “examine how disciplines, fields, specialties, and individual papers are related to one another” (Zupic and Cater 2015, p.429). Following Khan and Wood (2016) these methods can be assigned to the group of social network analyses, conventional literature reviews, and topic analyses. Pristine research works (e.g., Cattell 1906; Pritchard 1969; Broadus 1987) demonstrate that bibliometric methods feature a long tradition. However, these days two major factors contribute to taking on greater significance: For one new databases aim to provide a consistent single-source data basis, for another novel tools afford an intelligent data processing (van Eck and Waltman 2014; Zupic and Cater 2015). Such methods have given proof of making contributions in distinct research communities such as business and management (e.g., Olczyk 2016) or innovation and technology (e.g., Remneland Wikhamn and Wikhamn 2013). In the information systems domain an emerging number of publications in quality outlets (e.g., Beverungen 2011; Simon et al. 2013; Khan and Wood 2016) demonstrates that these types of works are on the rise.

For this paper, the single-source reference for bibliometric methods compiled by Zupic and Cater (2015) is used as sound guidance. More precisely, the recommended workflow is pursued: (1) Development of research design, (2) compilation of bibliometric data, (3) analysis, (4) visualization, and (5) interpretation. Scholars providing methodic guidance for qualitative (e.g., vom Brocke et al. 2009; vom Brocke et al. 2015) and quantitative (e.g., Börner and Polley 2014; Thiede 2017) reviews alike plea for rigor, thus this paper aims for end-to-end transparency. Beyond, each step outlined hereinafter is augmented by further methodological guidance (e.g., Webster and Watson 2002; Rowe 2014; Schryen 2015).

Workflow for Bibliometric Studies

Step 1: Development of research design. Within the objective of an initial mapping of the field and the restricted space, this paper strives for the most established and insightful analyses: In particular, the documents, authors, and journals with the most impact (RQ1), the intellectual structure (RQ2), the intellectual structure of emerging literature (RQ3), the social structure (RQ4), and the topics associated with the field (RQ5) are targeted (Zupic and Cater 2015). Hence, (1) a citation analysis, (2) a co-citation analysis, (3) a bibliographic coupling analysis, (4) a co-author analysis, and (5) a co-word analysis serve as proper research design (Zupic and Cater 2015).

Step 2: Compilation of bibliometric data. Basically, several databases such as Web of Science by Thomson Reuters, Scopus by Elsevier, or Google Scholar by Google are qualified for the data provision. For the selection process, comparative research on databases (Bakkalbasi et al. 2006; Falagas et al. 2008) was consulted and finally Scopus which is according to their own statements “the largest abstract and citation database of peer-reviewed literature” (Elsevier 2017) was selected. One critical reason was that the International Journal of Product Lifecycle Management as essential source is currently not included in Web of Science (Thomson Reuters 2017). The compilation of the data – accomplished on July 31, 2017 – proceeded as follows (vom Brocke et al. 2009): With product lifecycle management as unique term (Pinquié et al. 2015), a database search in title, abstract, and keywords seemed adequate to grasp the literature ($\Sigma 4,055$ hits). Targeting recent contributions, results were reduced involving a ten year time frame ($\Sigma 3,091$ hits). For the sake of the most enduring pieces, these hits were restricted to journals ($\Sigma 1,134$ hits) and limited to results published in English ($\Sigma 1,018$ hits). Thereafter, obviously non-relevant scientific domains ($\Sigma 830$ hits) and journals ($\Sigma 552$ hits) were removed. Bibliometric data were downloaded.

Steps 3/4/5: Analysis/visualization/interpretation. Subsequent steps were prepared by quality check and reworking of bibliometric data. So far not known articles were screened for fit. Concerning the analysis and visualization diverse tools (e.g., CiteSpace, Gephi, Pajek, and VOSviewer (van Eck and Waltman 2014)) are available. The software VOSviewer (van Eck and Waltman 2010; Waltman et al. 2010) was chosen as this tool supports the developed research design and has proven as successful in several similar cases (e.g., Khan and Wood 2016). Particularly for the important step of interpreting, several focus groups (Morgan 1988; Tremblay et al. 2010) helped to discuss the findings and draw implications (Zupic and Cater 2015). Here, senior researchers for experience and junior scholars for an unbiased mindset were included as stressed by Zupic and Cater (2015).

Bibliometric Study Results

Documents, Authors, Journals with the Most Impact: Citation Analysis

Table 1 visualizes the findings of the accomplished citation analysis. A citation analysis “estimates influence of documents, authors, or journals through citation rates” (Zupic and Cater 2015, p.432). Thus, this type of bibliometric analysis enables to answer the first research question (RQ1) “*What documents, authors, and journals have the most impact in the field of product lifecycle management?*”. In line with the posed research question, documents, authors, and journals were used as units of analysis. It should be noted that for this sub-section no network visualization was selected as direct citation networks are commonly parsimonious (Zupic and Cater 2015).

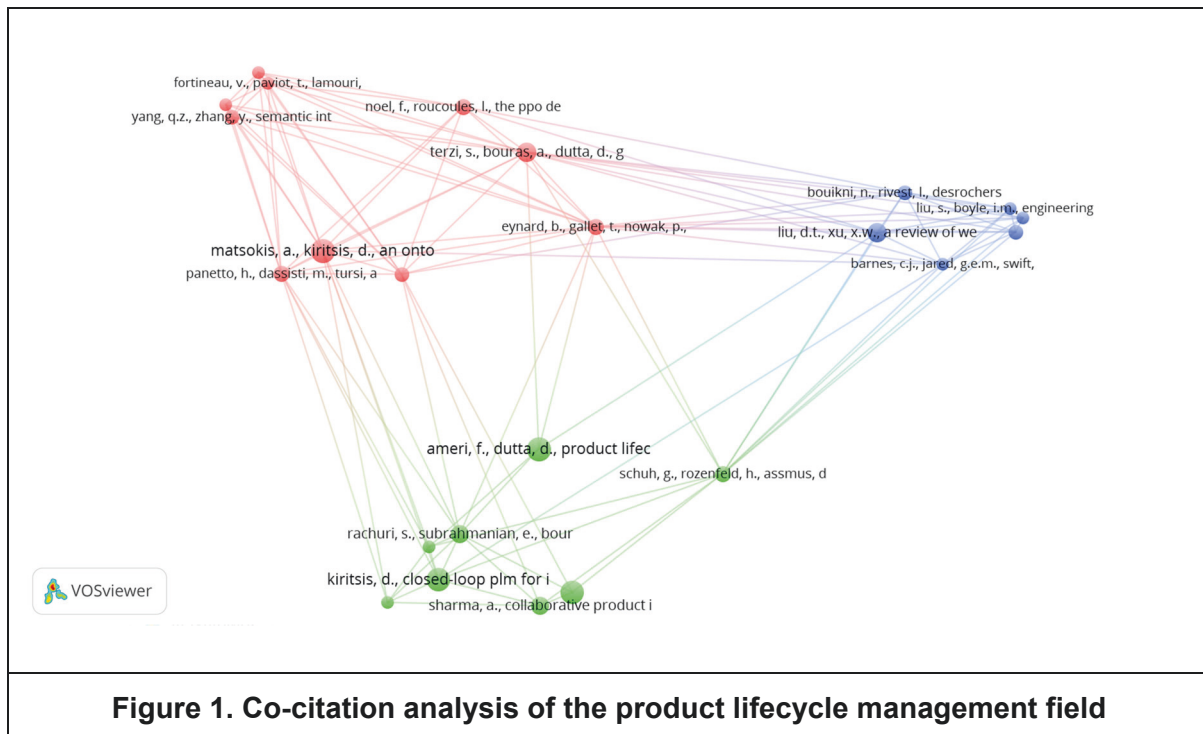
To summarize Table 1, the paper on intelligent products by Meyer et al. (2009) as most cited document, senior scholar Dimitris Kiritsis from the École Polytechnique Fédérale de Lausanne as most cited author, and the IT-oriented outlet Computers in Industry as most cited journal in the field of product lifecycle management can be seen. Examining the quantity of citations, the field can be classified as established, compared to other fields such service science where most cited documents show around 400 citations (Beverungen 2011). Studying in contrast their distribution, the citations are rather unequally distributed. Particularly author and journal citations clearly expose a “star” author (Dimitris Kiritsis) and a “star” journal (Computers in Industry) with the next author respectively next journal accounting for around the half respectively a third of received citations. Generally, it becomes evident that a large share of the items in Table 1 comprises a rather technical focus. Research is especially published in strongly IT-related journals (e.g., Computers in Industry) or specific outlets (e.g., International Journal of Computer Integrated Manufacturing). These enumerations suggest the field’s most impactful documents, authors, and journals in an unambiguous manner, yet imply that “much that is read is not cited, and citation behavior can be biased” as noted by Culnan (1987, p.342).

Table 1. Citation analysis of the product lifecycle management field			
#	<i>Documents (no. of cit.)</i>	<i>Authors (no. of cit.)</i>	<i>Journals (no. of cit.)</i>
1	Meyer et al. 2009 (226)	Kiritsis, D. (700)	Computers in Industry (1600)
2	Kiritsis 2011 (176)	Främling, K. (359)	CAD Computer-Aided Design (564)
3	Kumar/Putnam 2008 (137)	Holmström, J. (292)	Int. J. of Computer Integrated Manufacturing (424)
4	Shen et al. 2010 (130)	Rivest, L. (290)	Int. J. of Product Lifecycle Management (371)
5	Jun et al. 2007 (119)	Eynard, B. (250)	CIRP Annals Manufacturing Technology (353)
6	Baxter et al. 2007 (111)	Foufou, S. (246)	Advanced Engineering Informatics (288)
7	Terzi et al. 2010 (106)	Sriram, R. D. (245)	Int. J. of Production Economics (253)
8	Vanlande et al. 2008 (104)	Meyer, G. G. (226)	Int. J. of Advanced Manufacturing Technology (227)
9	Maropoulos/Ceglarek 2010 (101)	Vezzetti, E. (196)	Robotics and Computer-Integrated Manufacturing (217)
10	Panetto et al. 2012 (95)	Bouras, A. (194)	Research in Engineering Design (216)

Intellectual Structure: Co-citation Analysis

Figure 1 illustrates the result of the conducted co-citation analysis. A co-citation analysis “connects documents, authors, or journals on the basis of joint appearances in reference lists” (Zupic and Cater 2015, p.432). Consequently, the second research question (RQ2) “*What is the intellectual structure of the field of product lifecycle management?*” can be addressed with such an analysis. For the generation of the co-citation network, the focus lay on the content-oriented unit of analysis document. For an expressive visualization, key parameters were set to a Minimum number of citations of a cited reference $m=3$ and a Number of cited references to be selected $n=24$. In addition, the Full Counting Methodology was used. In the resulting network a node represents a document and the node size corresponds with the number of citations. Furthermore, VOSviewer uses distance-based visualization, consequently two documents appear closer in the visualization if these two documents are cited together in a third document more often (van Eck and Waltman 2010; Waltman et al. 2010).

Closer inspection of Figure 1 unveils three co-citation clusters, shaded in different colors. The first cluster (red) comprises documents around Matsokis and Kiritsis (2010), the second cluster (blue) exhibits works around Liu and Xu (2001), and the third cluster (green) features documents around Kiritsis (2011). Externally, the clusters are quite self-contained and delimited from one another. Internally, the clusters can be qualified as rather dense. For instance, Matsokis and Kiritsis (2010) and Panetto et al. (2012) show a strong connection in the co-citation network. Both documents approach product lifecycle management ontology-based, thus show high content-oriented similarity. This corroborates the statement of Zupic and Cater (2015) who introduce co-citation as measure for similarity. Generally, from a content-oriented viewpoint, the intellectual structure is dominated by conceptual (e.g., Matsokis and Kiritsis 2010) and technical (e.g., Kiritsis 2011) works on product lifecycle management. By way of contrast empirical and theory-driven research is mainly missing. As publishing and citation processes usually take time, it needs to be remarked that the network maps the field with certain temporal delay (Zupic and Cater 2015).



Intellectual Structure of Emerging Literature: Bibliographic Coupling Analysis

Figure 2 depicts the outcome of the performed bibliographic coupling analysis. A bibliographic coupling analysis “connects documents, authors, or journals on the basis of the number of shared references” (Zupic and Cater 2015, p.432). Hence, such an analysis technique affords to answer the third research question (RQ3) “*What is the intellectual structure of emerging literature of the field of product lifecycle management?*”. As for the previous co-citation analysis, again documents serve as insightful units of analysis. For the creation of the bibliographic coupling network, the visualization parameters were adjusted as follows: Minimum number of citations of a document $m=5$ and a Number of documents to be selected $n=30$. Additionally, in turn the Full Counting Methodology was applied. In the resulting bibliographic coupling network with distance-based visualization, documents are represented by nodes with the node size matching with the quantity of received citations. A short distance between two documents (i.e. the length of the edges) can be viewed as a good match of their reference lists (van Eck and Waltman 2010; Waltman et al. 2010).

From the Figure 2 four individual, differently colored bibliographic coupling clusters become nascent. Dominant documents in these clusters are Terzi et al. (2010) [green cluster], Maropoulos and Ceglarek (2010) [red cluster], Panetto et al. (2012) [yellow cluster], and Demoly et al. (2011) [blue cluster]. Compared to the previous co-citation network, the clusters of the bibliographic coupling network can be described as less distinct and more interconnected. Beyond, it can be seen that, for example, Panetto et al. (2012) and El Kadiri and Kiritsis (2015) exhibit a tight relationship in the network. Both documents focus on ontologies in the context of product lifecycle management, hence this can be construed as measure for similarity, which goes in line with Zupic and Cater (2015). The intellectual structure of emerging literature is also shaped by conceptual (e.g., Panetto et al. 2012) and technical (e.g., Cao et al. 2009) works, complemented by reviews on specific topics (e.g., El Kadiri and Kiritsis 2015). Furthermore, it is assembled by few authors (or author teams) such as Hui Cao and Frédéric Demoly. In contrast, empirical and theory-driven research is practically non-existent. As there is no retardation in comparing reference lists, the network at hand is appropriate to describe the structure of nascent literature (Zupic and Cater 2015).

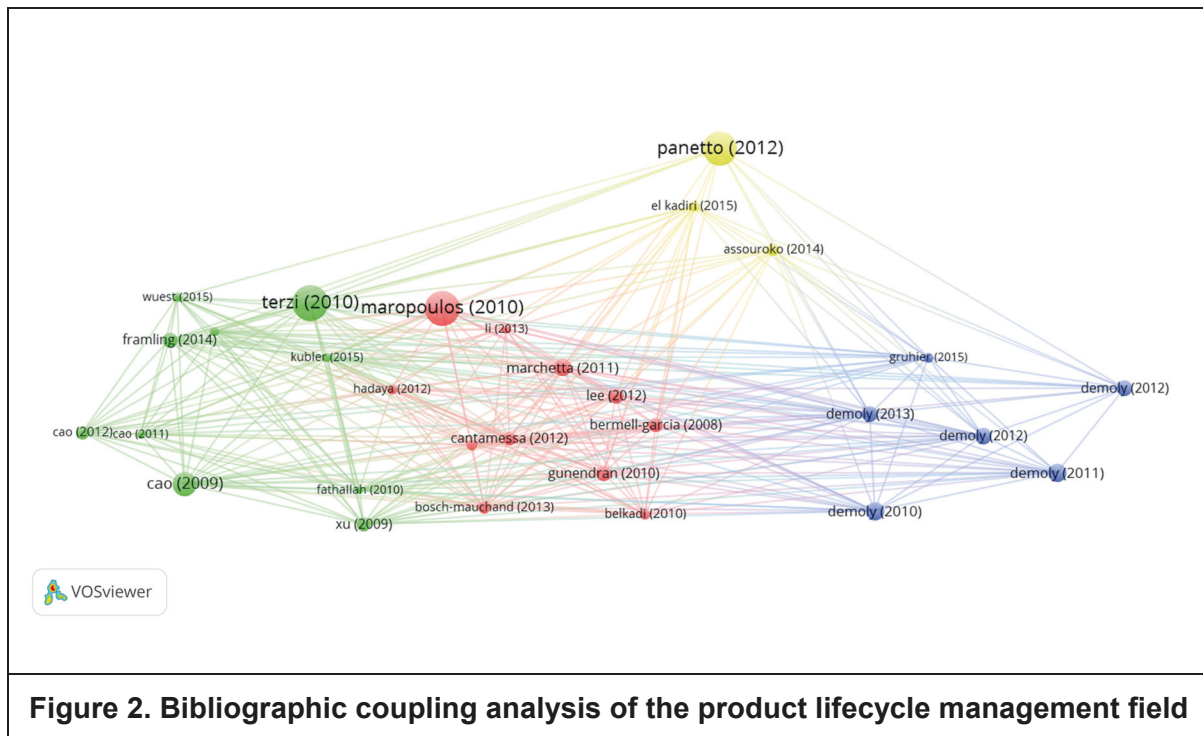


Figure 2. Bibliographic coupling analysis of the product lifecycle management field

Social Structure: Co-author Analysis

Figure 3 demonstrates the result of the carried out co-author analysis. A co-author analysis “connects authors when they co-author the paper” (Zupic and Cater 2015, p.432). Thus, the posed fourth research question (RQ4) “*What is the social structure of the field of product lifecycle management?*” can be answered with a co-author analysis. For this particular study, a unit of analysis at an author level, rather than an increasingly anonymous organization or even country level, was decided. For a revelatory visualization of the co-author analysis, the network parameters were tuned to a Minimum number of documents of an author $m=2$, Minimum number of citations of an author $n=10$, and Number of authors to be selected $o=63$. With regard to the counting approach, the Full Counting Methodology was harnessed. In the co-author analysis figure, the nodes represent authors and the size of the nodes serve as measure for the number of authored documents. The proximity of two authors on the other hand is higher if they co-authored more documents together (van Eck and Waltman 2010; Waltman et al. 2010).

In Figure 3 nine different inked co-authorship clusters become evident. Thereby, each co-author cluster comprises one (e.g., Dimitris Kiritsis for the green cluster) or more (e.g., Frédéric Demoly and Samuel Gomes for the brown cluster) key authors. The clusters themselves are organized rather independently which implies a rather loose social structure and weak collaboration beyond the borders of the individual clusters. In particular, the strong connection between Dimitris Kiritsis and Aristeidis Matsokis, for example, can be detected which seems plausible as both scientists have been working at the École Polytechnique Fédérale de Lausanne. However, at this point it is remarkable that co-authorship needs be understood rather as measure for co-authoring documents than for co-working on product lifecycle management as authorships are often given upon social and political reasons (Zupic and Cater 2015).

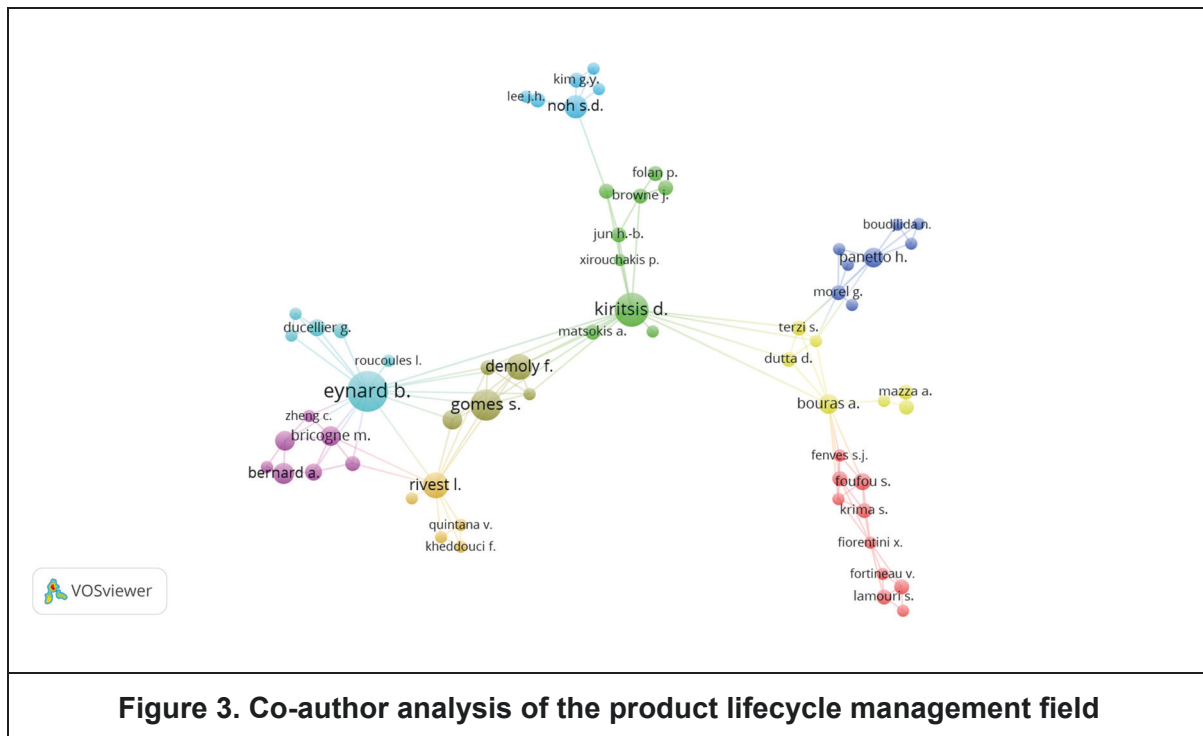


Figure 3. Co-author analysis of the product lifecycle management field

Topics Associated: Co-word Analysis

Finally, Figure 4 displays the outcome of the undertaken co-word analysis. A co-word analysis “connects keywords when they appear in the same title, abstract, or keyword list” (Zupic and Cater 2015, p.432). Consequently, co-word analyses are suitable to address the fifth research question (RQ5) “*What are the topics associated with the field of product lifecycle management?*”. For this last work, the co-word analysis was applied to words appearing in the author keywords field as these describe the content more precisely than standard classification systems. Beyond, parameters were set to a Minimum number of occurrences of a keyword $m=3$ and a Number of keywords be selected $n=40$ to generate an informative, yet manageable network. For this ultimate analysis, also the Full Counting Methodology was employed. In the originating co-word analysis network, each node represents a key word, the node size corresponds with the number of occurrences. In the distance-based network representation, two key words adjoin closer the more often they occur together in documents (van Eck and Waltman 2010; Waltman et al. 2010).

It can be seen from the data in Figure 4 that the borders of the many co-word clusters were blurring this time, hence a monochromatic representation seems proper. Naturally, terms of product lifecycle management as center of the network can be seen. Furthermore, exempli gratia, strong relationships to notions of information management and knowledge management are identifiable. From a technology perspective, the important role of the Internet of Things and accordingly closed-loop product lifecycle management emerges. Nevertheless, despite the nomenclature of product lifecycle management, the field seems to focus on applications in the early lifecycle stages such as product development and manufacturing and corresponding sub-functions like simulation. This approach uses actual paper content instead of meta-data like the antecedent analyses (Zupic and Cater 2015). Special consideration however is necessary as “words can appear in different forms and can have different meanings” (Zupic and Cater 2015, p.432).

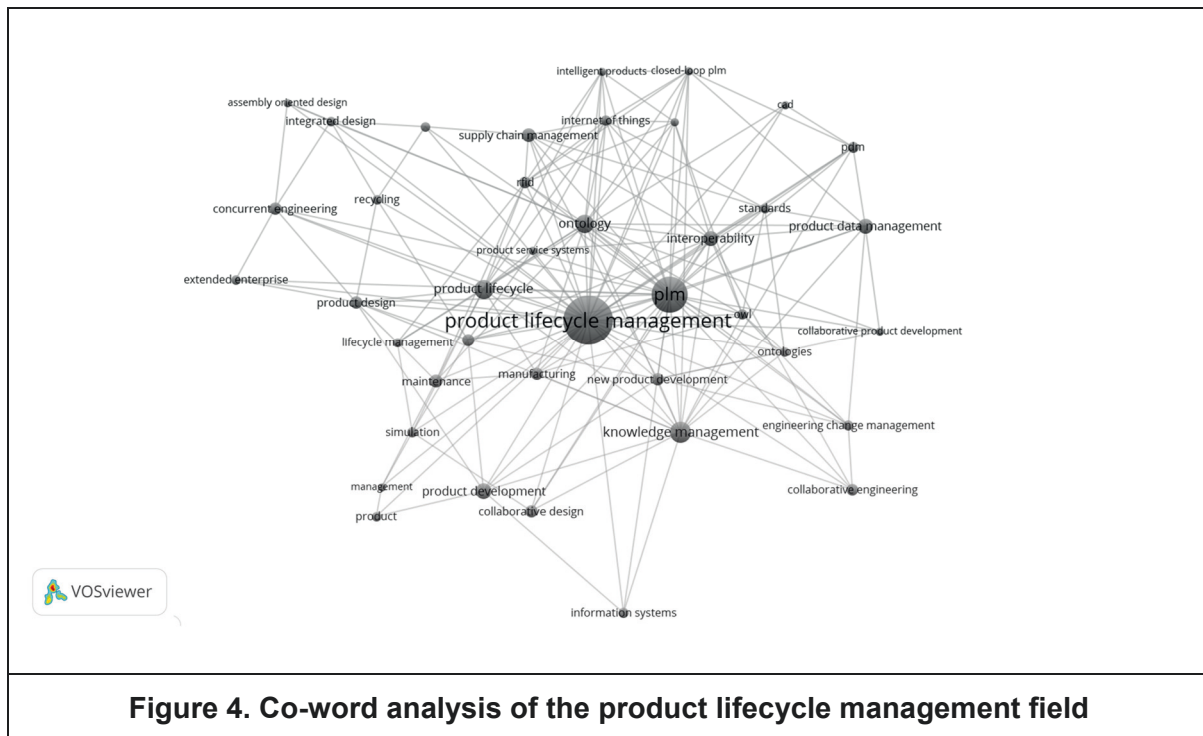


Figure 4. Co-word analysis of the product lifecycle management field

Discussion

Typically triggered by the timeliness and relevance of product lifecycle management and methodically fostered by the limited scope and rigor of qualitative literature reviews, it was set out to map the field which yielded in five bibliometric analyses. The purpose of this successive discussion is two-fold, elaborating for one main findings, research gaps, and potential avenues for further research including a comparison with existing reviews, and assessing for another scholarly quality measures of the conducted bibliometric study.

Concerning the first objective, referring to the guiding research question “*How is the field of product lifecycle management in manufacturing industries organized?*”, Table 2 enumerates main findings of the bibliometric study. The performed mapping of 552 published journal articles showed that the field can be considered established and diverse alike. With a view to research gaps and potential avenues for further research (Webster and Watson 2002; vom Brocke et al. 2009; Schryen et al. 2017), implications can be drawn from findings of the content-related analyses (i.e. co-citation analysis, bibliographic coupling analysis, and co-word analysis). These implications are carved out with a particular look to the information systems domain which “helps key decision makers understand IT’s potential and impact so they can take advantage of what technology offers” (Agarwal and Lucas 2005, p.382; Chen et al. 2010). Additionally, to elaborate research gaps and avenues for further research in a methodical and rigorous way, the framework by Müller-Bloch and Kranz (2015) was leveraged when reviewing the content-related analyses in detail. This evidence at document level portrays beside minor knowledge voids particularly methodological voids, action-knowledge conflicts, and theory application voids (Müller-Bloch and Kranz 2015) which in turn led to three potential avenues for further research.

Table 2. Main findings of the bibliometric study	
<i>The documents, authors, and journals with the most impact...</i>	comprise the paper on intelligent products by Meyer et al. (2009), senior scholar Dimitris Kiritsis from the École Polytechnique Fédérale de Lausanne, and the IT-oriented outlet Computers in Industry with generally imbalanced citation distributions resulting in citation "stars".
<i>The intellectual structure...</i>	comprises three co-citation clusters around the documents Matsokis and Kiritsis (2010), Liu and Xu (2001), and Kiritsis (2011) with externally rather self-contained and delimited and internally rather dense clusters and is shaped by conceptual and technical works lacking in empirical and theory-driven research.
<i>The intellectual structure of emerging literature...</i>	comprises four bibliographic coupling clusters around the documents Terzi et al. (2010), Maropoulos and Ceglarek (2010), Panetto et al. (2012), and Demoly et al. (2011) with less distinct and more interconnected clusters, is dominated by conceptual and technical – missing empirical and theory-driven – research, and is assembled by few authors.
<i>The social structure...</i>	comprises nine co-authorship clusters around one (e.g., Dimitris Kiritsis) or more leading authors (e.g., Frédéric Demoly and Samuel Gomes) with rather independently organized clusters.
<i>The topics associated...</i>	comprise many co-word clusters with a spectrum of topics and blurring borders including strong relationships to information management and knowledge management, the Internet of Things technology, and applications in early lifecycle stages such as product development and manufacturing.

Avenue 1 based on methodological void and action-knowledge conflict. In the first place, it seems worthwhile to increasingly tribute to the complex phenomenon product lifecycle management in its real-world environment. The co-citation analysis, bibliographic coupling analysis, and co-word analysis unveiled that product lifecycle management is mainly investigated from conceptual and technical perspectives. Future research may increasingly study how manufacturing enterprises organize the lifecycle management of their industrial products in a complex real-world setting. Here, strategies of inquiry such as case study research (Yin 2003) or action research (Baskerville and Wood-Harper 1998) seem well-qualified.

Avenue 2 based on theory application void. In the second place, an ameliorated application of theories on the phenomenon product lifecycle management seems valuable. The co-citation analysis, bibliographic coupling analysis, and co-word analysis indicated that theory-infused research is not widely distributed in the knowledge base. An application of theories in prospective research endeavors can generate new insights and make a substantial contribution towards a technology in use. For instance, the socio-technical systems theory (Bostrom and Heinen 1977) or the organizational information processing theory (Galbraith 1973) may represent qualified theoretical perspectives.

Avenue 3 based on knowledge void. In the third place, an increasing absorbance of relevant digital technologies seems desirable. The co-citation analysis, bibliographic coupling analysis, and co-word analysis disclosed that the field – with the exception of the Internet of Things technology – mainly deals with traditional topics of information management. Research needs to keep pace with the profound further development of product development and product lifecycle management technologies. For example, the role of Big Data analytics (Chen et al. 2012) or cloud computing (Yang and Tate 2012) in the context of product lifecycle management may represent fruitful areas of interest.

For embedding these findings and implications in existing literature, the introduced reviews serve as reference points. Whereas more earlier works (e.g., Abramovici 2007; Garetti et al. 2007) plea for a more overarching scope of product lifecycle management, more recent works (e.g., Terzi et al. 2010; David and Rowe 2015) highlight the demand for a socio-technical – rather than a technical – approach to the field. Thus, the accomplished analyses corroborate – and moreover quantify – the ideas of David and Rowe (2015, p.273) as most insightful contribution who recommend to enhance “our understanding of human and managerial dimensions” of product lifecycle management. An introduction and strengthening in the information systems domain seems opportune.

Concerning the second objective, scholarly quality assessment is crucial for any kind of research. As in all conscience no explicit methodic aid for the assessment of bibliometric studies is available, this paper refers to the seminal article by vom Brocke et al. (2009) where classic criteria validity and reliability are discussed in the context of literature reviews: Validity is described as the degree of accordance of actually searched and purposed literature (vom Brocke et al. 2009). For this study, profound reflections on the search process in general and the databases in particular contributed to increase validity. However, validity reducing aspects – as outlined in the limitations – apply which should be factored in. Reliability deals with repeatability of the process solely with the information presented (vom Brocke et al. 2009). To augment reliability, a detailed protocol documented the activities and process repetitions using this protocol came up with congruent results – aside from slightly fluctuating databases (vom Brocke et al. 2015). In sum, this study offers valid and reliable findings that afford to grasp the field en bloc, complementing qualitative reviews rather than substituting them (Beverungen 2011; Zupic and Cater 2015).

Conclusion

The research presented in this paper was undertaken to map the field of product lifecycle management in manufacturing industries leveraging bibliometric methods. Consolidating the findings of the complex individual analyses, it can be concluded that the field at hand is characterized by (1) selected prominent documents, authors, and journals, (2/3) a conceptual and technical research-dominated knowledge base and knowledge base of emerging literature, (4) a rather loose social structure, and (5) a variety of associated topics. These insights in turn evoke the demand for further empiricism-based, theory-driven, and digital technologies-focused research.

To research, the paper contributes threefold, (1) content-wise, (2) method-wise, and (3) discipline-wise: Firstly and foremost, this work is likely to be the first bibliometric study for the field embracing such a comprehensive scope. Thus, for beginners it enables a jump-start and for experts hidden structures are unveiled and novel implications (Culnan 1986) are provided. Secondly, Benbasat and Weber (1996) plea for diversity in the information systems domain. Hence, the prevailing qualitative structured literature reviews are enriched with a bibliometric study helping to establish this methodological approach. Here, this paper can be seen as valuable, repeatable example. Thirdly, the necessity of interdisciplinary research is highlighted by Webster and Watson (2002). With links to bordering fields from near (e.g., computer science) and far (e.g., engineering) communities, this paper fosters this demand as well.

Indeed, with a mapping of the academic literature the contribution to research overweighs. Yet, with product lifecycle management as applied approach by definition, to practice the necessity and utility of the approach is shown likewise. Additionally, most important and established information sources such as documents, authors, and journals are unraveled for executives and consultants working in manufacturing industries.

These contributions are precious in spite of potential limitations: Certainly, a major challenge is linked to the chosen database (Zupic and Cater 2015). Its coverage and data quality profoundly implies the results quality and may partially distort them. Furthermore, minor obstacles are associated with the bibliometric methods themselves (Zupic and Cater 2015). For example, citation analyses generally show a bias towards older works. As for any kind of reviews, conceivable weaknesses arise from the selection of search criteria (vom Brocke et al. 2015).

Looking ahead, firstly, more advanced analytic (e.g., time-related) and visualization (e.g., interactive) methods may be harnessed for even richer and deeper insights. Secondly, for the purpose of triangulation a comparison with other databases and analysis and visualization tools can augment the validity of the findings. With respect to the introduced third category of literature reviews, meta-analyses in the field of product lifecycle management are currently still an untouched field.

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List of Publications

Publications in chronological order from new to old; official order of authors that indicates the contributions of the authors; all entries are blind or double-blind peer-reviewed; rankings according to (1) VHB-Jourqual 3 and (2) WI-Orientierungslisten.

Holler, Manuel. 2018. "Mapping the Field of Product Lifecycle Management: A Bibliometric Study," *Working Paper, Institute of Information Management of the University of St. Gallen (Accessible Online via Alexandria Repository)*.

VHB-Jourqual 3: N/A // WI-Orientierungslisten: N/A

Holler, Manuel, Uebernicket, Falk, and Brenner, Walter. 2018. "The Evolution of IS Projects in Manufacturing Industries: The Case of Product Lifecycle Management," *Proceedings of the 51st Hawaii International Conference on System Sciences (HICSS 2018)*, Waikoloa Village, Hawaii, United States.

VHB-Jourqual 3: C // WI-Orientierungslisten: B

Holler, Manuel, Herterich, Matthias, Dremel, Christian, Uebernicket, Falk, and Brenner, Walter. 2018. "Towards a Method Compendium for the Development of Digitized Products - Findings from a Case Study," *International Journal of Product Lifecycle Management - Special Issue on Lifecycle Management of Product-Service Systems and Smart Products (forthcoming)*.

VHB-Jourqual 3: C // WI-Orientierungslisten: N/A

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Curriculum Vitae

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