Yan Xin

KNOWLEDGE SHARING AND REUSE IN PRODUCT-SERVICE SYSTEMS WITH A PRODUCT LIFECYCLE PERSPECTIVE

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LUT University

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Supervisors Professor Ville Ojanen
LUT School of Engineering Science
Lappeenranta-Lahti University of Technology LUT
Finland

Professor Janne Huiskonen
LUT School of Engineering Science
Lappeenranta-Lahti University of Technology LUT
Finland

Reviewers Associate Professor (tenure track) Tuomas Ahola
Department of Industrial Management
Faculty of Management and Business
Tampere University
Finland

Associate Professor (tenured) Congcong Zheng
Department of Management
College of Business Administration
San Diego State University
United States

Opponents Associate Professor Yang Liu
Department of Management and Engineering
Linköping University
Sweden

Senior Research Fellow Hannele Lampela
Department of Industrial Engineering and Management
University of Oulu
Finland

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Abstract

Yan Xin
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Contemporary phenomena such as sustainability, and emerging digital technologies and ecosystems shift the basis of competition from the functionality of a discrete product to the performance of the broader product system throughout the product lifecycle (PLC), and a single firm is only one of actors among many. With this trend, product-service systems (PSS) integrating bundles of products and services to create customer utility and generate value have become an emerging issue in both academia and industry, and have been identified as one of the most effective instruments for moving society towards sustainability. In the sustainability-oriented PSS scenario, the requirements of integrating diverse knowledge relating to economic, social and environmental considerations across the entire product lifecycle inherently makes knowledge and its management more crucial and challenging than ever. Identified as key processes for successful knowledge management, knowledge sharing and knowledge reuse have been investigated in research articles for decades. However, few studies examine them together, especially in the PSS context from a PLC perspective. Especially, when examining PLC beginning-of-life (BOL), middle-of-life (MOL), and end-of-life (EOL) phases, the existing studies have mainly focused on the BOL phase, and the studies on the MOL phase have not been comprehensive. In addition, the opportunities and challenges brought by digitalization transformation should be stressed as they have shaped the sharing and reuse behavior.

The purpose of this study is to further investigate knowledge sharing and reuse as well as the impact of digitalization on them in the PSS context from a PLC perspective. In particular, knowledge sharing and knowledge reuse at both the beginning-of-life (represented by R&D, purchasing, and production) and the middle-of-life (represented by logistics, customer service, and sales) phases are the focus. Combining systematic literature reviews with multiple case studies and a supplementary questionnaire survey, this dissertation enriches the PSS research and refines the knowledge management research. The systematic literature review specifically focusing on empirical PSS studies contributes to product-service systems (PSS) development by complementing the existing PSS review studies to provide possible directions or considerations for future empirical PSS research. Empirically, the current study not only investigates knowledge sharing and knowledge reuse together in the PSS context, but also distinguishes them by focusing on knowledge sharing from the knowledge sender's perspective and knowledge reuse from the knowledge receiver's perspective. The findings of this study provide a more fine-grained understanding of knowledge sharing and reuse practice in the PSS context from different levels of analysis, and across different PLC phases and their corresponding sub-phases. They figure out the similarities and differences of knowledge sharing and knowledge reuse practice/strategies and the corresponding mechanisms in different PLC phases (i.e., BOL and MOL). By separating people-related factors and mechanism-selection-related factors, the findings enhance the understanding of the influencing factors surrounding knowledge sharing and knowledge reuse. The findings also identify benefits and challenges of digitalization in the above-mentioned practices. Digitalization facilitates knowledge sharing and reuse by facilitating standardization, by providing a comprehensive knowledge repository and convenient knowledge sharing platform, and by reducing the associated money and time cost. The challenges are issues related to data security, large investments, and timely maintenance. In addition to the contribution to the relevant research fields, this dissertation highlights some managerial implications on promoting knowledge sharing/reuse in the PSS context and from a PSS provider's perspective, including identifying the knowledge requirements in different PLC phases and sub-phases, advocating standardization, emphasizing the importance of competent people/personnel, strengthening external collaboration, matching the knowledge shared/sourced and the mechanism used, and investing in both human resource and digital technology/systems.

Keywords: product-service systems, product lifecycle, knowledge reuse, knowledge sharing, digitalization

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Yan Xin
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The way to get started is to quit talking and begin doing.

- *Walt Disney*

Contents

List of publications

This thesis is based on five individual publications that are included in Part II. The publications are listed below, together with the author's contribution to each publication. The rights have been granted by the publishers to include the papers in the thesis.

PUBLICATION I

Xin, Y., Ojanen, V., and Huiskonen, J. (2017). Empirical studies on product-service systems: A systematic literature review. *Procedia CIRP*, 64, pp. 399-404. DOI: https://doi.org/10.1016/j.procir.2017.03.054

Yan Xin was the principle author and investigator in the paper. The author designed the research plan in cooperation with the co-authors. The author collected and analyzed the data and wrote the paper. The paper was jointly revised in cooperation with the co-authors. The paper was published following a double-blinded review of the full paper.

PUBLICATION II

Xin, Y. and Ojanen, V. (2017). The impact of digitalization on product lifecycle management: How to deal with it?. *Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*. 10-13 Dec 2017, Singapore. DOI: 10.1109/IEEM.2017.8290062

Yan Xin was the principle author and investigator in the paper. The author designed the research plan in cooperation with the co-author. The author was responsible for data collection and analysis, and for writing the paper. The review process was done in collaboration with the co-author. The paper was presented at the conference and was accepted for publication in the conference proceedings based on a double-blinded review of the full paper.

PUBLICATION III

Xin, Y., Ojanen, V., and Huiskonen, J. (2018). Knowledge management in product-service systems - A product lifecycle perspective. *Procedia CIRP*, 73, pp. 203-209. DOI: https://doi.org/10.1016/j.procir.2018.03.306

Yan Xin was the principle author and investigator in the paper. The author designed the research plan, collected and analyzed the data, and wrote the paper. The paper was jointly revised in cooperation with the co-authors. The paper was published following a double-blinded review of the full paper.

PUBLICATION IV

Xin, Y., Ojanen, V., and Huiskonen, J. (2019). Dealing with knowledge management practices in different lifecycle phases within product-service systems. *Procedia CIRP*, 83, pp. 111-117. DOI: https://doi.org/10.1016/j.procir.2019.02.132

Yan Xin was the principle author and investigator in the paper. The author designed the research plan in cooperation with the co-authors. The interview guidelines were jointly designed in cooperation with the first co-author. Overall, the author was responsible for data collection and analysis, and writing the paper. The paper was finalized and revised in cooperation with the co-authors. The paper was published following a double-blinded review of the full paper.

PUBLICATION V

Xin, Y., Ojanen, V., and Huiskonen, J. (2020). Sharing and reusing knowledge for innovation and competitiveness in PSS. *Proceedings of the XXXI ISPIM Innovation Conference – Innovating Our Common Future*, 7-10 June 2020. Berlin, Germany (virtual).

Yan Xin was the principle author and investigator in the paper. The author designed the research plan in cooperation with the co-authors. The interview guidelines were jointly designed in cooperation with the first co-author. Overall, the author was responsible for survey design, data collection and analysis, and writing the paper. The paper was jointly revised in cooperation with the co-authors. The paper was presented at the conference by the author and was accepted for the conference proceedings based on a double-blinded review of the extended abstract.

Nomenclature

BOL	beginning-of-life
CL2M	Closed Loop Lifecycle Management
EOL	end-of-life
EU	European Union
ICT	information and communications technology
IoT	Internet of Things
KBV	knowledge-based view
MAO	Motivation-Ability-Opportunity
MOL	middle-of-life
NGOs	non-governmental organizations
PLC	product lifecycle
PLM	product lifecycle management
PSS	product-service systems
DEOM	design, evaluation, and operation methods
R&D	research and development
RBV	resource-based view
SQ	sub-question
TAM	Technology Acceptance Model

1 Introduction

1.1 Research background and motivation

Severe challenges such as shrinking natural resources, climate change, deforestation, biodiversity loss, food security, and deterioration of the natural environment are making people more aware of sustainability. Some of these challenges are issues of global survival that must be stressed on global and national levels. Based on the principles of sustainable development, governments set development policies to promote economic growth, social development, and environmental protection. For instance, Finnish development policy strives to concentrate on fields such as forest and water management, in addition to renewable energy, where it has cutting-edge expertise and carries out some of its objectives in cooperation with non-governmental organizations (NGOs) (United Nations, 2008). At the corporate level, sustainability has been integrated into strategies for manufacturing companies due to the increasing legal, competitive and monetary pressures that have been raised by these severe challenges and imposed by various stakeholders, including, for example, suppliers, investors and governmental authorities (European Commission, 2011; Lozano, 2013; Maxwell and van der Vorst, 2003). The focus has shifted from purely producing goods with certain functionalities towards providing material or intangible value to the customer (Sundin, 2009). With this trend, product-service systems (PSS) have become an emerging issue in both academia and industry (i.e., Goedkoop, van Halen, te Riele, and Rommens, 1999; Tukker, 2004 and 2015; Vandermerwe and Rada, 1988).

Originating from Europe, the focal idea of PSS is to deliver value to the customer and fulfill their needs by providing an integrated bundle of tangible products and intangible services (i.e. Boehm and Thomas, 2013; Roy and Baxter, 2009; Tukker and Tischner, 2006). PSS has the potential to embrace sustainability, especially environmental sustainability due to the possibility to reduce overall resource consumption through better utilization and maintenance of resources and better adaptation to changing market conditions and customer needs (Aurich, Fuchs, and Wagenknecht, 2006; Baines, Lightfoot, Evans, Neely, Greenough, and Wilson, 2007; Roy and Baxter, 2009; Tukker, 2004). In the PSS context, multiple stakeholders with certain responsibilities are integrated to create extended value-creation networks (Mert, Herder, Menck, and Aurich, 2016) throughout the entire product lifecycle (PLC). Companies, especially PSS providers, are more PLC-oriented because all the relevant stakeholders must collaborate to provide customer solutions, i.e., an integrated bundle of products and services (Aurich et al., 2006). Through cooperation, the stakeholders' awareness of sustainability consciousness is increasing as well because they share knowledge and information during the process (Dal Lago, Corti, and Wellsandt, 2017).

Knowledge is considered as a vital strategic resource and source of the firm's competitive advantage according to the knowledge-based view (KBV) of the firm (Grant, 1996; Kogut and Zander, 1992; Spender, 1996). In particular, the tacit and sticky nature of firm-specific knowledge guards against imitation from the competitors, which helps the company build a competitive advantage (Nonaka, 1994; Szulanski, 1996). Nevertheless, knowledge is valuable only if it is managed in the right way (Hislop, 2009). As an umbrella term, knowledge management refers to any managerial processes and practice that focuses on effective and efficient means of leveraging knowledge resources to enhance performance and to create a competitive advantage (i.e., Alavi and Leidner, 2001; Plessis, 2015; Swan, Newell, Scarbrough and Hislop, 1999). However, efficient knowledge management is difficult (Gloet and Terziovski, 2004). Although companies in various industries have invested in knowledge management initiatives and gained benefits, many companies are still struggling to reap the value from knowledge management (Newell, Scarbrough, and Swan, 2001; Rao, 2012). The requirements to integrate diverse knowledge relating to economic, social, and environmental considerations across the entire product lifecycle (PLC) inherently make knowledge and its management even more crucial and challenging to companies in the PSS context (Adams, Jeanrenaud, Bessant, Denyer, and Overy, 2016).

The above-mentioned perspectives motivated the author to address the challenges of knowledge management in the PSS context from a PLC perspective to help cope with these challenges. This section identifies the research gaps that will be addressed by this thesis. After that, the research objectives, research questions, and scope of the study are presented. Finally, the key concepts used will be elaborated and the overall outline of the thesis will be presented.

1.2 Research gaps

Studies focusing on product-service systems (PSS) have become more prolific since the late 1990s due to the potential of PSS to generate ecological and economic benefits (Goedkoop et al., 1999; Reim, Parida, and Örtqvist, 2015; Tukker, 2015). These studies have been reviewed from different perspectives, including: the clarification of PSS concepts and features as well as potential benefits and barriers to PSS adoption in the manufacturing context (Baines et al., 2007), overviews of the PSS design, evaluation, and operation methodologies (Qu, Yu, Chen, Chu, and Tian, 2016; Vasantha, Roy, Lelah, and Brissaud, 2012), contribution to knowledge production in manufacturing contexts from various researcher communities (Lightfoot, Baines, and Smart, 2013), a supporting framework for the implementation of product-, use- and result-oriented PSS business models (Reim et al., 2015), challenges faced by manufacturing companies when transforming into PSS providers (Nudurupati, Lascelles, Wright, and Yip, 2016), and challenges in the evaluation of the environmental performance of PSS (Kjaer, Pagoropoulos, Schmidt, and McAloone, 2016; Nudurupati et al., 2016). Reviews have also been conducted by focusing on different fields such as Information Systems, Business Management, and Engineering & Design (Boehm and Thomas, 2013) and different geographic areas (Tukker and Tischner, 2006; Tukker, 2015). PSS research is progressing well as a research field spreading across various disciplines, research domains (Reim et al., 2015; Tukker, 2015), and geographical areas (Tukker, 2015).

However, empirical evaluation of the tools and methods is scarce (Baines et al., 2007; Vasantha et al., 2012) and the number of empirical studies is limited (Nudurupati et al., 2016). In addition, to the best of the author's knowledge, there has been no review paper focusing on empirical studies in PSS.

In the PSS context, the value creation of PSS providers has been extended to the entire product lifecycle (PLC) (Russo, Birolini and Ceresoli, 2016). This requires PSS providers to adopt a PLC perspective for the product-service offering (Sundin, Lindahl, and Ijomah, 2009). Generally, the entire PLC can be divided into three major phases: the beginning-of-life (BOL), middle-of-life (MOL), and end-of-life (EOL) (Kiritsis, 2011; Stark, 2011; Vila and Albiñana, 2016). It is challenging to manage the information for the entire PLC due to the complexity of products, processes, value creation networks and IT environments in a PSS context (Stark, Damerau, Hayka, Neumeyer, and Woll, 2014), which naturally highlights the importance of product lifecycle management (PLM) as a strategic weapon for the company (Golovatchev and Budde, 2007). As a business strategy, PLM concerns various stakeholders across the entire PLC, whereas as a technical solution, PLM establishes various tools and technologies to facilitate knowledge creation, transformation, and sharing throughout the entire PLC. Combing the above two perspectives, PLM can thus be treated as a knowledge management system supporting different PLC phases (Ameri and Dutta, 2005). Therefore, PLM can be qualified as a case example of the implementation of a knowledge management strategy in the company.

The information gap in traditional PLM, i.e., only focusing on data collection at the beginning-of-life (BOL) phase with incoherent and incomplete production information during the middle-of-life (MOL) and end-of-life (EOL) phases limits the ability of manufacturing companies to provide holistic product-service offerings when transforming themselves to become PSS providers (Terzi, Bouras, Dutta, Garetti, and Kiritsis, 2010). However, modelling products with multi-disciplinary teams distributed in different stakeholders throughout the PLC is a necessity for a PSS provider. This can be realized through digitalization (Figay, Ghodous, Khalfallah, and Barhamgi, 2012) thanks to its capability to access product information across the entire PLC and to integrate huge amounts of data within and outside of the company (Parviainen, Kääriäinen, Tihinen, and Teppola, 2017; Thomas, Neckel, and Wagner, 1999). With the potential to reduce resource usage and facilitate the circular economy, tools and approaches facilitated by digitalization from a PLC perspective have been introduced to improve the product-service offering (Bertoni and Larsson, 2011; Bertoni, Bertoni, and Isaksson, 2013; Moreno and Charnley, 2016). However, they were more focused on design in the BOL phase and with little concern for the other PLC phases. In addition, although digitalization enhances the accuracy of information, increases the amount of information that can be obtained, reduces the cost of information (Wilts and Berg, 2017), and even enables sharing and reuse of useful product information throughout the entire PLC (Kiritsis, 2011;), in practice product data collection is still limited to sensor-generated data, and other types of useful information during the MOL or EOL phases are rarely considered (Yoo, Grozel, and Kiritsis, 2016).

Some studies have been conducted from PLC perspective in the PSS context, such as proposing a framework for a life cycle-oriented configuration of PSS (Aurich, Wolf, Siener, and Schweitzer, 2009) and investigating how manufacturing companies adapted their physical products for PSS in product redesign by considering middle-of-life (MOL) and beginning-of-life (BOL) phases (Sundin et al., 2009). In a literature review paper identifying challenges in PSS evaluation through life cycle assessments, it was found that most studies were conceptual in nature and the number of empirical studies in PSS from the PLC perspective was limited (Kjaer et al., 2016).

According to the knowledge-based view (KBV), knowledge management enables an organization to be capable of utilizing and developing knowledge resources to create competitive advantages (Kogut and Zander, 1992; Grant, 1996; Spender, 1996). In the PSS context, multiple stakeholders with certain responsibilities and different knowledge requirements/strategies are integrated to create extended value-creation networks (Mert et al., 2016), indicating a need for holistic knowledge exchange between R&D (designers), manufacturers, users, and even recyclers (Terzi et al., 2010). The multi-disciplinary knowledge from different stakeholders in different PLC phases, compounded by the huge volume and diverse forms of data brought by digitalization, makes it even more difficult to manage the information and knowledge (Figay et al., 2012; Li, Tao, Cheng, and Zhao, 2015; Stark et al., 2014; Zhang, Hu, Xu, and Zhang, 2012). Although research on PSS design, evaluation, and operation methods have been progressing well, there are only a limited number of studies concerning knowledge management practice in PSS operations (Qu et al., 2016).

Being identified as the key processes in knowledge management, knowledge sharing (i.e., knowledge contribution) and knowledge reuse (i.e., knowledge seeking and reuse) are considered crucial in the PSS context as they can be used to overcome the rebound effects raised from the prolonged product life in PSS (Chierici and Copani, 2016; Goh and McMahon, 2009). However, in the PSS context and especially from the PLC perspective, only limited research on knowledge sharing and reuse has been carried out, and those few exceptions have mainly focused on knowledge sharing and reuse at the beginning-of-life (BOL) phase while paying limited attention to the middle-of-life (MOL) phase empirically (Baxter, Roy, Doultsinou, Gao, and Kalta, 2009; Cai, Xu, Xu, Xie, Qin, And Jiang, 2014; Durst and Evangelista, 2018). In addition, as two interrelated and inseparable knowledge management processes, knowledge sharing and knowledge reuse are related to different focuses and needs (Kankanhalli, Tan, and Wei, 2005; Watson and Hewett, 2006). However, little research has been conducted to systematically study both knowledge sharing and reuse (He and Wei, 2009).

Digitalization has revolutionized the means of communication and has enabled access to a vast amount of information. It has enhanced data analysis capacity, and it shapes an individual's sharing and reuse behavior (Kankanhalli, Tanudidjaja, Sutanto, and Bernard, 2003; Treem and Leonardi, 2012; Vuori, 2011). Thus it has the potential to facilitate knowledge sharing and reuse in the company (Choi, Lee, and Yoo, 2010). However, the application of information technology tools cannot guarantee the success of knowledge management (Hendriks, 2001). Finding suitable ways to make digitalization play a greater role in knowledge management is still challenging (Markus, 2001).

The research gaps identified above and which will be addressed in this thesis are summarized as follows:

Research gap 1: Limited number of empirical PSS studies and no literature review focused on these. PSS research has been progressing well as a research field. However, empirical studies in PSS are limited. In addition, there has been no review paper focusing on empirical studies in PSS.

Research gap 2: Incomprehensive understanding of the impact of digitalization on PLM in a PSS context. Treated as a knowledge management system supporting different PLC phases, or a case example of the implementation of knowledge management strategy, studies focusing on PLM facilitated by digitalization in PSS contexts have still mostly focused on beginning-of-life (BOL) phase and with limited attention paid to other PLC phases.

Research gap 3: Lack of knowledge management studies, especially focusing on both knowledge sharing and reuse in PSS from a PLC perspective. With the requirement of utilizing multi-disciplinary knowledge from different stakeholders in different PLC phases, knowledge management is important and challenging in the PSS context. However, knowledge management is rarely explored in the PSS context. In particular, although knowledge sharing and knowledge reuse are considered to be crucial in the PSS context to overcome rebound effects, only limited research on knowledge sharing and reuse has been carried out in the PSS context and especially from the PLC perspective. For those few studies targeting at this issue, the focus has been on the beginning-of-life (BOL) phase while paying limited attention to the middle-of-life (MOL) phase empirically. Furthermore, knowledge sharing and knowledge reuse are essentially two interrelated and inseparable knowledge management processes relating to different focuses and needs. However, little research has been conducted to systematically study both knowledge sharing and reuse.

Research gap 4: Challenges exist in finding suitable ways to make digitalization play a greater role in knowledge management. As the most significant technological trend faced globally, digitalization has the potential to facilitate knowledge sharing and reuse in the company. However, it cannot guarantee the success of knowledge management. It is still challenging to find suitable ways to make digitalization play a greater role in knowledge management.

1.3 Research objectives, research questions, and scope of the study

The main objective of this thesis is to increase the understanding of knowledge sharing and knowledge reuse in the PSS context from a PLC perspective. The thesis addresses research gaps concerning knowledge management in the PSS context in the digital era, including the limited empirical PSS studies, incomprehensive understanding of the impact of digitalization on PLM in a PSS context, and the lack of knowledge management studies in PSS from a PLC perspective. Furthermore, challenges exist in finding suitable ways to make digitalization play a greater role in knowledge management. Given the research objective of the thesis, the main research question guiding the research is:

> *What are the knowledge management practices/strategies in (industrial) companies in the product-service systems context from a product lifecycle perspective in the digital era?*

Initiating from the concern of sustainability, this study focuses on the research streams of PSS and knowledge management. In order to answer the main research question, six sub research questions are defined to facilitate and structure the research efforts and analysis. The current body of literature was reviewed first to understand the current state of studies on PSS and especially knowledge management in PSS, as well as to identify the research structure of the study. To meet this objective, three systematic literature reviews were conducted with the aim of answering the following three sub-questions (SQs):

> SQ1: What is the current state of empirical studies on PSS and what are the focuses of these studies?
>
> SQ2: How does digitalization influence PLM in the PSS context when treating PLM as the implementation of a knowledge management strategy?
>
> SQ3: What is the current state of the art of knowledge management practices in PSS from a PLC perspective?

With the results from the literature review, this study moves towards the empirical section to answer the following sub-questions:

> SQ4: What are the knowledge requirements, knowledge sharing and knowledge reuse strategies/practices in different PLC phases in the PSS context?
>
> SQ5: What are the enablers and barriers to knowledge sharing and knowledge reuse in different PLC phases in the PSS context?
>
> SQ6: How does digitalization influence the above-mentioned requirements, strategies/practices, and enablers/barriers in the above-mentioned context?

Considering the practical need to enrich the PSS research (i.e., Kjaer et al., 2016; Qu et al., 2016; Nudurupati et al., 2016; Tukker and Tischner, 2006; Vasantha et al., 2012) and the gaps identified in the literature (i.e., in section 1.2), the research questions, objectives, and publication information are listed in Table 1.

Table 1. Research gaps, questions, and objectives

Research gap	Research question	Objectives	Publication
Limited number of empirical PSS studies and no literature review focused on this area.	SQ1: What is the current state of empirical studies on PSS and what are the focuses of these studies?	To understand the current state of the empirical studies on PSS and especially the focuses of these studies.	I
Incomprehensive understanding of the impact of digitalization on PLM in PSS context.	SQ2: How does digitalization influence PLM in the PSS context when treating PLM as the implementation of a knowledge management strategy?	To identify the impact of digitalization on PLM for manufacturing companies when treating PLM as a knowledge management strategy. To provide suggestions for manufacturing companies to respond and remain competitive.	II
Lack of knowledge management studies in PSS from a PLC perspective.	SQ3: What is the current state of the art of knowledge management practices in PSS from a PLC perspective?	To identify the knowledge requirements, knowledge sharing and reuse practices in manufacturing companies from the existing literature. To propose possible research directions to academia and raise suggestions for practitioners on facilitating knowledge sharing and knowledge reuse.	III
	SQ4: What are the knowledge requirements, knowledge sharing and knowledge reuse strategies/practices in different PLC phases in the PSS context?	To investigate the similarities and differences of knowledge requirements, knowledge sharing, and knowledge reuse in different PLC phases in the PSS context from different stakeholders' perspectives, and from a PSS provider's perspective. To provide managerial implications to facilitate knowledge sharing and knowledge reuse in the PSS context.	IV, V
	SQ5: What are the enablers and barriers to knowledge sharing and knowledge reuse in different PLC phases in the PSS context?	To identify the enablers and barriers to knowledge sharing and knowledge reuse in different PLC phases in the PSS context.	IV, V

		To reveal managerial implications to facilitate knowledge sharing and knowledge reuse in the PSS context.	
Challenges exist in finding suitable ways to make digitalization play a greater role in knowledge management.	SQ6: How does digitalization influence the above-mentioned requirements, strategies/practices, and enablers/barriers in the above-mentioned context?	To investigate the impact of digitalization on the knowledge requirements, knowledge sharing, and knowledge reuse in different PLC phases in the PSS context. To reveal managerial implications to facilitate knowledge sharing and knowledge reuse in the digital era.	IV, V

From the research gaps, objectives and research questions discussed above, the positioning of the current study can be described as narrowing the scope of research to the PSS context with an emphasis on knowledge management from a PLC perspective. Therefore, the first theoretical background area of this thesis concerns the *product-service systems* (PSS) field. PSS was introduced to deliver value to customers and fulfill their needs by providing an integrated bundle of product-service offering with the potential to embrace sustainability by considering the entire product lifecycle (PLC) and collaboration with the various stakeholders (e.g. Baines et al., 2007; Boehm and Thomas, 2013; Lindahl et al., 2014; Mert et al., 2016; Mont, 2002; Tukker, 2015; Russo et al., 2016; Sundin et al., 2009; Visnjic and Van Looy, 2013). The product-service duality of PSS combines both product-dominated and service-dominated logic in which product-dominated logic contributes to the service effectiveness (Martinez, Bastl, Kingston, and Evans, 2010; Oliva and Kallenberg, 2003). As a research field, PSS research has progressed well spreading across various disciplines, research domains, and geographical areas (e.g. Reim et al., 2015; Tukker, 2015), with various tools and methods created to facilitate the PSS development (i.e. Qu et al., 2016; Vasantha et al., 2012). However, the lack of empirical studies in this field calls for more insights from industry to enrich the theories of PSS (Baines et al., 2007; Nudurupati et al., 2016; Vasantha et al., 2012). In particular, studies from the PLC perspective or with a knowledge management focus are scarce (Kjaer et al., 2016; Qu et al., 2016). This thesis therefore focuses primarily on knowledge management from a PLC perspective in the PSS context, which leads to the other two theoretical background areas of this article, *knowledge management* and the *product lifecycle* (PLC).

In the PSS context, companies, especially PSS providers, have become more PLC-oriented and this requires collaboration with all the relevant stakeholders to provide a full customer solution (Aurich et al., 2006). This inevitably requires a holistic information exchange between, within, and beyond the firm's boundaries throughout the PLC (Terzi et al., 2010). According to both the resource-based view (RBV) and the knowledge-based view (KBV), knowledge and its appropriate management are sources of competitive advantage for an organization (Grant, 1996a; Nonaka, 1994; Spender, 1996; Szulanski, 1996). PLM can be viewed as a strategy and a technical solution and it can be treated as a knowledge management system supporting different PLC phases (Ameri and Dutta, 2005), or it can be seen as an example of the implementation of knowledge management strategy. The open innovation concept proposed by Chesbrough (2003) is especially true in the PSS context as firms should rely on external knowledge sources to complement their own knowledge domains to innovate faster and better (Martín-de Castro, 2015). Digitalization is revolutionizing the way companies are operated in the industrial value chain (Parida, Sjödin, and Reim, 2019). This has led companies to increasingly rely on virtualization and outsourcing, which requires companies to manage knowledge from inside and outside the company and repackage this in integrated product-service offerings to customers (Figay et al., 2012). This is essentially the key process for knowledge management, i.e., knowledge sharing and knowledge reuse (Bemret and Bennetz, 2003). Therefore, this thesis will focus on knowledge sharing and knowledge reuse in the PSS context. Considering the key elements in a generic knowledge sharing and reuse model, i.e., knowledge senders, knowledge recipients, the transfer mechanism, the knowledge being transferred, and the context in which the knowledge transfer takes place (Szulanski, 1996, 2000) and the overall objective of this study, both knowledge sharing and knowledge reuse processes as well as the influencing factors behind them will be investigated.

Digitalization increases the amount and accuracy of information and reduces the cost of information (Wilts and Berg, 2017). It also enhances the easy distribution and accessibility of knowledge to facilitate knowledge transfer and it creates more opportunities for knowledge sharing and reuse (Alavi and Leidner, 2001; Choi et al., 2010). Subsequently it holds the potential to reduce resource usage and facilitate the circular economy (Moreno and Charnley, 2016). However, digitalization also increases the complexity of products, processes, and value creation networks, bringing extremely large volumes and incredibly diverse forms of data, and consequently increasing the difficulty of managing knowledge (Li et al., 2015; Stark et al., 2014). Considering the opportunities and challenges it has brought, the impact of digitalization on knowledge management will be investigated in this thesis. The scope of the thesis is depicted in Figure 1 (on the next page).

1.4 Summary of the key concepts

This thesis is primarily embedded within the literature on product-service systems (PSS), knowledge management, product lifecycle (PLC) and product lifecycle management (PLM), as well as related to the impact of digitalization on the above-mentioned research fields (see Figure 1). In order to establish a solid theoretical foundation, it incorporates well-grounded management and organizational theories, such as the resource-based view (RBV) (e.g. Penrose, 1959; Barney, 1991) and the knowledge-based view (KBV) (Grant, 1996), which have been extensively explored in the strategic management literature and the research streams noted above. Key definitions used in this thesis are presented in this section.

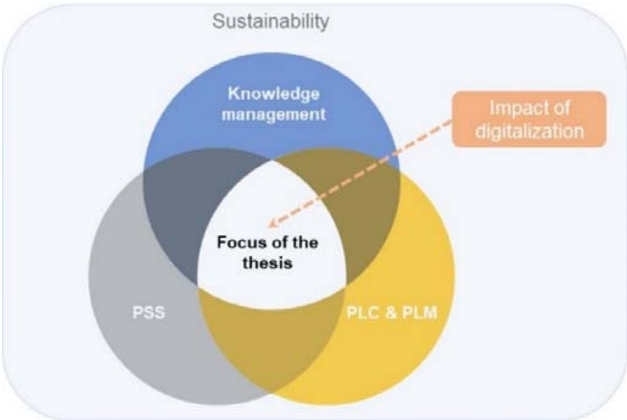

Figure 1. The scope of the thesis

Product-service systems (PSS)

The definition of PSS proposed by Mont (2002) is adopted in this thesis as her definition incorporates sustainability. *Product-service systems (PSS)* refers to "*a system of products, services, supporting networks and infrastructures that are designed to be competitive, satisfy customer needs and have a lower environmental impact than traditional business models*" (Mont, 2002, p.239)."

Product lifecycle (PLC) and product lifecycle management (PLM)

To facilitate understanding, a product lifecycle (PLC) in this thesis is defined relatively broadly to also include the lifecycle of an integrated service as the 'product' in the PSS context is an integrated product-service offering. The PLC concept adopted in this study can be divided into three major phases based on different states of the product (Kiritsis, Bufardi, and Xirouchakis, 2003; Kiritsis, 2011; Stark, 2011; Vila and Albiñana, 2016) which are: the beginning-of-life (BOL), middle-of-life (MOL), and the end-of-life (EOL). In the BOL phase the product is within the boundaries of the manufacturing company, while in the MOL phase the product is in the hands of the final customer or the service providers, and in the EOL phase the product is no longer useful or no longer satisfies its users.

Product lifecycle management (PLM) is a concept with multiple interpretations. As a business strategy, PLM concerns various stakeholders throughout the entire PLC to manage the product related information efficiently during the whole product lifecycle and accelerate business performance. As a technological solution, PLM enables knowledge creation, transformation, and sharing throughout the entire PLC by establishing various tools and technologies. In this thesis, the two perspectives above are combined, thus PLM can be treated as the implementation of a knowledge management strategy which manages product related knowledge throughout the entire PLC to support different PLC phases (Ameri and Dutta, 2005; Kurkin and Januska, 2010).

Knowledge

In a continuum with data, information, and knowledge, data comprises the simple facts which can be structured to be information, while information becomes knowledge when it is interpreted, put into context, or has meaning added to it (Grover and Davenport, 2001). In this thesis, the definition by Alavi and Leidner is adopted and *knowledge* is defined as "*a justified belief that increases the entity's capacity for taking effective action*" (Alavi and Leidner, 2001, p.109), which considers the interpretation and contextualization of information (Nissen, 2006).

Knowledge management, knowledge sharing, knowledge reuse, and knowledge transfer

Knowledge management refers to the deliberate efforts focused on the management of knowledge of a firm (Hislop, 2009). Knowledge sharing, knowledge reuse, and knowledge transfer are intertwined concepts, but with different emphase and can be viewed from different perspectives. Knowledge sharing typically emphasizes the sender's contribution to knowledge (i.e., knowledge contribution) from a supplier's (sender's) perspective, while knowledge reuse focuses on the demand of knowledge from a consumer's (recipient's) perspective (i.e., knowledge seeking and reuse), and knowledge transfer emphasizes the efficacy of the knowledge movement between a predetermined sender to the recipient (i.e., effective and efficient transfer) (Gray and Meister, 2004; Majchrzak, Cooper, and Neece, 2004; Szulanski, 1996; Wang and Neo, 2000). Considering the relationships and differences in knowledge sharing and knowledge reuse, knowledge transfer in this thesis will be treated as a stage which is covered by both knowledge sharing and knowledge reuse processes (Majchrzak et al., 2004; Markus, 2001; Szulanski, 2000). Therefore, the working definitions of these concepts in this thesis are: *Knowledge sharing* is the process in which the knowledge sender contributes his/her knowledge to the recipient and initiates the knowledge movement from the sender to the recipient, where the focal actor is the knowledge sender. *Knowledge reuse* is the process in which the recipient seeks and acquires knowledge from the sender, initiates the knowledge movement from the sender to the recipient and applies the knowledge received, where the focal actor is the knowledge recipient. Here, the focus of knowledge reuse is especially on the aspect of reusing knowledge within the sender-receiver relationship, i.e. reusing knowledge from a different individual or group, rather than reusing the recipient's own knowledge. *Knowledge transfer* is the knowledge movement from the sender to the recipient, where the focus is the mechanism used to facilitate the knowledge movement.

Digitalization and digital era

In the production mode, digitalization means to design products in a digital form, to virtually compose and exercise components before really producing the product, and to maintain the relationship between product, users, and the producing company (Gray and Rumpe, 2015). In this thesis, *digitalization* (also known as digital transformation) is more business oriented, and refers to the changes that digital technologies can bring to a company's business model, products, processes and organizational structure (Hess, Matt, Benlian, and Wiesböck, 2016). Following Liyanage (2012), *digital era* in this thesis refers to '*the period where digital technologies play a prominent role in shaping up and regulating the behaviors, performances, standards, etc., of societies, communities, organizations, and individuals*'.

Sustainability

In mainstream discussion, sustainability refers to the humanity's target goal of human ecosystem equilibrium (Shaker, 2015). To develop further, the "three pillars", or Triple Bottom Line (TBL) conceptualisation of sustainability calls for a balance between economic, social, and environmental dimensions (Elkington, 1997). In this thesis, *sustainability* is more related to corporate sustainability, that is a '*business approach that creates long-term value for the organization by incorporating economic, environmental, and social dimensions into its core business decisions*' (Benn and Bolton, 2011, p. 63).

1.5 Outline of the thesis

The thesis comprises two main parts. Part I presents an overview of the thesis and Part II includes the five individual, complementary publications. The outline of the thesis is presented in Figure 2. Part I begins with an introduction providing the research background, identifying the research gaps and research objectives, and raising the research questions of the thesis. In the second chapter, the theoretical background of the thesis, including product service systems and knowledge management is summarized, which helps the reader to better understand the position of this thesis against the existing research. Chapter 3 details the research approach and the methodological choices. Chapter 4 summarizes the objectives, key findings, and contributions of the five individual publications one by one. Chapter 5 concludes Part I by presenting the findings of the study with regard to the research questions, the theoretical contributions, the managerial implications, and the limitations of the study. Suggestions for future research are provided as well. Part II comprises the individual publications, each providing different perspectives on the main research topic with separate research questions.

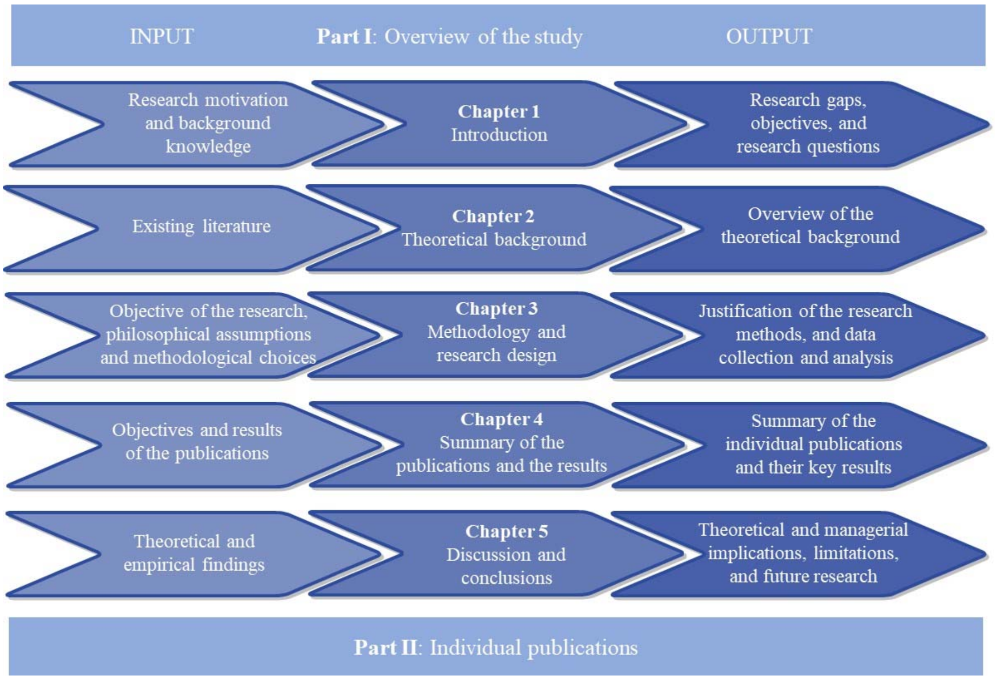

Figure 2. Outline of the thesis

2 Theoretical background

2.1 Product service systems

Over the past few decades, manufacturing firms have faced significantly higher competition due to rising production costs, which has led to the development of service offerings as a way to add value and differentiate them from those of the competitors (Gebauer, Ren, Valtakoski, and Reynoso, 2012; Quinn, Doorley, and Paquette, 1990; Sundin, 2009). In today's competitive business environment, integrating products and services has been a growing trend among manufacturing companies and providing services has turned out to be a major source of revenue (Mont, 2002; Neely, 2008). As a result, a number of studies have been dedicated to investigating this phenomenon. One of the earliest publications among them used the term '*servitization of business*' to specifically describe manufacturing companies' behavior of incorporating service into their business and was written by Vandermerwe and Rada (1988). Since then, different terms have been used to describe the various perspectives of the same phenomenon, including: servitization, service-oriented manufacturing, service-dominant logic, and product-service systems (PSS) (Baines et al., 2007; Boehm and Thomas, 2013; Gebauer et al., 2012; Goedkoop et al., 1999; Mont, 2002; Neely, Benedetinni, and Visnjic, 2011; Tukker, 2015; Vandermerwe and Rada, 1988; Vargo and Lusch, 2004). In line with this, studies focused on this area have become more prolific since the late 1990s due to the recognition of the ecological and economic benefits brought by PSS (Goedkoop et al., 1999; Reim et al., 2015; Tukker, 2015).

2.1.1 PSS definitions and categorizations

In general, servitization refers to the business transition of manufacturing companies from product -producing into providing services to enable their product-service offerings (Martinez et al., 2010; Ren, 2009; Vandermerwe and Rada, 1988). Compared to that, product-service systems (PSS) refer to an integrated bundle of tangible product and intangible service offerings that deliver value rather than just functionalities to customers and fulfill their needs (Boehm and Thomas, 2013; Roy and Baxter, 2009; Tukker and Tischner, 2006). Although sometimes it is believed that PSS is the same as servitization, some researchers take PSS as a special case of servitization focusing on sustainability perspectives (Baines et al., 2007; Spring and Araujo, 2009). Incorporating sustainability, PSS has been defined as "*a system of products, services, supporting networks and infrastructures that are designed to be competitive, satisfy customer needs and have a lower environmental impact than traditional business models*" (Mont, 2002, p.239). Although servitization and PSS have been defined from different perspectives, with different focuses and have started from different origins, both tend to converge in the research area on the transition from product to service (Baines et al., 2007; Neely et al., 2011; Tukker and Tischner, 2006), with the central concept of shifting the focus of traditional businesses based on the design, manufacturing and sale of physical products to a new business orientation that considers functionalities and benefits delivered through the combination of products and services (Manzini and Vezzoli, 2003). With this transition, products can be seen as distribution mechanisms for service provision (Kowalkowski, 2010). In this thesis, the term product-service systems (PSS) will be adopted to denote this phenomenon.

Implied from the definition, a range of PSS possibilities exist in a spectrum ranging from pure products as one extreme and pure services as the other extreme. In general, PSS can be categorized into three types: i.e., product-oriented PSS, use-oriented PSS and result-oriented PSS (Baines et al. 2007; Manzini and Vezzoli, 2003; Reim et al., 2015; Tukker 2004 and 2015; Yang, Moore, and Chong, 2009). This is according to the evolution and the relationship between the PSS provider, customer and revenue model (Barquet, de Oliveira, Amigo, Cunha, and Rozenfeld, 2013), as shown in Figure 3.

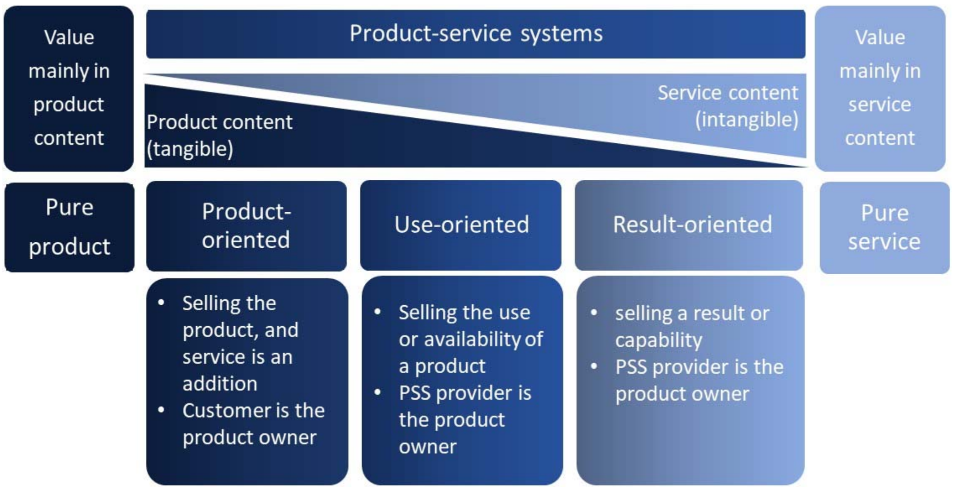

Figure 3. Categorization of PSS (adapted from Tukker, 2004)

In product-oriented PSS, the prime focus of the offering by the manufacturers is the product, and service is an addition including examples such as upgrades, maintenance, repairs, distribution, and consultancy. In this case, manufacturers sell a product, and the product is considered a means to deliver service to the customers who have the ownership of product. The service provided may reduce the costs of using the product (Barquet et al., 2013). Product-oriented PSS can probably be applied easily by manufacturing companies because it requires the least radical changes (Tukker, 2004).

In use-oriented PSS, manufacturers make the product available for use in the form of product leasing, renting, or sharing. In this case, the manufacturers have the ownership of product and sell the use or availability of the product to the customers. Although the product still plays a central role, the focus of the manufacturers is not on selling product, but maximizing the availability of products (Tukker, 2004), for instance through extending the product lifecycle and reusing some of the materials (Barquet et al., 2013).

One example of use-oriented PSS is Rolls-Royce's 'power-by-the-hour' service, where the customers pay a fixed fee for actual usage of engines rather than paying for jet engines and maintenance services separately. In this case, the customers have unlimited and individual access to the engines, although they do not own them (Tukker, 2004). Another well-known example of use-oriented PSS is car-sharing, where the same car can be used sequentially by different customers at different times (Firnkorn and Müller, 2011 and 2012).

In result-oriented PSS, the manufacturers provide results or capabilities to customers through a customized mix of services which are independent of product choice. In this case, the manufactures sell results to the customers based on their mutual agreements without a pre-determined product, and the customers pay for the results. This may include for instance payment based on the unit of service delivered (Tukker, 2004). Xerox's 'pay-per-print' system is one such example, where Xerox is responsible for the all the required activities (i.e., both operation and maintenance) that ensure the copying function, whereas users pay for plain-paper copies. In result-oriented PSS, the PSS provider is free to determine how to deliver the result. For instance, the PSS provider could deliver a 'pleasant climate' as a functional result to the customer's office rather than selling cooling equipment.

Along the spectrum ranging from product-, use-, and result-oriented PSS (as shown in Figure 3), the dependence on products decreases gradually (Tukker, 2004). While a product-dominated logic highlights standardization, and a service-dominated logic emphasizes more individualized customer-integrated solutions (Martinez et al., 2010; Oliva and Kallenberg, 2003), the product-service duality of PSS naturally combines both logics, in which product-dominated logic contributes to the service effectiveness.

2.1.2 The importance and benefits of PSS

The similarity and high quality of products in most markets limits the space to differentiate products, hence designing and manufacturing functional products is no longer a sole source of competitive advantage for a company (Tukker, 2015). In order to be competitive, companies have to increase the added value of their offerings by providing integrated solutions to improve their position in the value chain (Pine and Gilmore, 1999). With the potential to create higher value by involving different stakeholders, PSS fulfills this objective (Mont, 2002). One famous example of successful adoption of PSS is IBM, which was one of the largest computer and computer accessories manufacturer in the world. On the verge of going bankrupt during the 1990s, IBM successfully returned to be one of the top companies in the world by integrating services and software in their offerings (Ahamed, Inohara, and Kamoshida, 2013). At the same time, manufacturing companies have experienced an increasing amount of legal, competitive and monetary pressure to use resources more effectively and sustainably (Maxwell and van der Vorst, 2003), which could potentially be solved through the advantages brought by PSS, i.e., through balancing the economic, social, and environmental benefits (Mont, 2002; Sundin and Bras, 2005; Tukker, 2004). From the discussion above, it is clear that PSS could turn out to be a common means to combine economic prosperity and sustainability naturally, which has been confirmed by multiple researchers (Reim et al., 2015; Tukker, 2015).

In relation to economic benefits, in the PSS context, the locus of value creation shifts from the PSS provider (normally the traditional manufacturing company) to the process of co-creation among different stakeholders (Jacob and Ulaga, 2008) with extended value-creation networks (Mert et al., 2016). Accordingly, this co-creation and co-production of activities among PSS providers and the various stakeholders (i.e., the value network partners) bring competitive advantages to the firm (Grönroos, 2011; Vargo and Lusch, 2004). As value is provided to customers through the bundle of products and services, some changes are required in the way of conducting business within manufacturing companies. For instance, they may become more specialized in producing products and components while sharing and outsourcing some services with other service providers (Huang et al., 2011). In fact, the trend toward outsourcing logistics in manufacturing companies is such a strategy to gain a competitive advantage by cooperating with other stakeholders to streamline the value chain (Franceschini, Galetto, Pignatelli, and Varetto, 2003).

The economic benefits of PSS can also be realized through product ownership transformation. In the traditional way, a customer buys product and is responsible for the performance, maintenance and even disposal of the product. In PSS, the ownership of a product is not necessarily transferred to the customer, but can be retained by the manufacturer (Baines et al., 2007). In this way, the manufacturer (i.e., the PSS provider) is still responsible for the product after its sale, and it will support the customer to ensure the usefulness of the product throughout its lifecycle (Tan, Anumba, Carrillo, Bouchlaghem, Kamara, and Udeaja, 2010). From the manufacturing company's point of view, the combination of product-service offerings creates new market opportunities, allowing it to access the product's performance information when it is at the customer's side (i.e., in the usage phase), and increases customer loyalty through strengthened customer relationships, which can eventually lead to a higher profit margin (Baines et al., 2007; Barquet et al., 2013; Tan et al., 2010). Particularly, manufacturing companies can learn more about customer needs by engaging in service activities, which enable them to further customize and extend their product-service offerings and cumulate additional sales. Customers who are satisfied with the services are more likely to purchase next product replacements (i.e., new products) from the same manufacturer (Visnjic and Van Looy, 2013). In addition, the retainment of the product ownership after product sales motivates the manufacturer to enhance the utilization, reliability, design, and protection of the product so that more value can be extracted from the product, which can potentially increase profits (Baines et al., 2007). Lastly, the different key evaluation criteria used in PSS to measure the company's business performance, i.e., from the perspectives of financial, customer, internal process, and learning & growth, can serve as guidelines for the company to increase customer satisfaction because it helps to prioritize business improvement projects for better continuous improvement (Pan and Nguyen, 2015).

From the customer's point of view, some of the risks, responsibilities and cost associated with the ownership of the product shift to the manufacturer, such as the responsibility for dealing with the end-of-life product. At the same time, the customer may not only get more customized product-service offerings, but also more new functionalities from product-service offerings to suit their needs, and therefore get higher overall value and satisfaction (Baines et al., 2007; Barquet et al., 2013; Tan et al., 2010). Therefore, PSS brings economic benefits to both the manufacturing company and the customer (Baines et al., 2007; Barquet et al., 2013; Tan et al., 2010).

With regards to sustainability, the benefits brought by PSS have been discussed extensively in different studies. Compared to traditional product offerings, PSS enables the shift to a more sustainable economy because it has the potential to reduce overall resource consumption and environmental impacts through better design of the product-service offering, better selection and utilization of the materials, better maintenance of the products, and more efficient recycling, remanufacturing and reuse of the products (Aurich et al., 2006; Baines et al., 2007; Lindahl, Sundin and Sakao, 2014; Mont, 2002; Roy and Baxter, 2009). Traditionally, manufacturing companies have been incented to maximize product sales as this is their prime method to boost sales, increase market share, and generate profits. When manufacturing companies are transformed to become PSS providers, they have incentives to lower the product- and material-related costs as much as possible since the profits are mainly generated by the service offered. Therefore, they strive to make the products as material-efficiently as possible, to extend the service life of products as long as possible, to ensure the products are used by the customers as intensively as possible, and to reuse the parts of the products as far as possible after the end of their product life (Tukker, 2015). Through such efforts of better resource utilization, the manufacturing companies not only gain economic benefits by maximizing their service output and enhancing customer satisfaction, but also achieve sustainable advantages by minimizing the material flows in the economy (Boehm and Thomas, 2013; Gaiardelli, Resta, Martinez, Pinto, and Albores, 2014; Lindahl et al., 2014; Tukker, 2015). The environmental sustainability of use-oriented PSS and result-oriented PSS might be even stronger than product-oriented PSS (Tukker and Tischner, 2006) because of the change in the ownership structures (Glavič and Lukman, 2007; Mont, 2002). For instance, the launching of a use-oriented PSS, i.e., carsharing systems, has been shown in one study to reduce the total number of cars in a city, which brings great potential for environmental gains (Firnkorn and Müller, 2011, 2012). As concluded by Tukker (2015), PSS is one of the most effective instruments to move society towards a sustainable economy.

2.1.3 Product lifecycle and its management in PSS

In the PSS context, the meaning and composition of products have shifted from being mere artefacts sold to generate revenue to becoming a complex system comprising tangible products and intangible services provided to the customer (Terzi et al., 2010). In line with this, the value proposition of manufacturing companies does not end when delivering a product to the customer. Rather, the value must be created after the sales and throughout the life cycle (Russo et al., 2016). Therefore, a key success factor when developing products for PSS is to design the product from a life-cycle perspective by considering all of the product’s lifecycle phases (Sundin et al., 2009). However, with the increasing complexity of products, processes, value creation networks and IT environments in the PSS context, managing all the information from the entire product lifecycle (PLC) has become challenging (Stark et al., 2014). Given the current changing business environment, product lifecycle management (PLM) can be viewed as a strategic weapon that enables a company to provide added value to customers and thus gain a competitive advantage over competitors (Golovatchev and Budde, 2007).

In general, the entire product lifecycle (PLC) can be divided into three major phases based on different states of the product (Kiritsis et al., 2003; Kiritsis, 2011; Stark, 2011; Vila and Albiñana, 2016): the beginning-of-life (BOL), middle-of-life (MOL), and the end-of-life (EOL). I will go through the key activities involved in each stage here.

Normally, design and manufacturing sub-phases are included in the beginning-of-life (BOL), where the product concept is generated, designed, and physically realized. In this phase, the product is in the manufacturing company’s hands within the boundaries of the company. Design is a recursive and iterative intellectual activity in which designers and engineers try to find solutions for given problems through product, process, and plant design. Thus, designers and engineers are generally measured by efficacy. Compared to that, manufacturing is a repetitive transactional-based activity where the primary focus is to concretize the decisions taken by others, thus manufacturing personnel are generally measured in terms of efficiency (Terzi et al., 2010).

The middle-of-life (MOL) phase includes distribution (external logistic), use and support service (in terms of repair and maintenance), in which the product is distributed, used, and supported by customers and/or service providers. In the MOL phase, the product is beyond the boundaries of the manufacturing company and in the hands of the final customer or the service providers, such as maintenance actors and logistic providers, implying that the ‘real life’ of the product is dealt with in this phase (Terzi et al., 2010). Sometimes sales also belong to MOL (Vila and Albiñana, 2016).

Finally, the product reaches the end-of-life (EOL) phase when it is no longer useful, or the product no longer satisfies its users, whether they are the initial purchasers or second-hand owners. During the EOL phase, the product can be processed by reusing some of its components for the same purpose for which they are conceived, by remanufacturing the product into a sound working condition through disassembly, repair, replace and reassembly, by recycling the waste materials for the original or other purposes, and by disposing of the product in a landfill or incineration plant, etc. (Stark, 2011).

Being a business strategy, the idea of product lifecycle management (PLM) is to efficiently manage the product through all phases of its lifecycle (Kiritsis, 2011; Stark, 2011; Wegst and Ashby, 2002) to support efficiency, flexibility, and efficacy in the business processes (Terzi et al., 2010). It is an integrated approach to manage the product-related information throughout the entire lifecycle of the product through a combination of process, organization, methodology, and technology to support the full lifecycle of the product and accelerate business performance (Kurkin and Januska, 2010; Saaksvuori and Immonen, 2004; Stark, 2011). PLM not only enables a company to reduce product-related costs and improve product quality (Miller, 2007; Patrick, 2008; Stark, 2011), but also directly enhances customer satisfaction and indirectly increases market share by shortening the time-to-market and providing more complex products (Affonso, Cheutet, Ayadi, and Haddar, 2013; Teresko, 2004). In each phase of the product lifecycle (PLC), the objectives of PLM are different. For instance, PLM focuses on product design and production quality improvement in the beginning-of-life phase, whereas the improvement of product availability, reliability, and maintainability is the focus of in the middle-of-life phase (Yoo et al., 2016).

Some studies have been conducted from the PLC perspective in the PSS context (Aurich et al., 2009; Kjaer et al., 2016; Sundin et al., 2009). Considering customer, manufacturer, and product life cycle specific aspects, Aurich, Wolf, Siener, and Schweitzer (2009) presented a lifecycle-oriented configuration framework of PSS with seven core elements, including the physical product, the product life cycle, services, the impact of PLC on the physical product, the impact of services on the physical product, technical configuration, and service configuration. Although the framework was applied successfully in an exemplary case in a cultivator for loosening compacted soil by winegrowers, corresponding software was still required to further develop and realize this framework.

Sundin, Lindahl, and Ijomah (2009) conducted case studies about product redesign in three different manufacturing companies in Sweden to explain how they adapted their physical products for PSS. They found that compared to traditional products, PSS placed new requirements on products such as easy-to-perform maintenance, repair, and remanufacturing. Although the three companies were from quite different industries, including manufacturers of forklift trucks, soil compactors and household appliances, all of them adapted for the MOL and EOL phases of the products when redesigning the products, i.e., considering the maintenance, repairs and remanufacturing, and this led to cost reductions and an increase in profits.

Combining a systematic literature review of 75 publications with expert consultations, Kjaer, Pagoropoulos, Schmidt, and McAloone (2016) identified a set of PSS characteristics that might challenge the evaluation of the environmental performance of PSS when conducting life cycle assessments. They distinguished three relevant scopes to apply a life cycle assessment (i.e., to evaluate options within the PSS itself, to compare the PSS with an alternative, and to model the actual contextual changes caused by the PSS), derived three challenges when conducting life cycle assessments within the above-mentioned scopes. This included identifying and defining the reference system, defining functional units, and setting system boundaries. Suggestions were provided to overcome these challenges based on the literature. However, most of the publications reviewed by them were conceptual papers, indicating that empirical studies on PSS from a PLC perspective were limited (Kjaer et al., 2016). This motivated the author of this dissertation to conduct studies on PSS from a PLC perspective, which are addressed in sub research questions 3 to 6, and are reflected in Publications III, IV, and V.

2.1.4 Digitalization and product lifecycle management in PSS

As one of the most significant on-going transformations of contemporary society (Hagberg, Sundstrom, and Egels-Zandén, 2016), digitalization has been said to be the most significant technological trend faced globally (Leviäkangas, 2016). In general, digitalization (also known as digital transformation) refers to the changes that digital technologies can bring to a company's business model, products, processes, and organizational structure (Hess et al., 2016), as well as to all aspects of human society (Stolterman and Fors, 2004). Through the use of the Internet of Things (IoT), intensive data exchange, and predictive analytics, digitalization is revolutionizing the way businesses are operated in the industrial value chain (Parida et al., 2019). Digitalization impacts organizations from three perspectives: (1) it improves internal efficiency, which refers to improving ways of working through digital means and re-planning the internal processes, which leads to improved business process efficiency, quality, and consistency; (2) it increases external opportunities, which refers to the new business opportunities in the existing business domain in the form of new services, new customers, etc.; and (3) it raises disruptive change, which refers to the complete changes of business roles brought about by digitalization (Parviainen et al., 2017).

With regards to the second aspect above, digitalization has the potential to reduce resource usage, facilitate the circular economy (Moreno and Charnley, 2016), and improve the product-service offering from product lifecycle (PLC) perspective. To increase the quality of early design decisions, Web 2.0 tools have been introduced to help overcome knowledge sharing barriers between complex and cross-functional design teams (Bertoni and Larsson, 2011). Through the analysis of real problems in European aerospace manufacturing industry, a study conducted by Bertoni, Bertoni, and Isaksson (2013) revealed the importance of taking requirements-based information that reflected the fulfilment of the customers and system value into the overall PSS offering. A Lifecycle Value Representation Approach was proposed to address this by visualizing the value of alternative hardware concepts in the preliminary design of PSS (Bertoni et al., 2013). Mostly, however, these studies focused on the beginning-of-life (BOL) phase, especially design, whereas other PLC phases were seldom investigated.

Viewing information management as a silo, traditional product lifecycle management has focused on data collection for a tangible product (Yoo et al., 2016). In this view, the manufacturing company is responsible for the beginning-of-life (BOL) phase only (Kiritsis, 2011) and traditionally there was no information flow between the manufacturing company and the customer after product delivery (Terzi et al., 2010). This information gap in the PLC, i.e., incoherent and incomplete production information during the middle-of-life and end-of-life phases, limits the ability of the manufacturing company to provide holistic products and services when it wishes to transform into a PSS provider (Terzi et al., 2010). With the increasing complexity of the product-service offering and the competitive environments, it is necessary for manufacturing companies to model products with multi-disciplinary teams distributed in different companies throughout the PLC (Figay et al., 2012). Digitalization can facilitate this because it enables a better real-time view of operations and results, and improves the efficiency, quality, and consistency of business processes by accessing the product information throughout the entire PLC and integrates the company's internal and external data (Parviainen et al., 2017; Thomas et al., 1999).

The increased digitalization of work has led to more networked and knowledge-based practices in the company (Jonsson, Mathiassen, and Holmström, 2018). Although digitalization increases the amount and accuracy of information and reduces the cost of information (Wilts and Berg, 2017), and even enables Closed Loop Lifecycle Management (CL2M) to collect and reuse useful product information throughout the entire product lifecycle (Kiritsis, 2011;), product data collection in practice is still restricted to sensor-generated data, while excluding or seldom considering other types of information on MOL or EOL phases, even though some of those information could be collected through human technicians' observation (Yoo et al., 2016). In the PSS context, for instance, more attention has been given to the MOL phase with regard to the product information itself that is generated in this phase, rather than considering the reuse of this information in other PLC phases (Yoo et al., 2016). Therefore, research is needed regarding the types of other product data/information required to improve the product-service offering throughout the entire PLC (Sundin et al., 2009).

The above-mentioned discussion motivated the author to further investigate the impact of digitalization in the PSS context, which is addressed by sub research questions 2 and 6, and is reflected in Publications II, IV, and V.

2.1.5 Summary of the extant studies on PSS

Since the term PSS was first convincingly established (Goedkoop et al., 1999), PSS research has been reviewed by many scholars from different perspectives. Below, I will go through the main review articles in this field regarding the topics of PSS.

Baines, Lightfoot, Evans, Neely, Greenough, Peppard, and Wilson (2007) engaged in a clinical review of forty articles related to PSS within a wider manufacturing context. They described the PSS concepts and features, presented the application of PSS with potential benefits and barriers to adoption, summarized the features needed to design PSS effectively by presenting the available tools and methodologies in PSS design, and identified the challenges for future research. They concluded that although there were various tools and methodologies for designing PSS, studies had rarely evaluated their performance critically in practice, and there was not sufficient evidence to show the completeness of these tools and methodologies. Therefore, better understanding of PSS practices would be beneficial for the adoption of the PSS concept (Baines et al., 2007).

Boehm and Thomas (2013) reviewed 265 relevant articles with focusing on the fields of Information Systems, Business Management, and Engineering & Design. Despite the fact that different understandings of PSS exist in the disciplines under investigation, similarities were found from the definition graphs and a core definition of PSS across all disciplines was formulated as '*an integrated bundle of products and services which aims at creating customer utility and generating value*' (Boehm and Thomas, 2013, p. 252).

Lightfoot, Baines, and Smart (2013) analyzed 148 peer-reviewed journal articles from the knowledge production perspective and found that various distinct researcher communities contributed to knowledge production in the manufacturing industry in the PSS context, including researchers from service marketing, service management, operations management, product-service systems and service science management and engineering. The largest number of publications were from operations management researchers. Actively contributing to knowledge production, all these communities shared an interest in the concepts related to product-service differentiation, competitive strategies, customer value, customer relationships and product-service configuration. With regards to the knowledge flow, the more mature communities such as service marketing, service management, and operation management made more use of locally produced knowledge reserves, while the emerging PSS and service science communities made use of a more evenly distributed knowledge base among the researcher communities (Lightfoot et al., 2013).

Regarding the methods relevant to PSS, Vasantha, Roy, Lelah, and Brissaud (2012) reviewed eight of the most referred state-of-the-art PSS design methodologies in the literature to evaluate the maturity level of PSS design based on six categories, including: the context, stakeholders, design stages, development cycle, life cycle and representation. The results showed that PSS design was at an initial stage of development, and even the most referred design methodologies had not been evaluated empirically in the industry context (Vasantha et al., 2012).

Reim, Parida, and Örtqvist (2015) analyzed 67 articles in-depth and presented a supporting framework for the implementation of product-, use- and result-oriented PSS business models. To ensure the successful implementation of the business models, each category of business model was linked to five equally important operational-level tactics, namely contracts, marketing, networks, product and service design, and sustainability practices (as shown in Figure 4 on next page). In addition, their review demonstrated that PSS had been applied to a variety of research areas, and PSS business models were well connected to sustainability (Reim et al., 2015).

Qu, Yu, Qu, Yu, Chen, Chu, and Tian (2016) reviewed 125 articles on PSS design, evaluation, and operation methods (PSS-DEOM). Their analysis indicated that research in PSS-DEOM was rapidly developing. In particular, the majority of studies on PSS design methods investigated the customer perspective and modeling techniques; while the majority of studies on PSS evaluation methods evaluated PSS from the customer value perspective; and the majority of studies on PSS operation methods focused on PSS business models. The body of work on PSS operation methods had only a limited number of studies related to knowledge management, hence they concluded that more studies in this field were needed (Qu et al., 2016).

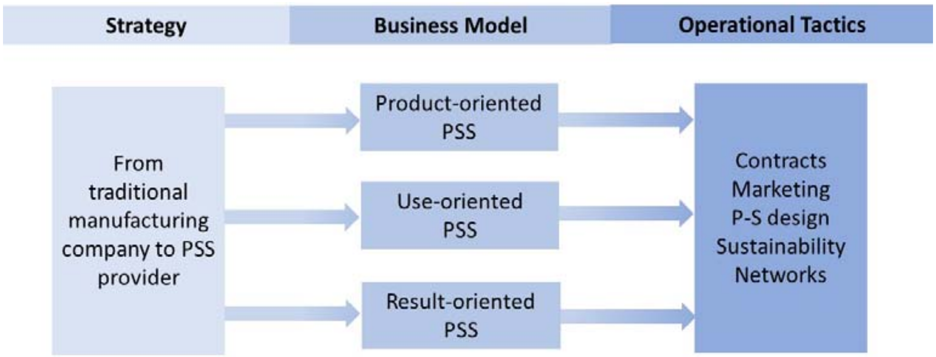

Figure 4. Relationships between strategy, business models, and tactics for PSS (adapted from Reim et al., 2015)

PSS in specific geographic areas such as the EU have been reviewed as well (Tukker and Tischner, 2006). Summarizing PSS research linked to the European Union, Tukker and Tischner (2006) found that although PSS in theory could enhance competitiveness and contribute to sustainability, in reality this benefit was not always achievable even if the PSS had been carefully designed. In addition, involving practitioners was crucial to create a PSS science field and to realize the benefits of PSS (Tukker and Tischner, 2006).

Comparing the findings with his review paper in 2006, Tukker (2015) conducted another review based on the literature on PSS from a business and sustainability perspective. He found that PSS research had become more prolific since the year 2000. As a subject, PSS had been adopted in a wider range of scientific fields such as manufacturing, ICT, business management and design as well as in wider geographic regions. The number of publications on PSS from Asia exceeded that of Europe (Tukker, 2015). He concluded that in order to gain a competitive advantage through PSS, companies should focus on availability rather than production of the product for clients, emphasize diversification in their service offerings rather than product ranges, and pay attention to the need for competent personnel with both product knowledge and relation management skills (Tukker, 2015).

Challenges in PSS were discussed as well (Kjaer et al., 2016; Nudurupati et al., 2016). Reviewing 60 relevant papers published between 1990 and 2013 from multi-disciplinary sources, Nudurupati, Lascelles, Wright, and Yip (2016) identified eight challenges faced by manufacturing companies in transforming to become PSS providers: (1) to explore the customer perspective focusing on understanding value-in-use rather than only on product requirements, (2) to redefine the interface with the customer, (3) to price, sell, and get revenue from PSS, (4) to develop a generic approach to designing PSS and to understanding the supporting methods, tools and techniques, (5) to renew the relationship with suppliers in the supply network, (6) to explore the organizational architecture, (7) to identify the performance measurement metrics, and (8) to manage the culture transition. They concluded that many existing studies were conceptual in nature with limited practicality, which was compounded by the limited number of empirical studies, which led to limited applicability of the results from those papers (Nudurupati et al., 2016).

Conducting a literature review of 75 publications, Kjaer, Pagoropoulos, Schmidt, and McAloone (2016) identified a set of PSS characteristics that might challenge the evaluation of the environmental performance of PSS through life cycle assessment, and subsequently summarized the challenges, i.e., to identify and define the reference system, to define the functional unit, and to set system boundaries. The literature reviewed indicated a lack of empirical studies on PSS from the PLC perspective as most of the publications were conceptual papers (Kjaer et al., 2016).

In summary, PSS research has been progressing well as a research field spreading across various disciplines, research domains (Reim et al., 2015; Tukker, 2015), and geographical areas (Tukker, 2015). However, empirical evaluation of the tools and methods has been scarce (Baines et al., 2007; Vasantha et al., 2012), and the number of empirical studies is limited (Nudurupati et al., 2016). Therefore, it would be beneficial to have a better understanding of PSS practice so that the application of PSS as well as the benefits realized from PSS could be clearly identified. This motivated the author to conduct a literature review focusing on empirical PSS studies, which was addressed by sub research question 1 and is reflected in Publication I.

With the limited number of PSS studies concerning knowledge management, more studies in this field has been suggested (Qu et al., 2016). In addition, knowledge management has been identified as a challenge for PSS providers, thus further investigation on how to capture and manage knowledge through the entire PLC of the product-service offering, as well as to identify the people skills required in PSS would be valuable (Nudurupati et al., 2016). This motivated the author to conduct research on knowledge management in the PSS context and from a PLC perspective, which is addressed in sub research questions 3 to 6 and is reflected in Publications III, IV, and V.

2.2 Knowledge management in the PSS context in the digital era

2.2.1 Knowledge and its management as the basis of competitive advantage

External pressures from the turbulent environment, growing competition, digitalization, shortening product lifecycles, and increasing interdependences have stimulated discussions on the basis of a firm's competitive advantage from different theoretical views with different capabilities, such as the resource-based view, knowledge-based view, relational view, and from a dynamic capabilities perspective (Dyer and Singh, 1998; Eloranta and Turunen, 2015; Kraaijenbrink, Spender and Groen, 2010; Teece et al., 1997; Teece, 2007).

The resource-based view (RBV) of the firm claims that difference between firms mainly stem from the firm heterogeneity in terms of resources and capabilities (Barney, 1991; Makadok, 2001; Penrose, 1959; Wernerfelt, 1984). In particular, a firm's sustainable competitive advantage comes from those valuable, rare, inimitable, and non-substitutable (VRIN) resources and the capabilities to deploy them (Barney, 1991; Conner, 1991; Zott, 2003) because these four characteristics indicate the degree of heterogeneity and immobility of a company's resources. According to the literature review conducted by Eloranta and Turunen (2015), when a manufacturing firm transits to become a PSS provider, RBV is the most popular strategic perspective to explain the basis of competitive advantage.

Sharing fundamental similarities with the RBV on the one hand, the knowledge-based view (KBV) argues that a firm's competitive advantage originates from possession and deployment of valuable knowledge resources (Grant, 1996; Spender, 1996) as this is essential for many organizational activities and processes such as technology management, organizational learning, and organizational innovation (Grant, 1996a; Spender, 1996). On the other hand, KBV extends RBV as it examines both the exploitation of the firm's existing resources and the ability of the firm to develop new capabilities as well as to acquire external knowledge beyond the boundaries of the firm (Grant and Baden-Fuller, 2004). In the past two decades, KBV has received considerable attention from management scholars in the knowledge management literature. Related to RBV and KBV, knowledge management deals with the organizational and managerial processes and practices which enable more effective and efficient management of the valuable resource, i.e., knowledge (Alavi and Leidner, 2001; Andreeva and Kianto, 2012; Davenport and Prusak, 2000).

Extending the firm's boundaries to the external environment, the relational view extends RBV and believes that the critical resources or capabilities required by a firm to gain a competitive advantage may reside outside the firm, which can be accessed or created by establishing inter-organizational relationships with other firms (Douglas and Ryman, 2003; Dyer and Singh, 1998; Lavie, 2006). One of the key aspects of the inter-organizational relationships is relational inter-firm knowledge sharing and joint learning (Dyer and Singh, 1998; Grant, 1996).

Addressing the environmental dynamics, RBV evolved towards the dynamic capabilities perspective, which argues that a firm's competitive advantage comes from "*the firm's ability to integrate, build, and reconfigure internal and external competencies to address rapidly changing environments*" (Teece, Pisano, and Shuen, 1997, p.516). In view of the increasing availability of external knowledge resources in the modern economy, dynamic capabilities influencing a company's ability to target, absorb, and deploy external knowledge have become a crucial source of competitive advantage (Fosfuri and Tribó, 2008). In addition, dynamic capabilities enable the transition of a traditional manufacturing company to become a PSS provider (Visnjic Kastalli and Van Looy, 2013).

In summary, considering the classic RBV and its extension or evolvement towards KBV, the relational view, and dynamic capabilities, knowledge and its management are always treated as a basis of competitive advantage for the firm. Considering the crucial role of knowledge in the current rapidly changing environment (Hameed, Khan, Sheikh, Islam, Rasheed, and Naeem, 2019), it is essential and necessary for firms to initiate knowledge management (Donnely, 2019).

2.2.2 Knowledge as a concept and knowledge management strategy

Knowledge – definition and categorization

Before discussing knowledge management, the subject, i.e., knowledge itself, will be discussed in this section. In a continuum starting from data, then information, and ending with knowledge, knowledge is seen to be the most valuable as data consists of simple facts which can be structured to become information, and information becomes knowledge when it is interpreted, put into context, or when it has meaning added to it (Grover and Davenport, 2001). In other words, knowledge is created from information and is closely related to a person's beliefs and commitments (Nonaka, 1994). As a multi-faceted concept, knowledge has been defined from different perspectives and with different focuses (Alavi and Leidner, 2001). Reviewing various definitions of knowledge in the extant literature, knowledge could be defined as a state of mind, an object, a process, a capability, or a condition of having access to information (Alavi and Leidner, 2001). As a state of mind, knowledge is an understanding through experience or learning; as an object, knowledge can be used, stored, and manipulated to suit the needs of the company; as a process, knowledge is the application of one’s experience; as a capability, knowledge is the ability of knowing how to use information to influence future action; as a condition of having access to information, knowledge focuses on the way to organize access and retrieve the information in the company (Alavi and Leidner, 2001). In the current study, by considering the interpretation and contextualization of information (Davenport and Pruzak, 2000; Nissen, 2006), knowledge is defined as “*a justified belief that increases the entity’s capacity for taking effective action*” (Alavi and Leidner, 2001, p.109).

One of the most widely acknowledged categories of knowledge is the distinction between explicit and tacit knowledge (Nonaka, 1994; Nonaka et al., 2000; Nonaka and Von Krogh, 2009; Polanyi, 1966), which reflect the status of knowledge (Mesmer-Magnus and Dechurch, 2012). *Explicit knowledge* refers to knowledge outside the human mind that can be expressed in formal and systematic language, be codified and stored in words, documents or other explicit forms, and can be captured and shared in records such as databases and archives (Nonaka, 1994; Nonaka et al., 2000). Explicit knowledge comprises data, formulae, manuals, drawings, and specifications etc. which can be processed, transmitted, shared, and stored relatively easily (Nonaka et al., 2000). However, explicit knowledge can only show the tip of the iceberg of what someone knows

(Nonaka, 1994), and '*we can know more than we can tell*' due to the tacit nature of knowledge (Polanyi, 1966, p. 4). Frist introduced by Polanyi (1966), *tacit knowledge* refers to knowledge indwelling in the person's mind that is difficult or sometimes even impossible to formalize and articulate (Nonaka, 1994; Nonaka et al., 2000). The time required to explain and learn tacit knowledge slows down its transfer (Argote, 2013). The more tacit the knowledge is, the more difficult it is to articulate, and the greater interaction and socialization between individuals is required to make the transfer successful (Hansen, 1999).

Explicit and tacit knowledge are dependent on each other, which makes it difficult to identify the most valuables between these two types of knowledge (Nonaka, 1994). In order to understand explicit knowledge, tacit knowledge is a necessity (Alavi and Leidner, 2001). Without explicit knowledge, tacit knowledge is meaningless (Sánchez, Sánchez, Ruiz, and Tarrasóna, 2012). In addition, these two types of knowledge can be converted to each other through different processes in a classic SECI model for knowledge creation (Nonaka, 1994; Nonaka et al., 2000), i.e., socialization, externalization, combination, and internalization. Movement through the four knowledge conversion modes forms a spiral and dynamic process of knowledge creation taking place both intra- and inter-organizationally, where the interaction between tacit knowledge and explicit knowledge is amplified (Nonaka, 1994; Nonaka et al., 2000).

Knowledge can also be categorized based on its functions or related discipline, such as design knowledge (e.g. product design, process design, service design, service operation design, etc.), product knowledge, task knowledge (e.g., design task, logistics task, etc.), production/manufacturing knowledge, customer knowledge, and market knowledge, etc. (Baxter et al. 2009; Zhang et al., 2012).

It is important to describe the types of knowledge for further analysis, for instance to identify which type of knowledge is most important in a company, or in a special context. However, the previously described categories or distinctions are not independent, rather their scope of definition may overlap in various ways. Knowledge can be described as one or several categories.

Knowledge management – the process view and strategy

From the KBV's perspective, knowledge management enables an organization to be capable of utilizing and developing knowledge resources to create a competitive advantage, and thus it represents the capability- and activity-oriented aspects of the KBV (Kogut and Zander, 1992; Grant, 1996; Spender, 1996). Organizations in various industries have invested heavily in knowledge management initiatives (i.e. Dyer and Nobeoka, 2000; Ezingeard, Leigh, and Chandler-Wilde, 2000; Jang, Hong, Bock, and Kim, 2002; Massey, Montoya-Weiss, and O'Driscoll, 2002). Some organizations, such as Boeing, IBM, and Siemens, have achieved great success from their knowledge management investments (Rao, 2012). However, knowledge management expenditures are not necessarily proportional to the gains obtained. Numerous knowledge management initiatives have failed to achieve the desired results (Malhotra, 2004). Quite a few companies are still struggling with low returns on knowledge management investments (Chai and Nebus, 2012; Rao, 2012;). Therefore, finding a more systematic way to manage knowledge management initiatives has become an urgent issue for both academia and industry.

Given the importance and complexity of knowledge management, researchers have investigated it in various disciplines (Wang and Noe, 2010). To better understand the concept and key points of knowledge management, some definitions in the extant literature are listed in Table 2.

Table 2. Definitions and key points of knowledge management

Reference	**Definition**	**Key points**
Alavi and Leidner, 1999	Knowledge management is a systematic and organizationally specified process to acquire, organize, and communicate employees' knowledge so that other employees can use this knowledge to improve work efficiency and productivity.	Process Acquisition, sharing, and application/reuse
Alavi and Leidner, 2001	Knowledge management is regarded as a process to a large extent, involving at least four basic processes of creating, storing/retrieving, transferring and applying knowledge.	Process Creation, storage/retrieval, transfer, and application
Argote, 2003	Knowledge management research focuses on the "fundamental set of questions" relating to knowledge creation, retention and transfer within and across companies, as well as the management of company's knowledge reserves.	Process + practice Creation, retention, and transfer
Bemret and Bennetz, 2003	Knowledge management is a systematic process of creating, maintaining, and cultivating an organization to fully utilize its knowledge to realize its vision, which is broadly regarded as a sustainable competitive advantage or achieving high performance.	Process Creation, maintain, cultivation, and application / reuse
Hislop, 2009	Knowledge management is the processes in an organization related to knowledge acquisition, codification, sharing, creation, and application.	Process Acquisition, codification, sharing, creation, and application
Janz and Prasarnphanich, 2003	Knowledge management is an organizational strategy to manage the development, flow, and application of knowledge.	Process + practice Development, flow (movement), and application
Navimipour and Charband, 2016	Knowledge management is the process of efficiently capturing, sharing, developing, and using the knowledge.	Process

		Capturing, sharing, development, and use (application)
Scarborough, Swan, and Preston, 1999	Knowledge management refers to the process of creating, acquiring, sharing, and using knowledge to enhance learning and performance in an organization.	Process Creation, acquisition, sharing, and application
Swan, Newell, Scarbrough, and Hislop, 1999	Knowledge management concerns any processes and practices related to the creation, acquisition, sharing and use of knowledge, skills and expertise.	Process + practice Creation, acquisition, sharing, and application

As an umbrella term, *knowledge management* refers to the deliberate efforts focused on the management of knowledge of a firm (Hislop, 2009). Despite the diversity of processes or practices when enumerating knowledge management, such as knowledge acquisition, sharing, transfer, flow (movement), codification, storage/retrieval,, retention, maintain, development, cultivation, creation, and application/reuse (as shown in Table 2), the process view of knowledge management in its most simplistic form basically comprises three broad intertwined stages: knowledge creation, transfer/sharing, and application/reuse. *Knowledge creation* refers to the development of new content or the replacement of already existing content within a firm's knowledge, both tacit and explicit (Alavi and Leidner, 2001). *Knowledge transfer* refers to process through which one social unit learns from or is influenced by the experience of another unit (Argote, 2013; Argote and Fahrenkopf, 2016). Broadly, this involves both knowledge sharing and knowledge reuse (Wang and Neo, 2010). *Knowledge application* is the process of knowledge utilization. Especially, the ability to gain competitive advantage is more about applying existing knowledge to take action than the knowledge itself (Grant, 1996), indicating the importance of knowledge reuse.

Knowledge creation is generally regarded as more important and more difficult to manage. However, as indicated in the literature, the low returns on knowledge management initiatives has mostly been due to failing to share and reuse knowledge (Majchrzak, Wagner, and Yates, 2013; Wang and Neo, 2010). Therefore, a better understanding of knowledge sharing and reuse in a company is needed to improve returns on knowledge management investments, which motivated the author to narrow the focus of knowledge management to particular processes, i.e., knowledge sharing and knowledge reuse, which will be discussed in detail in section 2.2.3.

Further building on the importance of knowledge sharing and knowledge reuse, studies have also been conducted on knowledge management strategies to understand how knowledge sharing and reuse has performed. Codification and personalization are two types of knowledge management strategies in a broad sense (Hansen, Nohria, and Tierney, 1999). In the *codification strategy*, knowledge is codified and stored so that potential consumers/users can reuse it without necessarily knowing the knowledge producer. It is a 'people-to-document' approach to separate knowledge from the person and focuses on the use of technology, such as databases, electronic repositories, and decision support systems, etc. In contrast, in the *personalization strategy*, there are direct interactions between knowledge producers and the potential knowledge consumers of knowledge communication, i.e., through face-to-face communication, such as on-the-job learning, storytelling, training activities and communities of practice (Brown and Duguid, 2001). It is a 'people-to-people' approach that facilitates interactions among people through networks, where knowledge is tied to a person and may remain tacit.

Codification and personalization strategies are associated with different costs and benefits, which make it challenging for organizations to develop an optimum knowledge management strategy. The codification strategy requires companies to invest in electronic repositories and knowledge must be codified by the producers before knowledge reuse takes place, whereas the cost involved in the personalization strategy is incurred mostly when knowledge reuse takes place and is proportional to the number of potential knowledge consumers (Chai and Nebus, 2012). In the codification strategy, a large number of people can access a standardized repository simultaneously, whereas only a limited number of people can be reached in the personalization strategy although rich information can be conveyed (Chai, Gregory, and Shi, 2003). In addition, potential consumers can retrieve knowledge from a repository whenever they need it, whereas whether they can obtain knowledge from the knowledge producers depends on the availability of that particular person (Lee and Van den Steen, 2010). The codification strategy can only transfer explicit knowledge, whereas the personalization strategy can transfer both explicit and tacit knowledge (Hahn and Mukherjee, 2007). However, due to the dramatically increased cost of knowledge codification incurred by the increased tacitness of knowledge, firms prefer to keep the tacit form of knowledge (Jasimuddin and Zhang, 2009).

Despite extensive research on the choice of strategies between codification and personalization, not many consistent results or recommendations could be found in the literature. In their pioneering and highly cited work proposing the classification of codification and personalization strategies, Hansen, Nohria and Tierney (1999) found that it was not an optimal choice to adopt a single strategy or to use two strategies simultaneously with the same effort. Rather, they found that companies should choose a knowledge management strategy based on their products' characteristics and their employees' working needs. It would be better to use one strategy predominantly (e.g., 80%) and use the other one in a supporting role (e.g., 20%), which was supported by their findings from management consulting firms, computer companies, and healthcare providers (Hansen et al., 1999). However, a balanced 50-50 split between the two strategies has been found to be preferred in certain industries such as the pharmaceutical industry (Koenig, 2001) and in certain organizations such as NASA (Moll, 2019). In order to reconcile these contradictory views, some researchers have pointed out that companies may need to evolve their knowledge management strategies by adding a temporal dimension and adjusting the proportion of codification and personalization to align with the various stages of knowledge management, i.e., to adopt one strategy predominantly at the beginning and move towards a balanced portfolio as it matures (Scheepers, Venkitachalam, and Gibbs, 2004). A case study in NASA confirmed this view, which showed that NASA's knowledge management strategy evolved from an emphasis on a personalization strategy in the 1980s which changed to an emphasis on a codification strategy in the 1990s, and finally had adopted a balanced approach since around 2012. No detrimental effects on NASA's performance had been found since adopting this balanced approach (Moll, 2019).

The discussions above revealed that both codification and personalization strategies should be adopted by complementing each other to achieve the focused objectives of the company (Powell and Ambrosini, 2012). However, no conclusive guidelines on the mix ratio could be found in the literature and the studies were from different industries without any focus on a PSS context, which motivated the author to investigate knowledge management strategies and practices in the PSS context. Considering the various stakeholders, entire lifecycle concerns, and multi-disciplinary knowledge required in the PSS context would provide insight to both PSS and knowledge management research.

2.2.3 Knowledge sharing and knowledge reuse – definition and mechanisms

Broadly speaking, knowledge sharing, knowledge reuse, and knowledge transfer refer to the same process of knowledge movement (Argote, 2013; Argote and Fahrenkopf, 2016; Argote and Ingram 2000; Davenport and Prusak, 2000; Majchrzak et al., 2004; Markus, 2001; Szulanski, 1996; Van den Hooff and De Leeuw van Weenen, 2004; Wang and Neo, 2010). Generally, there are two parties involved in the knowledge movement process: the knowledge sender/contributor/producer, which refers to the roles of employees when they have knowledge to share with others; and the knowledge recipient or potential consumer/user, which refers to the roles of employees when they try to seek and use knowledge from others (Szulanski 1996; Alavi and Leidner 2001). To make the knowledge movement successful, effective and efficient transmission channels, i.e., the mechanisms, are necessary (Gupta and Govindarajan, 2000).

Wang and Neo (2010) defined knowledge sharing as the provision of task information and know-how to help and to collaborate with others with the objective of problem solving, the development of new ideas, or the implementation of policies/procedures . Compared to that, Davenport and Prusak (2000) defined knowledge sharing as a two-way process, including both the provision and receipt of task information and know-how concerning a product or a procedure. Similar to the definition from Davenport and Prusak (2000), the knowledge sharing process proposed by Van den Hooff and De Leeuw van Weenen (2004) contains knowledge donation and knowledge collection, in which donation occurs when a sender shares knowledge with others. This is similar to knowledge sharing defined by Wang and Neo (2010), whereas collection takes place when a recipient gathers knowledge from others. In addition, in their definition, knowledge reuse is also included in knowledge collection (Van den Hooff and De Leeuw van Weenen, 2004).

Defined by Markus (2001), knowledge reuse is a process with four stages, including knowledge capture or documentation, knowledge packaging for reuse (processing documents in accordance with the classification scheme), knowledge distribution or dissemination (providing people with access to it), and knowledge reuse (recall from where the required knowledge is and the actual application of it), as shown in Figure 5. In particular, this process highlighted the importance of knowledge capture and packaging of the existing knowledge, which is from the knowledge recipient's perspective. In addition, it was found that an IT-focus was crucial in knowledge reuse, especially concerning knowledge storage and retrieval (Markus, 2001).

Figure 5. Knowledge reuse process (adapted from Markus, 2001)

More focused on the understanding of knowledge reuse for innovation, Majchrzak, Cooper and Neece (2004) proposed a different knowledge reuse process with three main stages, where stage one focuses on reconceptualizing the problem which needs to be solved for innovation, stage two concerns searching and evaluating existing knowledge within or outside the company to select a usable one, and stage three is the actual acquisition of the knowledge and full application into a final solution, as shown in Figure 6. Compared to the process proposed by Markus (2001), the process proposed by Majchrzak et al. (2004) paid more attention to the search and actual use of the existing shared knowledge from the knowledge recipient's perspective.

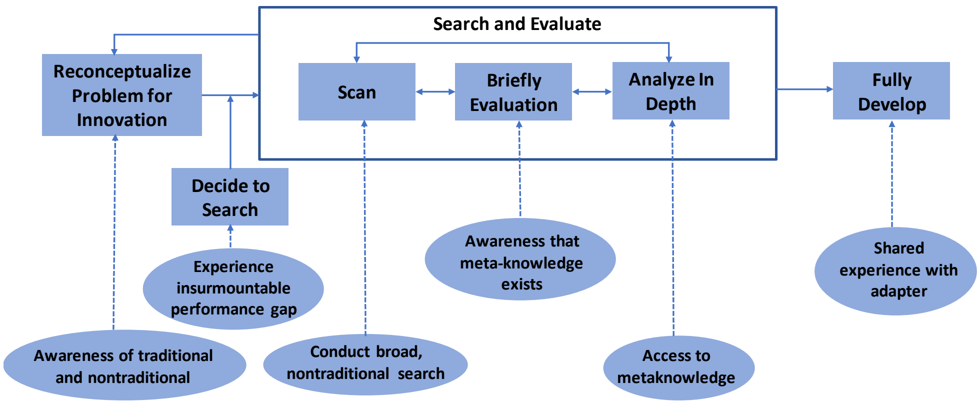

Figure 6. Knowledge reuse process for innovation (source: Majchrzak, et al., 2004)

Compared to knowledge sharing and knowledge reuse, knowledge transfer refers to a process through which one social unit learns from or is influenced by the experience of another unit (Argote, 2013; Argote and Fahrenkopf, 2016), i.e., knowledge acquired in one situation is applied to another situation (Argote and Ingram 2000; Szulanski, 1996). Therefore, as a process, knowledge transfer comprises both knowledge sharing and knowledge reuse (Alavi and Leidner, 2001; Appleyard, 1996).

Knowledge sharing, knowledge reuse, and knowledge transfer are intertwined concepts, but with a different emphasis and from different perspectives. Knowledge sharing typically emphasizes the sender's contribution to knowledge (i.e., their knowledge contribution) from a supplier's (sender's) perspective; knowledge reuse focuses on the demand for knowledge from a consumer's (recipient's) perspective (i.e. knowledge seeking and reuse), and knowledge transfer emphasizes the efficacy of knowledge movement between the predetermined sender and recipient (i.e. the effective and efficient transfer) (Gray and Meister, 2004; Majchrzak et al., 2004; Szulanski, 1996; Wang and Neo, 2010). As two interrelated and inseparable knowledge management processes, knowledge sharing (i.e., knowledge contributing) and knowledge reuse (i.e., knowledge seeking and reuse) are associated with different needs (Kankanhalli et al., 2005; Watson and Hewett, 2006). However, little research has been conducted to investigate both knowledge sharing and knowledge reuse systematically (He and Wei, 2009). Based on this, knowledge sharing and knowledge reuse will be the emphasized areas in this thesis. Considering the relationships and difference between these two processes, knowledge transfer in this thesis will be treated as a stage covered by both knowledge sharing and knowledge reuse processes (Majchrzak et al., 2004; Markus, 2001; Szulanski, 2000). Therefore, this thesis will further explore knowledge sharing and knowledge reuse from the sender's and the recipient's perspective respectively, with the emphasize on the mechanism used. The working definition of knowledge sharing, knowledge reuse, and knowledge transfer used in this thesis are listed as follows by considering different emphasis:

- *Knowledge sharing* is the process in which the knowledge sender contributes his/her knowledge to the recipient and initiates the knowledge movement from the sender to the recipient. The focal actor is the knowledge sender.

- *Knowledge reuse* is the process in which the recipient seeks and acquires the knowledge from the sender (different from the recipient herself/himself), initiates the knowledge movement from the sender to the recipient and applies the knowledge received. The focal actor is the knowledge recipient and the focus is on the reuse of knowledge from the sender, rather than reuse of the recipient's own knowledge.

- *Knowledge transfer* is the knowledge movement from the sender to the recipient. The focus is on the mechanism used to facilitate the knowledge movement.

Mechanisms in knowledge transfer (i.e., including both knowledge sharing and knowledge reuse in this thesis) describe how and through what intermediate steps certain knowledge is delivered following a set of initial conditions from the knowledge sender to the recipient, including the methods, procedures, or processes involved in knowledge movement (Chai et al., 2003). The success of knowledge transfer depends largely on the mechanisms used as they provide opportunities to transfer documents or experienced personnel as well as communicate with others or other units (Argote, 2013). The capability of knowledge transfer mechanisms can be described based on their richness and reach (Evans and Wurster, 1997). Table 3 summarizes the characteristics of the knowledge transfer mechanism based on their richness and reach.

Table 3. Characteristics of the knowledge transfer mechanism based on richness and reach (modified from Chai, et al., 2003; Daft and Lengel, 1986; Evans and Wurster, 1997; Gupta and Govindarajan, 2000; Sambamurthy, Bharadwaj, and Grover, 2003)

Mechanism with high richness	Mechanism with high reach
Example: personnel movement, face-to-face communication such as group meeting, on-site training	Example: best practice guidelines, reports, IT systems
• Ability to transfer large amounts of information in a certain time interval • Ability to transfer various types of information at one time • Ability to transfer customized information • High interactivity between the senders and the recipients	• Large number of recipients at one time • Ability to overcome geographical and temporal barriers • Ability to overcome hierarchical barriers (functional/departmental)

According to Media Richness Theory (Daft and Lengel, 1986), communication mechanisms differ in their ability to transfer the 'richness' of knowledge. Richness refers to the amount and type of information that a mechanism can transmit in a certain time interval, which is determined by bandwidth (that is, the amount of information that can be moved from the sender to the recipient in a given time), customization (the degree to which the information can be customized), and interactivity (the degree to which the sender can interact with the recipient) (Daft and Lengel, 1986; Evans and Wurster, 1997). The amount of tacit and explicit knowledge transferred through the mechanism reflects the capability of the mechanism to reduce uncertainty and equivocality in knowledge processing (Daft and Lengel, 1986). From rich to less rich (lean), i.e., from personal to impersonal methods, the mechanisms ranked were: group meeting (e.g., teams, task forces, and committees with the ability to reach a collective judgment and consensus), direct contact, special reports (e.g., single studies or surveys with the purpose of gathering and synthesizing data on a certain issue), formal information systems (e.g., periodic reports and e-databases), and rules and regulations. The transfer mechanisms must be adjusted to the type of knowledge being transferred in order to make knowledge transfer effective (Gupta and Govindarajan, 2000). The use of information technology can facilitate the transfer of codified knowledge, whereas the transfer of tacit knowledge requires the usage of rich mechanisms, such as face-to-face communication (Gupta and Govindarajan, 2000) or the movement of personnel across an organization (Argote and Miron-Spektor, 2011; Argote, 2013).

Different from richness, reach was originally proposed to interpret the change in economics of information brought by the Internet (Evans and Wurster, 1997) and then was expanded into the scope of digital knowledge through communication channels (Sambamurthy et al., 2003). Reach refers to the number of people that the communication medium can influence or spread at one time, and is associated with ‘connectivity’ (Evans and Wurster, 1997). Chai, Gregory and Shi (2003) extended this concept to describe the knowledge transfer mechanism’s ability to overcome the geographical, temporal and hierarchical barriers in the transfer of knowledge.

Further, there is a trade-off between richness and reach (Chai et al., 2003; Evans and Wurster, 1997). For example, the transfer of rich information requires proximity and dedicated mechanisms, such as the transfer of people or face-to-face meetings, and the costs or physical constraints of these mechanism result in a limited number of recipients at a time, which thus reduces the reach level of the mechanism. On the other hand, knowledge transfer mechanisms reaching a wider range of people, such as best practice guidelines, can only transfer a limited amount of information, which thus reduces the degree of richness (Chai et al., 2003; Evans and Wurster, 1997).

2.2.4 Knowledge sharing and knowledge reuse – influencing factors and mechanisms

Knowledge sharing and knowledge reuse is often not a natural act (Davenport and Prusak, 2000). In order to enhance knowledge sharing and knowledge reuse in an organization, it is important to understand the influencing factors, which have been explored by various researchers. In a generic knowledge sharing and reuse model, the knowledge sender, the knowledge recipient, the transfer mechanism, the knowledge being transferred, and the context where the knowledge transfer takes place are the key elements (Szulanski, 1996, 2000). Taking this model into account and in line with the working definition of knowledge sharing, knowledge reuse, and knowledge transfer in this thesis, the influencing factors are categorized into two sets. The first category includes factors related to the people who share and reuse the knowledge (i.e., the knowledge sender and recipient), and the Motivation-Ability-Opportunity (MAO) framework will be used to summarize these factors. The second category includes factors influencing the selection of the mechanisms to transfer knowledge between the sender and recipient, and the Technology Acceptance Model (TAM) will be used to explain this set of factors.

Influencing factors related to people summarized in the MAO framework

Originating in the social-psychological domain, the Motivation-Ability-Opportunity (MAO) framework was used to explain human behavior and its subsequent results

(Blumberg and Pringle, 1982; Kang and Kim, 2017; Pringle and Blumberg, 1996). Later, it was used in the knowledge management context to examine how to stimulate knowledge transfer in a more structural manner (Argote, McEvily, and Reagans, 2003; Reinholt, Foss, and Torben, 2011; Siemsen, Roth, and Balasubramanian, 2008). According to Siemsen, Roth, and Balasubramanian (2008), *motivation* represents one's willingness to act, *ability* refers to one's skills or knowledge base related to the action, and *opportunity* refers to the environmental or contextual mechanisms which enable action.

Some researchers believed that motivation, ability and opportunity are complementary to improve knowledge management performance (Argote et al., 2003), while some researchers point out that constraining factors, i.e., a 'bottleneck', among these three factors determines the knowledge transfer performance (Siemsen et al., 2008), while future still, some researchers have proposed that ability and opportunity moderate the relationship between motivation and an employee's performance (Maclnnis and Jaworski, 1989). Finally, some researchers have shown that motivation and ability moderate the relationship between opportunity and an employee's knowledge sharing efficacy (Reinholt et al., 2011). Although different viewpoints have been presented on the relationship between motivation, ability, opportunity, and performance (i.e., knowledge management, knowledge transfer, knowledge sharing, etc.), the basic idea of the MOA framework in knowledge management is the same, that is, in order to facilitate knowledge transfer, the actors should not only be motivated to engage in knowledge transfer and have the ability to transfer the knowledge, but also need to have the opportunity to be involved in the knowledge transfer.

Both intrinsic and extrinsic motivation influences knowledge transfer behavior (Argote et al., 2003; Lin, 2007; Wang and Noe, 2010). Intrinsic motivation is based on self-desire that means the pleasure and inherent satisfaction obtained from specific activities or experiences, i.e., self-efficacy, whereas extrinsic motivation arises from outside influence of the individual (i.e., the external environment) which indirectly satisfy the individual's needs, such as (monetary) rewards or benefits gained from performing some activities (Lin, 2007; Osterloh and Frey, 2000; Quigley, Tesluk, Locke, and Bartol, 2007).

It has been found that a higher level of self-efficacy intrinsically motivates the knowledge sender to share knowledge. Through knowledge sharing, the knowledge sender's sense of helping others prompts them to participate in knowledge sharing in the future (Wasko and Faraj, 2000). Employees can be satisfied by enhancing the confidence in their ability to provide useful knowledge to others through successful knowledge sharing practices, thus be motivated to share more (Quigley et al., 2007). In addition, intrinsic motivation is essential for the transfer of tacit knowledge as it can overcome multiple task and 'free-riding' problems (Osterloh and Frey, 2000).

From the perspective of extrinsic motivation, an individual's behavior is driven by the perceived value and the benefits of taking an action (Lin, 2007). Sharing knowledge with others may create reciprocal benefits, that is the knowledge sender's future knowledge requirements may be met by others (Wasko and Faraj 2000). The more reciprocal benefits obtained from successful knowledge transfer, the more trust will develop in obtaining benefits in the future. Thus, more willingness to maintain long-term relationships between the knowledge sender and the recipient will be initiated, thus motivating further knowledge exchange/transfer (Hau, Kim, Lee, and KIm, 2013; Lin, 2007). This is a benefit for both the knowledge sender and the knowledge recipient. Although certain motivators have similar impacts on both knowledge sharing (from the knowledge sender's perspective) and knowledge seeking (from the knowledge recipient's perspective), such as the positive impact of trust and the negative impact of the effort required, there are different motivations for knowledge sharing and seeking as well (He and Wei, 2009). For instance, enjoyment in helping others has been found to motivate knowledge sharing, whereas perceived usefulness was found to motivate knowledge seeking. Therefore, it is valuable to further investigate the influencing factors for knowledge sharing from the sender's perspective and knowledge seeking (reuse) from the recipient's perspective. This is addressed in sub research question 5 in this thesis and is reflected in Publications IV and V.

Ability indicates an individual's capabilities, skills, and knowledge possessed or required to perform a task effectively (Blumberg and Pringle, 1982; Rothschild, 1999). Although motivation may initiate the willingness of the sender to share knowledge and the willingness of the recipient to seek and use/reuse the knowledge, it is difficult to take action without the ability to do so. From the knowledge sender's perspective, the disseminative capacity, i.e., the ability to make knowledge understandable for the recipient and diffuse the knowledge can facilitate successful knowledge sharing (Parent, Roy, and St. Jacques, 2007; Reagans and McEvily, 2003), which to some extent depends on the sender's existing knowledge base (Szulanski, 1996). With expertise and experience, i.e., both in-depth knowledge and a broader knowledge base, higher quality knowledge that is more accurate and comprehensive can be provided by the sender and shared with others (Haas and Hansen, 2007; Minbaeva, 2013). This is also related to the ability required of the knowledge recipient, i.e., the absorptive capacity. Absorptive capacity refers to the ability to recognize the value of the knowledge, acquire it, assimilate it, and apply it, which is highly determined by the prior related knowledge possessed by the sender (Cohen and Levinthal, 1990; Zahra and George 2002). A higher absorptive capacity enables knowledge recipients to identify useful knowledge relating to their expertise and apply it more easily (Reagans and McEvily, 2003). This is especially true in the case of the reuse of knowledge through an electronic repository due to the required relevant background knowledge for the application of the new knowledge (Haas and Hansen, 2007).

In addition, a better capability in knowledge sharing and reuse will increase self-confidence (Lin, 2007), thus motivating further knowledge sharing and reuse (Reinholt et al, 2011) and enriching the expertise and experience of the individuals, and finally increasing their disseminative capacity and absorptive capacity. As indicated by Szulanski (1996), lack of ability is more likely to impede knowledge reuse compared to lack of motivation. Therefore, continuous learning to enhance ability is crucial, which is consistent with Siemsen, Roth, and Balasubramanian (2008) who argue that ability is not a fixed capability, rather it can be improved through training, effort, and experience (Siemsen et al., 2008).

Personal related factors, i.e., motivation and ability, are not enough to ensure efficient knowledge sharing and reuse, as opportunities are necessary in these processes (Blumberg and Pringle, 1982; Siemsen et al., 2008). Opportunity is used to capture exogenous and environmental factors that enable or inhibit people to act (Rothschild, 1999). In the context of knowledge management, Siemsen, Roth, and Balasubramanian (2008) defined the opportunity to share knowledge as a combination of direct and uncontrollable factors surrounding the individuals and their task environment which enable or inhibit them to share knowledge with their colleagues. Using time availability, i.e., the degree to which an individual has slack time available at work, to proxy the opportunity to share knowledge, opportunity was found to be positively related to the intention to sharing knowledge, and this effect was even more significant when opportunity was the constraining factor, i.e. the opportunity was the bottleneck between motivation, ability and opportunity (Siemsen et al., 2008).

More available opportunities will enable more actions. Organizational culture is one important opportunity-related factor in knowledge sharing and reuse which is indicated in the literature, which can influence employees' behavior by specifying norms, attitudes, and beliefs as to how they should behave (Argote et al., 2003; Lee and Choi, 2010). A learning culture treats learning as an investment rather than a cost in the company so that knowledge is constantly used to improve the current situation, which promotes knowledge sharing and reuse (Mueller, 2014).

In addition to the organizational culture, more and better information and communications technology (ICT) tools can lead to more knowledge sharing and reuse opportunities by making the distribution of knowledge easier and improving the accessibility to the knowledge (Alavi and Leidner, 2001; Choi et al., 2010). The term ICT covers a variety of technologies such as the cloud, computers, databases, data mining systems, decision support system, e-mail, groupware, the internet, search engines, and social media etc. (Andreadis, Fourtounis, and Bouzakis, 2015; Chai and Nebus, 2012; Hislop, 2009; Leonardi, Huysman, and Steinfield, 2013), which is almost the only viable mechanism to effectively connect a large number of geographically dispersed people. ICT tools bring awareness (i.e., the recipients know where to find the knowledge), accessibility (i.e., it is easy to access the knowledge), availability (i.e., knowledge can be accessed and used wherever it is needed), and timeliness (i.e., knowledge can be accessed and used whenever it is needed) (Offsey, 1997), all of which can facilitate knowledge sharing and reuse in the company. With the support from ICT tools, the knowledge sender and recipient can interact in real time, thus facilitating knowledge transfer (Choi et al., 2010). Especially during the last decade, social media has become a trend which has shaped individuals' behavior of sharing and reuse thanks to its capability in terms of communication, collaboration, connectivity, completing and combining (Treem and Leonardi, 2012; Vuori, 2011). The unique characteristics of social media can help to overcome traditional barriers to knowledge transfer (McAfee, 2006). For instance, transparency, which refers to the degree to which the users believe that social media can provide accurate, comprehensive and reliable information about the current and past behavior of all members (Parameswaran and Whinston, 2007), is highly related to both knowledge sharing and knowledge reuse. From the knowledge sender's perspective, sharing high quality knowledge will be visible to all the members, which thus increases the reputation and credibility of the sender (Ardichvili, Cardozo, and Ray, 2003) and leads to more willingness to share. At the same time, transparency makes it difficult to hide poor knowledge contributions (Dalsgaard and Paulsen, 2009), thus motivating the knowledge sender to share high quality knowledge. From the knowledge recipient's perspective, transparency enables the knowledge recipient to identify and evaluate the quality of the knowledge by viewing the sender's records and other members' comments, thus saving time and effort in the knowledge seeking process. In addition, transparency enables the recipient to view the sender's profile, friend list, and past behaviors in the system, thus the recipient can better evaluate the credibility of the sender. A sender being the recipient's friend or friend's friend will make the recipient willing to trust the sender, and the positive comments from others on the sender's past behavior can allow the recipient to trust the quality of knowledge provided by the sender, thus increasing the possibility of acquiring knowledge from the sender.

Influencing factors related to mechanism selection summarized in the Technology Acceptance Model

In order to have a better understanding of knowledge sharing and knowledge reuse in the company, the mechanism selection is important because a sufficiently adequate adoption of the mechanism can facilitate knowledge sharing and knowledge reuse. First proposed by Davis (1985), the Technology Acceptance Model (TAM) has been used in many studies to predict users' acceptance of information systems. In TAM, two concepts are specified, namely perceived usefulness and perceived ease of use, as determinants of usage intentions and towards actual use.

According to Davis (1985), perceived usefulness refers to the degree to which people believe that using certain systems can improve their job performance, which has a direct impact on the technology adoption. In the context of knowledge sharing and knowledge reuse, the perceived usefulness of a knowledge transfer mechanism can be reflected in the perceived reach and richness of the mechanism, as explained in section 2.2.3. Both richness and reach are related to the characteristics of knowledge, such as how tacit it is, etc. The more tacit the knowledge is, the more time will be required for the sender to explain it and for the recipient to learn it (Argote, 2013; Levin and Cross, 2004). It will also require greater interaction and socialization between the knowledge sender and recipient when transferring the knowledge (Santoro and Saparito, 2006), which leads to the preference for the adoption of a mechanism with a high degree of richness. Therefore, a mechanism with a high degree of richness, such as personnel movement, allowing the knowledge sender and recipient to interact directly over a relatively long period of time, will be perceived as more useful for the transfer of tacit knowledge. Compared to this, a mechanism with a high degree of reach, such as an electronic knowledge repository, allowing more people to access the knowledge when needed by overcoming geographical, temporal, and hierarchical obstacles, will be perceived as more useful for transferring codified knowledge.

The perceived ease of use has been measured from different perspectives, including being easy-to-use, easy-to-learn, easy to become skillful, flexible to interact with (Gefen and Straub, 2000; Segars and Grover, 1993), which can be categorized into the physical or mental effort required, and how easy it is to learn a system. Using a mechanism that requires less physical and mental effort will be more likely to be accepted by the user. Similarly, a mechanism that is easier to learn will be more likely to be used.

The conceptual TAM used in this thesis is shown in Figure 7.

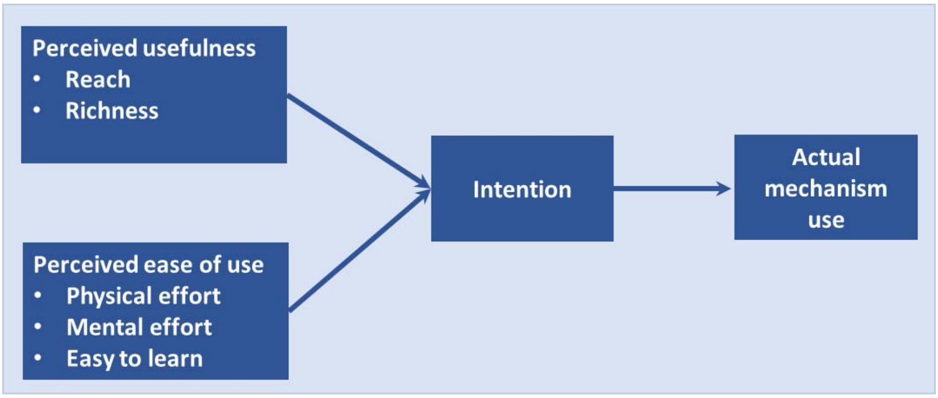

Figure 7. The Technology Acceptance Model in a knowledge management context (adapted from Davis, 1985)

Knowledge sharing and reuse can enhance mutual learning, promote best practices, reduce operational costs, and facilitate organizational innovation (Ahmad, 2017; Markus, 2001; Oliveira et al., 2019; Reychav and Weisberg, 2009). However, knowledge sharing and reuse does not happen naturally (Davenport and Prusak, 1998), and it normally cannot be forced by managers (Afshar-Jalili and Salemipour, 2019). In the existing literature, only a few studies have investigated the influencing factors concerning knowledge sharing and reuse systematically (Filieri and Alguezaui, 2015) making it hard to enhance knowledge sharing and reuse in the firm. This motivated the author to investigate the enablers and barriers to knowledge sharing and knowledge reuse, which are addressed in sub research question 5 and reflected in Publications IV and V.

2.2.5 Knowledge sharing and reuse in PSS in the digital era

In the PSS context, products are dealt with not only within the manufacturing company, but also in a distributed, mobile, and collaborative environment beyond the company's boundaries throughout the entire product lifecycle (PLC) phases (Cai et al., 2014), where multiple stakeholders with certain responsibilities are integrated to create the extended value-creation networks (Mert et al., 2016). Companies, especially PSS providers, are more PLC-oriented than traditional manufacturers, because all the relevant stakeholders must collaborate to provide the customer solution, i.e., an integrated product and service (Aurich et al., 2006). This almost inevitably requires a holistic information exchange between R&D (designers), manufacturers, users, and even recyclers (Terzi et al., 2010). Moreover, with the development of digitalization, the complexity is growing increasingly of products, processes, value creation networks and IT environments. Additionally, the volume of data is becoming extremely large, and the forms of data are incredibly diverse, which make it more difficult to manage the information (Li et al., 2015; Stark et al., 2014). Being able to interchange, share, and manage internal and external knowledge from different PLC phases with multiple disciplines has become increasingly challenging for PSS providers (Figay et al., 2012; Yang and Song, 2009; Zhang et al., 2012) and it is considered critical to the PSS providers (Bermell-Garcia and Fan, 2008).

With digitalization, the trend of relying on virtualization and outsourcing require companies to manage information and knowledge from different departments, different partners, and different information systems and repackage them as an integrated product to customers (Figay et al., 2012), which is essentially the process of knowledge sharing and knowledge reuse as defined in this thesis. In the PSS context, various stakeholders play their roles throughout the product lifecycle phases with different knowledge requirements and strategies. Although research on PSS design, evaluation, and operation methods has progressed well, there are only a limited number of studies concerning knowledge management practice in PSS operations (Qu et al., 2016).

Although PSS is considered more sustainable for the company and for society, however, some drawbacks of PSS have been raised, such as the rebound effects from the prolonged product life in the use-oriented PSS (Chierici and Copani, 2016). The rebound effect describes a situation in which an expected decrease of resource usage due to the use of innovative solutions does not occur because of changes in behavior (Berkhout, Muskens, and Velthuijsen, 2000). Compared with new products, reused products in the use-oriented PSS may be more harmful to the environment, which requires PSS providers to constantly update and enhance the functionalities and performance of the product to counteract the rebound effect (Chierici and Copani, 2016). This is essentially the main objective of knowledge sharing and reuse, which is even more important in the PSS context compared to a traditional product offering company (Goh and McMahon, 2009). However, only a limited number of studies on knowledge sharing and reuse have been conducted in the PSS context, especially from a PLC perspective, and those few exceptions have mainly focused on knowledge sharing and reuse in the BOL phase with limited attention paid to the MOL phase empirically (Baxter et al., 2009; Cai et al., 2014; Durst and Evangelista, 2018). For instance, the importance of reusing MOL knowledge (e.g., in-service information) to continuously improve the product-service offering has been emphasized by various researchers. In particular, MOL knowledge, especially in-service information, should be reused collectively to achieve greater value (Goh and McMahon, 2009).

However, most of the current studies have focused on the importance and usefulness of using MOL knowledge in the BOL phase for current product improvement and future new product design to increase the through-life performance of the product (i.e. Hassanain, Al-Hammad, and Fatayer, 2014; Igba, Alemzadeh, Gibbons, and Henningsen, 2015; Jagtap, Johnson, Aurisicchio, and Wallace, 2007; Roy, Mehnen, Addepalli, Redding, Tinsley, and Okoh, 2014). In fact, using MOL knowledge to improve the quality and the consistency of the service provided is feasible (Márquez and Herguedas, 2004). From the PSS providers' perspective, they must support their customers and ensure the usefulness of their product throughout the entire PLC. Therefore, it is valuable to investigate knowledge sharing and reuse further in the MOL phase. In particular, comparing the similarities and differences of knowledge sharing and reuse in both BOL and MOL phases would not only enrich the PSS research, but also refine the knowledge management research. This motivated the author to investigate knowledge sharing and reuse in the PSS context from a PLC perspective, especially focusing on the beginning-of-life and middle-of-life phases, which are addressed in sub research questions 3 to 6 and are reflected in Publications III, IV and V.

The increased digitalization of work has led to more networked and knowledge-based practices in the company (Jonsson et al., 2018). Digitalization has revolutionized the means of communication and enables access to huge amounts of information resources as well as the related data analysis (Kankanhalli et al., 2003), which provides alternative tools to implement knowledge management strategies. For example, to increase the quality of early design decisions, Bertoni and Larsson (2011) introduced Web 2.0 tools to help overcome knowledge sharing barriers between complex and cross-functional design teams (Bertoni and Larsson, 2011). Another example is social media. By allowing the creation and exchange of user-generated content, it and has been increasingly adopted by companies and can even been seen as an informal knowledge management tool to manage knowledge within and beyond the company's boundaries (Leonardi et al., 2013; Treem and Leonardi, 2012; Von Krogh, 2012). Providing a natural combination of codification (i.e. person-to-document) and personalization (i.e. person-to-person) knowledge management strategies, social media may help overcome the barriers to knowledge transfer through traditional mechanisms and could enable more effective and efficient knowledge transfer between knowledge senders and the potential recipients (Chai and Nebus, 2012; Hansen et al., 1999).

Although digitalization has the potential to facilitate knowledge management, the application of information technology tools cannot guarantee the success of knowledge management (Hendriks, 2001). For instance, information overload may increase the difficulty in finding essential information and may also increase the risk of misunderstanding information, this may result in impeded knowledge sharing and reuse in the company (Vuori, Helander, and Okkonen, 2019). Therefore, it is valuable to investigate the impact of digitalization on knowledge management practices/strategies, especially knowledge sharing and reuse, in detail and find suitable ways to make digitalization play a greater role in knowledge management (Markus, 2001). This is addressed in sub research questions 2 and 6 and is reflected in Publications III, IV, and V.

Table 4 summarizes the insights from the literature as a whole and their relation to the research questions.

Table 4. Insights from the literature and their relation to the research questions

Research question	Insights from the literature
SQ1: What is the current state of empirical studies on PSS and what are the focuses of these studies?	PSS research has been progressing well as a research field spreading across various disciplines, research domains, and geographical areas. However, empirical evaluation of the tools and methods has been scarce, and the number of empirical studies is limited. Therefore, it would be beneficial to have a better understanding of PSS practice so that the application of PSS as well as the benefits realized from PSS could be clearly identified. This motivated the author to conduct a literature review focusing on empirical PSS studies, which was addressed by sub research question 1.
SQ2: How does digitalization influence PLM in the PSS context when treating PLM as the implementation of a knowledge management strategy? SQ6: How does digitalization influence the above-mentioned requirements, strategies/practices, and enablers/barriers in the above-mentioned context?	Digitalization has the potential to reduce resource usage, facilitate the circular economy, and improve the product-service offering from PLC perspective. Mostly, however, the existing studies focused on the BOL phase, especially design, whereas other PLC phases were seldom investigated. Product data collection in practice is still restricted to sensor-generated data, while excluding or seldom considering other types of information on MOL or EOL phases. Therefore, research is needed regarding the types of other product data/information required to improve the product-service offering throughout the entire PLC. In addition, although digitalization has the potential to facilitate knowledge management, the application of information technology tools cannot guarantee the success of knowledge management. Therefore, it is valuable to investigate the impact of digitalization on knowledge management practices/strategies, especially knowledge sharing and reuse, in detail and find suitable ways to make digitalization play a greater role in knowledge management. The above-mentioned discussion motivated the author to further investigate the impact of digitalization in the PSS context, which is addressed by sub research questions 2 and 6.
SQ3: What is the current state of the art of knowledge management practices in PSS from a PLC perspective? SQ4: What are the knowledge requirements, knowledge sharing and knowledge reuse	Some studies have been conducted from the PLC perspective in the PSS context. However, the empirical studies mostly focused on exemplary cases, and most of the publications were conceptual papers, indicating that empirical studies on PSS from a PLC perspective were limited. This motivated the author to conduct studies on PSS from a PLC perspective, which are addressed in sub research questions 3 to 6. Knowledge management has been identified as a challenge for PSS providers. However, only a limited number of studies on knowledge

strategies/practices in different PLC phases in the PSS context? SQ5: What are the enablers and barriers to knowledge sharing and knowledge reuse in different PLC phases in the PSS context? SQ6: How does digitalization influence the above-mentioned requirements, strategies/practices, and enablers/barriers in the above-mentioned context?	management, more specifically knowledge sharing and reuse, have been conducted in the PSS context, especially from a PLC perspective, and those few exceptions have mainly focused on knowledge sharing and reuse in the BOL phase with limited attention paid to the MOL phase empirically. In fact, using MOL knowledge to improve the quality and the consistency of the service provided is feasible. From the PSS providers' perspective, they must support their customers and ensure the usefulness of their product throughout the entire PLC. Therefore, it is valuable to investigate knowledge sharing and reuse further in the MOL phase.In particular, comparing the similarities and differences of knowledge sharing and reuse in both BOL and MOL phases would not only enrich the PSS research, but also refine the knowledge management research. This motivated the author to investigate knowledge sharing and reuse in the PSS context from a PLC perspective, especially focusing on the beginning-of-life and middle-of-life phases, which are addressed in sub research questions 3 to 6.
SQ5: What are the enablers and barriers to knowledge sharing and knowledge reuse in different PLC phases in the PSS context?	Knowledge sharing and reuse does not happen naturally, and it normally cannot be forced by managers. In the existing literature, only a few studies have investigated the influencing factors concerning knowledge sharing and reuse systematically, making it hard to enhance knowledge sharing and reuse in the firm. This motivated the author to investigate the enablers and barriers to knowledge sharing and knowledge reuse. Although certain motivators have similar impacts on both knowledge sharing and knowledge seeking, there are different motivations for knowledge sharing and seeking as well. Therefore, it is valuable to further investigate the influencing factors for knowledge sharing from the sender's perspective and knowledge seeking (reuse) from the recipient's perspective. The insights above are addressed in sub research question 5.

3 Methodology and research design

This chapter first describes the philosophical assumptions and methodological considerations that have guided this research. Then, the selected research methods, data collection and analysis methods will be presented. Finally, the evaluation of the overall research quality will be discussed.

3.1 Methodological considerations

Recognizing and understanding the philosophical assumptions about reality that the research relies on plays a large role in determining the appropriate research approach and the entire research course for the topic in question (Creswell, 2014). In general, the basic philosophical assumptions to define a particular research paradigm in social research are basic beliefs about ontology, epistemology, axiology, and methodology (Creswell, 2013; Guba and Lincoln, 1994; Neuman, 2014). They are inextricably linked as the ontological views, epistemological standing points, and axiological positions guide the methodological selection (Braun and Clarke, 2013; Morgan, 2007).

Ontology is one of the most fundamental branches of metaphysics and can be defined as 'the study of being' (Crotty, 2003, p.10). It concerns the assumptions about the nature of reality and its characteristics (Creswell, 2013) and determines how the researcher sees the world of business and the choice of what to research (Saunders et al., 2019). Ontological considerations range between realist approaches, where reality is seen in an objective manner that is independent of people's beliefs and involves the perspective of objectivism, and subjectivist approaches, in which reality is seen in a subjective manner that is social constructed by people and with the perspective of subjectivism (Bryman, 2012; Creswell, 2014). In studies on social actors, the latter is also referred to as constructionism (Eriksson and Kovalainen, 2016).

Epistemology is a philosophical study of the nature of knowledge which concerns of what is (or should be) regarded as acceptable and legitimate knowledge and how it can be communicated (Bryman and Bell, 2011; Burrell and Morgan, 1979). It emphasizes the relationship between the researcher and the reality (Symon and Cassell, 2012), i.e., what is perceived/known to be true as classified by the researcher (Hallebone and Priest, 2009). As with ontology, epistemology ranges between objectivist and subjectivist perspectives (Braun and Clarke, 2013). The objectivist perspective asserts that true and observable facts exists in the external world, whereas the subjectivist perspective states that the world is built on observations and individuals' interpretations (Eriksson and Kovalainen, 2016). In business research, the main categories in epistemological positions are positivism, realism and interpretivism (Bryman and Bell, 2011). The positivist and realist paradigms of knowledge rely on objectivism and aim to explain phenomena, whereas an interpretive paradigm emphasizes the subjective meanings of social action and aims to understand the social world (ibid.).

Axiology is applicable in qualitative research and concerns the role of values and ethics within the research process (Saunders, Lewis, and Thornhill, 2019). It is related to the assumptions on how researchers position their values and goals in research, and it acknowledges the existence of biases (Creswell, 2013). The researcher's values may be reflected in the selected philosophy. In order to increase the credibility of the research, it is important for researchers to understand axiology as it enables researchers to articulate their values as a basis for judging the ongoing research (Heron, 1996).

Methodology is a series of choices that describe how to conduct the research (Braun and Clarke, 2013), referring to the research design, research process, and the selection of the research methods (Eriksson and Kovalainen, 2016). Broadly, it includes data collection, data analysis, participant selection, and the instruments used. The methodology used in research is significantly influenced by the ontological, epistemological and axiological positions (Morgan, 2007).

In business and management research, no single 'best' research philosophy exists as each philosophy plays a unique role and makes a valuable contribution to seeing the organizational world (Saunders et al., 2019). With its multi-dimensional nature and multidisciplinary context, business and management research has absorbed philosophies ranging from natural sciences, social sciences, arts, and humanities (Saunders et al., 2019). Therefore, the research philosophies adopted are scattered in a continuum between the objectivist and subjectivist extremes (Niglas, 2010). The ontological, epistemological, axiological, and methodological assumptions of the much-discussed philosophical positions, or research paradigms, are summarized in Table 5.

Table 5. Key research philosophies/paradigms in business studies (modified from Crotty, 2003; Guba and Lincoln, 1994; Järvensivu and Törnroos, 2010; Saunders et al., 2019)

	Positivism (explanation / verification)	**Postpositivism** (Prediction)	**Social constructionism /Interpretivism** (understanding /interpretation)	**Pragmatism** (Dialectic)
Ontology (the nature of reality or being) What is reality?	Naive realism – "real" reality but understandable External, objective, and independent of social actors One true reality (universalism) exists which can be measured and known	Critical realism – "real" reality but only imperfectly and probabilistically understood External, independent	Relativism – reality is local and socially constructed and co-constructed Subjective, differs from person to person Multiple realities	Reality is constantly renegotiated and interpreted in light of what is most useful Reality is the practical consequence of ideas Non-singular reality
Epistemology (what constitutes	Objectivist – findings true	Modified objectivist –	Subjectivist – findings are	Truth is the knowledge/theory

acceptable knowledge and how knowledge claims are justified) How can I know reality?	Law-like generalizations	findings probably true Objective reality shaped by the individuals' subjective views	constructed /created Interpretation made by researchers are shaped by their own experiences and background	which enables successful action The best approach is one that solves the problem Focus on practical applied research, integrating different perspectives to help interpret the data
Axiology (the role of values) How should we deal with the values of our own and our research participants?	Value-free: the researcher is detached, neutral and independent of the researched	Value-laden: the researcher acknowledges bias due to world views Facts about social reality are inseparable from values The researcher tries to minimize bias/errors	Value-bound: researchers are part of what is researched The researcher recognizes bias and negotiates the shared interpretations and worldviews with the participants Interpretations, meanings, motivations and values of social actors, structures and patterns	Value-driven: conducting research that benefits people Multiple stances Research based on intended consequences
Methodology (the process of research) How to find it out?	Experimental /manipulative, verification of hypotheses, chiefly quantitative methods	Modified experimental /manipulative, critical multiplism, falsification of hypotheses, may include quantitative and qualitative methods	Hermeneutical, interpretivism, qualitative methods	Determined by the research problem and the research question and is action-oriented Mixed or multiple method designs Using all approaches available to understand the problem

Positivism is commonly related to the use of quantitative research methods to establish generalizable data about social phenomena (Punch, 2013). It also states that only one objective reality is out there to be found and is not affected by the investigator (Hanson and Grimmer, 2007). With the philosophical stance of a natural scientist, the positivist paradigm cannot be fully applied in the context of the social world which involves human beings, thus another paradigm is derived, i.e., postpositivism. Being viewed as a variant of positivism, postpositivism assumes that reality is objective but only 'imperfectly and probabilistically apprehendable' (Guba and Lincoln, 1994, p. 109). Therefore, researchers in social science adopting a postpositivist position take a scientific approach to research based on a priori theories. They assume that there are multiple realities and cause and effect is a probability (Creswell, 2013) and speculate that the perception of the existence of objective reality is restricted by human cognition (Guba and Lincoln, 2005).

In contrast to the previous two stands, social constructionism (also described as interpretivism, see e.g., Denzin and Lincoln, 2011) assumes a subjective nature of reality and states that knowledge is shared among individuals and created in interaction (Hibberd, 2005). Creating new and richer understandings and interpretations of social worlds is the objective of social constructionist research (Saunders et al., 2019). Therefore, researchers with a constructionist perspective normally employ qualitative research methods to obtain an in-depth understanding of a given phenomenon in its specific context (Hanson and Grimmer, 2007) by addressing the interaction processes between individuals and positioning themselves in the research (Creswell, 2013). Social constructionism (or interpretivism) is the philosophical positioning of this thesis.

Pragmatism was proposed by philosophers who believed that a mono-paradigmatic orientation of research was not good enough, rather, they felt that a worldview that would provide research methods that could be considered more suitable to study the current phenomena was needed (Tashakkori and Teddlie, 2003; Patton, 2014). Aiming to provide practical solutions for informed future practice, the research of pragmatist often starts with a problem which later determines the research design and strategy (Saunders et al., 2019). With the emphasis on the outcomes of the research including actions, situations, and consequences (Creswell, 2014), pragmatists advocate the use of mixed methods to undertake research (Saunders et al., 2019).

As suggested by Guba and Lincoln (1994), the research paradigm selected should be the one whose assumptions are best met by the phenomenon under investigation. The philosophical positioning, or research paradigm adopted in this thesis is social constructionism, or interpretivism. The reasons for this are explained as follows. Knowledge is the focus of this thesis. Particularly, this thesis is devoted to exploring the phenomenon of knowledge movement, especially knowledge sharing and knowledge reuse in the PSS context from the PLC perspective. The ‘traditional’ idea of knowledge treats knowledge as a justified true belief in that people can claim knowledge only when an adequate justification for the beliefs can be provided (Ladyman, 2002). This view of knowledge is closely related to mode 1 of knowledge as specified by Gibbons, Limoges, Nowotny, Schwartzman, Scott, and Trow (1994) in which knowledge is formed in especially academic communities and which emphasizes theoretical knowledge. In addition to this, mode 2 of knowledge refers to production of knowledge in more practice-emphasized surroundings and concerns the practical (pragmatic) application of knowledge. This view of knowledge is context-driven, problem-oriented, and often involves multidisciplinary processes (Gibbons et al., 1994; Harmaakorpi and Melkas 2012). Both modes of knowledge highlight the relativism of knowledge. That is, to become knowledge, information, observations, theory, and ideas needs to be accepted by a community. In other words, subjective assessment by human is indispensable for knowledge. Therefore, this thesis adopts a relativist ontological stance and treats the topic under research as subjective.

The objective of the current study is to understand how and why knowledge is shared and reused in the company and to offer both theoretical and managerial insights into this phenomenon. This aligns with the objectives of an interpretive view as interpretivism facilitates an understanding of how and why and is appropriate when researching social processes (Bryman and Bell, 2011). Both knowledge sharing and knowledge reuse require a collaborative effort between the knowledge sender and the knowledge receiver. The influencing factors of effective and efficient knowledge sharing and reuse depends not only on the knowledge being shared/reused, the mechanism used, the network structure, but also on the capability of the sender/receiver, implying the socially constructed nature of the knowledge sharing and reuse process. To fulfill the research objectives, as a researcher, the author acknowledges that she needs to rely as much as possible on the participants' view of the phenomenon. At the same time, her own prior understanding of this phenomenon will influence the interpretation of the results, therefore it is necessary to minimize this kind of bias. In addition, the current study intends to improve the efficacy of knowledge sharing and reuse based on how it works now, rather than radically challenging the current position. Therefore, it should be categorized as regulation research (Burrell and Morgan, 2016).

Based on the discussion above and combining the trend of adopting descriptive methods in knowledge management research, the researcher thus treats herself as a social constructivist and positions the current study as an interpretive research among the four paradigms for organizational analysis proposed by Burrell and Morgan(2016) as shown in Figure 8.

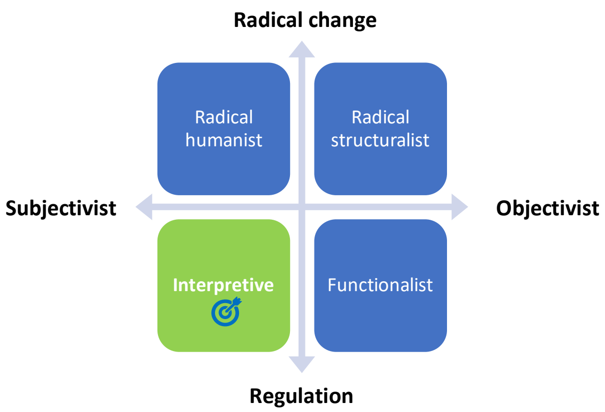

Figure 8. Positioning of this study in relation to the four paradigms for organizational studies (adapted from Burrell and Morgan, 2016)

3.2 Research approach and methodological choices

This section presents the research approach and methodological choices of the empirical part of the thesis. The research approach refers to research plans and procedures spanning steps from broad assumptions to detailed data collection, analysis and interpretation methods and generally includes quantitative, qualitative, and mixed methods approaches (Creswell, 2014). Quantitative research approaches aim to test objective theories by examining the relationship between measurable variables through statistical analysis of numerical data (Creswell, 2014). Usually, a quantitative study relies on standardized procedures that can be replicated to test the hypotheses deductively and with the ability to generalize the findings (Creswell, 2014; Neuman, 2014). In contrast, qualitative research approaches enable researchers to study social and human problems by conducting detailed examinations of specific cases raised in the natural flow of social life (Creswell, 2014; Neuman, 2014). A qualitative study usually uses non-standardized methods that can be adapted for each participant or case to generate emergent categories and theories inductively during the research process by taking the maximum advantage of the participants' perianal insight (Neuman, 2014). Combining deduction and induction and moving back-and-forth between theory and data, abductive theory development in qualitative studies matches what many business and management researchers actually do (Saunders et al., 2019; Suddaby 2006). Treating quantitative and qualitative approaches as different ends of a continuum, mixed methods approaches reside in the middle by incorporating elements of both approaches with the assumption that quantitative and qualitative approaches complement each other (Creswell, 2014).

This thesis is devoted to investigating how and why knowledge is shared and reused in the company from a product lifecycle (PLC) perspective in the product-service systems context. Since few of the existing studies concern knowledge sharing and reuse in the PSS context from the PLC perspective, this thesis is essentially an exploratory study as it aims to extend existing theory (Eisenhardt, 1989; Yin, 2014) and seek new insights into the phenomena under investigation (Saunders, 2011). Considering the subjective and context dependent nature of knowledge sharing and reuse in the company, and aligning with the paradigm stance (social constructionism, or interpretivism), overall, a qualitative research approach was considered as the primary choice to employ. However, the author complemented the predominant approach with a descriptive quantitative approach. For the individual publications of the thesis, careful consideration was taken in selecting the most appropriate research methods to support the goals of the study. The main empirical research method used in this thesis is a qualitative case study method (Publication IV and V) complemented by a quantitative survey (Publication V). In addition, systematic literature reviews (conceptual research approach) were conducted to establish a state-of-the-art understanding of the knowledge management practices throughout the PLC in the existing empirical studies (Publication I and III) as well as the impact of digitalization on product lifecycle management (Publication II), therefore not only revealing the research gaps, but also permitting point-of-view comparisons between the existing literature and the results of the empirical part of this thesis.

The methodological choices in the individual publications are summarized in Table 6 on next page and will be described in more detail in the following sub-sections.

Table 6. Overview of the methodological choices in the individual publications

	Publication I	Publication II	Publication III	Publication IV	Publication V
Title	Empirical studies on product-service systems – A systematic literature review	The impact of digitalization on product lifecycle management: How to deal with it?	Knowledge management in product-service systems – A product lifecycle perspective	Dealing with knowledge management practices in different product lifecycle phases within product-service systems	Sharing and reusing knowledge for innovation and competitiveness in PSS
Research objective	To analyze the current state of the empirical studies on PSS and provide possible research directions/considerations for future empirical PSS studies.	To identify the impact of digitalization on PLM and provide suggestions for manufacturing companies to respond and keep competitive in the digital era.	To analyze KM practices throughout the PLC and raise propositions for both academia and practitioners, as well as provide guidelines to the doctoral candidate to further investigate this topic.	To investigate knowledge requirements, knowledge sharing, and knowledge reuse in manufacturing companies and logistics companies in the PSS context from different stakeholders' perspectives and the impact of digitalization on the above topics.	To investigate KM practice in the BOL and MOL phases from the PSS provider's perspective. In particular, to identify similarities and differences in knowledge requirements, knowledge sharing, and knowledge reuse within and between BOL and MOL phases, the influencing factors of knowledge sharing and knowledge reuse, and the impact of digitalization on the above topics.
Research approach	Conceptual	Conceptual	Conceptual	Qualitative	Qualitative, complemented by a quantitative approach
Research purpose	Exploratory	Exploratory	Exploratory	Exploratory	Exploratory
Research strategy	N/A	N/A	N/A	Abductive	Abductive
Research method	Systematic literature review	Systematic literature review	Systematic literature review	Multiple case study	Multiple case study complemented by a questionnaire survey
Sampling strategy				Purposeful	Purposeful
Data collection	70 peer-reviewed journal articles published between 2006 and 2016	35 journal articles and conference papers published between 1999 and 2017	58 journal articles and conference papers published between 1995 and 2017	Six semi-structured interviews in three manufacturing companies and three logistics companies.	Twenty-seven semi-structured interviews in eleven companies and supplementary questionnaire survey.
Data analysis				Qualitative data analysis	Qualitative data analysis and complemented by descriptive quantitative data analysis

3.2.1 Systematic literature review

The research process began with systematic literature reviews which are organized around the first three sub research questions and to identify research gaps for further investigation. Through a systematic literature review, a large volume of disparate literature can be examined critically to assure the rigor of the research (Tranfield, Denyer and Smart, 2003). The online abstract and citation database Scopus was used to find the relevant body of literature for all the three literature review articles because it was perceived to cover a wider range of recent academic literature (published after 1995) compared to the Web of Science database (Falagas, Pitsouni, Malietzis, and Pappas, 2008) and covers multidisciplinary research from more than 5000 major and minor publishers (Scopus facts sheet, 2019). This time span and multidisciplinary research studies matches the literature requirement in this thesis. In addition, all these three articles used the systematic literature selection process because of its replicability and transparency (Tranfield et al., 2003).

Although the adoption of systematic literature review contributes to establish overall and a state-of-the-art understanding of the research topic by consolidating extant research, establishing connections in the disparate literature, and identifying gaps between different research streams (Crossan and Apaydin, 2010), the existence of its potential weakness related to literature selection should be kept in mind. To some extent, the findings from the systematic literature review may overlook some contributions from the existing literature as the detailed search was undertook in citation databases and limited to journal articles and conference papers. If a discipline prefers publish books and book chapters (such as sociology), such systematic literature review may potentially fail to notice these contributions (Pittaway et al., 2004). Meanwhile, it takes a lot of time and effort to filter a large volume of articles, therefore some articles will be excluded from the final list due to poorly written abstracts (Pittaway et al., 2004). In addition, during the review process, the reviewer's personal preferences and expertise can affect the outcome of the literature review as all the decisions concerning inclusions and exclusions are eventually executed on the premises of the reviewer's preference and expertise, albeit based on the pre-defined criteria. However, it is believed that although some relevant research may be overlooked, the rigorous systematic literature review procedure can greatly reduce the possibility that those omitted studies will have a serious impact on the results (Crossan and Apaydin, 2010).

The four-stage literature selection process is shown in Figure 9, and the detailed procedures for each of the review articles will be discussed in the following paragraphs. In all the reviews, only articles written in English were included, and the keyword search was limited to "title, abstract and keywords".

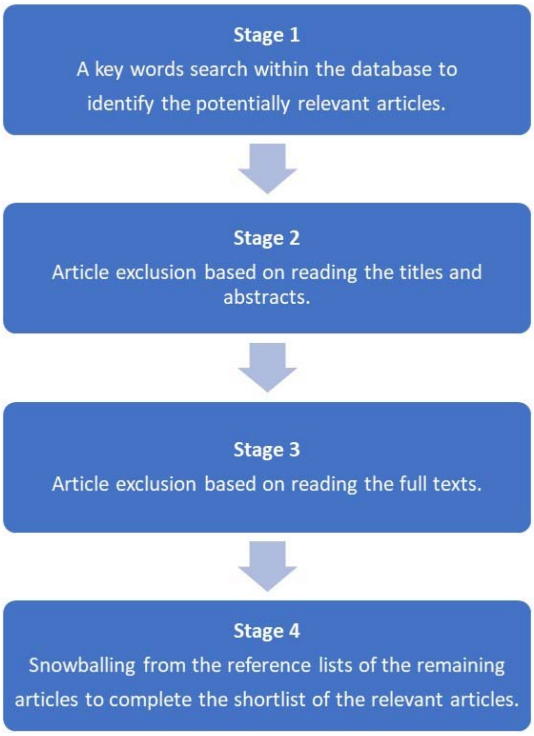

Figure 9. Systematic literature selection process

Data collection and analysis

The objective of Publication I was to understand the current state of the empirical studies of PSS. Therefore the key word search strings used were limited to ‘product service system*’, ‘product-service system*’, ‘empirical*’, ‘operation*’, and ‘appl*’, and the years of publication were limited to between 1995 and 2016 (Publication I was in 2016) given that PSS has been considerably developed since the late 1990s. The initial 357 peer-reviewed journal articles were reduced to 70 after reading the titles and abstracts because mostly articles from the initial search about PSS could not fulfill the inclusion criteria of real-word empirical studies. None of the 70 articles were excluded from further analysis after reading the full text and no new articles were added from the reference listed of these 70 articles, thus the final shortlist of the relevant journal articles remained at 70. Although the initial search was set for articles published since 1995, no relevant articles were found before 2006.

The data collection procedure of Publication II was similar to Publication I except for adding snowballing articles from the reference lists. With the objective of identifying the impact of digitalization on product lifecycle management (PLM), key words related to digitalization such as ‘digitalization’, ‘digit*’, ‘IoT’, and ‘information technology’ were combined with the key words related to PLM such as ‘lifecycle’ and ‘life cycle’ for initial searching. With the significant development of digitalization since 1990s, both journal articles and conference papers published between 1990 and 2017 (Publication II was completed in 2016) were considered as potentially relevant articles. The initial 281 articles were then filtered based on the relevance of the title and abstract, and only 28 remained after this process. All 28 articles were kept for further analysis after reading the full text, and 7 more articles were added from the reference lists of these articles. In total, 35 peer-reviewed journal articles and conference papers published between 1999 and 2017were included in the final analysis.

The literature selection for Publication III was different from the previous two and was more complicated. The objective of Publication III was to look into knowledge management practices across different PLC phases in the PSS context and raised propositions on this subject for both academia and practitioners. Therefore, the key words related to PSS, PLM, and knowledge management, such as ‘product-service system*’, ‘product service system*’, ‘knowledge’, ‘knowledge management’, ‘lifecycle’, and ‘life cycle’ were used to search relevant journal articles and conference papers published from 1990 to 2017. With only a limited number of articles found, the search strategy was revised by dividing the entire PLC into the beginning-of-life (design, manufacturing), middle-of-life (distribution, use and support, i.e., external logistics, repair and maintenance), and end-of-life (reuse, recycling, remanufacturing, and disposal) phases with the relevant sub-phases. Still using ‘knowledge’ and ‘knowledge management’ as the searching strings, relevant articles in each of the PLC phases were identified. Using the revised search strategy, 1164 articles were produced initially. The number was reduced to 58 after reading the titles, abstracts, and full texts. After snowballing from the reference list of the 58 articles, no new articles were added, which made a sample of 58 journal articles and conference papers for final analysis. Table 7 summarizes the literature selection process for the literature review articles.

Table 7. Summary of literature selection process for the systematic literature review

	Publication I	Publication II	Publication III
Database, search field, and language	online database Scopus, keyword search in “title, abstract and keywords”, English		
Types of articles and publication period	Journal articles, 1995~2016	Journal articles and conference papers, 1990~2017	Journal articles and conference papers, 1990~2017
Search strings and articles initially retrieved	‘product service system*’, ‘product-service system*’, ‘empirical*’, ‘operation*’, and ‘appl*’, 357 articles	‘digitalization’, ‘digit*’, ‘lifecycle’, ‘life cycle’, ‘IoT’, and ‘information technology’, 281 articles	‘knowledge’ and ‘knowledge management’ combined with the name of each PLC sub-phases, 1164 articles
Articles remaining after filtering by title, abstract, and title	Excluded articles with hypothesized, exemplar, or simulated studies, 70 articles remained	Only articles in manufacturing companies and which treat PLM as a strategy were included, 28 articles remained	Only articles dealing with knowledge management in manufacturing companies were included, 58 articles remained

Snowballing from the reference list	No new articles added	7 articles added	No new article added
Final set of articles	70 journal articles published between 2006 and 2016	35 journal articles and conference papers published between 1999 and 2017	58 journal articles and conference papers published between 1995 and 2017

3.2.2 Multiple case study

There are different definitions for case study, and one of the most prominent among them is the one proposed by Yin as '*an empirical inquiry that investigates a contemporary phenomenon within its real life context, especially when the boundaries between the phenomenon and context are not clearly evident*' (Yin, 2003, p. 13). To make it more fit for the research practice in industrial marketing, Piekkari, Plakoyiannaki and Welch (2010) modified the definition as '*an empirical inquiry that investigates a phenomenon in its real life context, relating it to theory and seeking to understand what the empirical phenomenon is a case of in theoretical terms*'. Their definitions emphasize the linkage between case and theory, the evolving nature of case study, and at the same time extend the scope of the phenomenon being investigated. With a considerable degree of open-endedness, case study enables researchers to gain rich insights about the focal phenomenon from intensive materials covering a range of aspects (Cresswell, 2013; Morgan, 2014).

Case study is more suitable for answering research questions of 'how' and 'why' in the absence of extensive fundamental theories (Eisenhardt, 1989) with the selection of both single in-depth case and multiple cases (Yin, 2014). Case study also suits the investigation of changing processes, because case study is a flexible and evolving process (Halinen and Törnroos, 2005). In particular, a multiple case study offers a great standpoint compared to a single case study for exploratory research as it provides both within case and cross-case analysis (Yin, 2014). Furthermore, in a multiple case study, the insights from multiple participants in multiple contexts can enhance the generalizability of the theory and extend the theory (Saunders et al., 2019). To fulfill this, appropriate case selection is a vital procedure for a multiple case study (Baxter and Jack, 2008). The most common sampling strategy in qualitative case research is purposive/purposeful sampling in which information-rich cases are selected deliberately and studied intensively (Eisenhardt, 1989; Patton, 2014). No research method is perfect, and the pros and cons of case studies are summarized in Table 8 on next page.

Publications IV and V of the thesis employ an explorative multiple case study methodology by considering the research objective, the existing fundamental theories, the nature of the research questions, the control of the researcher over the phenomena, and the focus on contemporary or historical events of the phenomena (Eisenhardt , 1989; Yin, 2014). The overall objective of this thesis is to develop a further understanding of knowledge management practice in the PSS context from a PLC perspective, and the lack of existing extensive literature on the phenomena calls for an in-depth study to enrich both knowledge management and PSS research. To fulfill the research objective, the main research questions in this study are of the ‘how’ and ‘what’ form. In addition, the control of knowledge management practices, especially knowledge sharing and reuse in this study, is limited. Focusing on contemporary events in knowledge management practices is crucial to this study, because only in this way can the data and research make sense to the real world. Therefore, case study was considered as the most appropriate methodology to employ in this study as it allows the researcher to dive into the context of the studied phenomenon and examine the issues in great depth. Focusing on the PLC perspective naturally requires a cross-case analysis in different PLC phases and sub-phases, and in different companies, thus a multiple case study methodology was selected. In addition, a multiple-level analysis was employed (Yin, 2014) in Publication IV and V to investigate the phenomenon from company and PLC-phase level, respectively.

Table 8. Pros & cons of case studies

Pros	Cons
Flexible method with iterative-parallel process (Easton, 2010). Can better understand the interaction between a phenomenon and its context in a specific case (Easton, 1995; Weick, 1979). Can better understand the phenomenon through multi-dimensional observations and a team of several researchers (Eisenhardt, 1989). The result can be novel because of the ‘unfreeze’ thinking (Eisenhardt, 1989).	Describe everything, but in fact describe nothing (Easton, 1995; Weick, 1979). Provide little basis for generalization (Easton, 1995; Eisenhardt, 1989; Weick, 1969; Yin, 1994). The resulting theory maybe be too complex due to the intensive use of empirical evidence (Eisenhardt, 1989). Lacking of controls in the case study may lead to problematic results (Morgan, 2014).

Reasoning

Deductive, inductive, and abductive logics are the three main types of reasoning (Saunders et al., 2019). Research with deductive reasoning logic starts with existing theories, develops hypotheses or conceptual structure based on theories, and tests them in an empirical setting for theory generalization (Eriksson and Kovalainen, 2016; Gummesson, 2000; Saunders et al., 2019). As the reverse of deductive reasoning, research utilizing inductive reasoning logic starts from empirical observations of particular instances and moves towards general theory development (Saunders et al., 2019). It is difficult to clearly distinguish the two reasoning logics in real life research and they can be used in the same study, which refers to abductive reasoning (Bryman, 2012; Cavaye, 1996). Rather than moving from theory to data (deductive) or data to theory (inductive), abductive reasoning combines both deductive and inductive reasoning and moves back and forth between data and theory (Suddaby, 2006). As a continuous process, abductive reasoning is unique to qualitative research and is consistent with actual work of many business and management researchers Saunders et al., 2019). Through this back and forth process, abductive reasoning fosters creativity to build new theories or modify existing theories (Saunders et al., 2019).

The overall research strategy of this thesis, especially the empirical part of this thesis, i.e., Publications IV and V, was abductive research strategy, as the focus of the study was to compare the empirical observations from the cases to the existing theories and studies. Knowledge management in general has been studied for decades, so the current understanding of knowledge management practice in general was obtained and lead the researcher to investigate the phenomenon in detail from a PLC perspective. Therefore, the study started from the familiarization with the existing literature and was followed by the empirical investigation. The literature always offered reference points for the results throughout the research process and the results were discussed in relation to the literature, demonstrating the contribution of the study to both theory and practice.

Data collection and analysis

The data collection and analysis of Publications VI and V followed a qualitative research approach (Eriksson and Kovalainen, 2016). Semi-structured interviews were conducted as the primary data collection method for both articles. As a data collection instrument, interviews allow instant clarification of the terminology involved and circumvent misunderstandings (Parkhe, 1993), which is particularly important for this study because some of the terminology used in academia are not familiar words for practitioners. Semi-structured interviews allow further elaboration on relevant topics by introducing follow-up questions that are considered important by both the interviewer and interviewees (Braun and Clarke, 2013) to achieve a rich understanding of the topic. Thus they were favored over fully structured interviews. In addition to the primary data collection, secondary data (e.g., press releases, company documentation and information from the company's websites, and other publicly available information on the studied companies' knowledge management practices) were used to enrich the data as well as achieve triangulation (Yin, 2014). A complementary questionnaire survey was conducted for Publication V, which will be discussed in detail in the next sub-section.

The key sources of the primary data for both case study articles consisted of 29 face-to-face semi-structured interviews conducted in seven manufacturing companies and four logistics companies in Beijing and Tianjin, China. The manufacturing companies were in different industries (e.g., traditional printing, high-tech electronic measurement, and biochemistry, etc.) and with different sizes. The company size was determined using the EU classification based on the number of people employed in the company. Micro enterprises were those with fewer than 10 employees, small enterprises were those with 10 to 49 employees, medium-sized enterprises were those with 50-250 employees, and large enterprises were those with more than 250 employees (Eurostat, 2016). Except for the biochemistry company which was medium-sized, all the other manufacturing companies were large (Eurostat, 2016). The logistics companies provided services to different industries, and two of them even served the manufacturing companies in this study. With regards to size, the logistics companies were relatively small compared to the manufacturing companies. Only one of these was medium sized and all the others were small. In order to get rich information, a purposeful sampling strategy was used to select key informants (Sandelowski, 2000) by considering their relevance and familiarity with the research topic. All the informants were managers in the respective functional department and were knowledgeable about knowledge management practices both in the department and in the company. In particular, the participants in the manufacturing companies were managers for the R&D department, purchasing department, production department, sales department, logistics department, and customer service department, and the participants in the logistics companies were responsible for logistics operations in the company. Multiple informants were selected in each manufacturing company so that information from one interviewee could be confirmed by other interviewees in the same company to increase the validity of the results (Golden, 1992). In order to protect the confidentiality of the interviewees, only their job titles were included, and the identifiable details were excluded (Parkinson, Eatough, Holmes, Stapley, and Midgley, 2016). The duration of each interview was between 45 and 120 minutes. The focus of the interview guidelines was on the thematic questions raised from the literature review, covering topics related to knowledge management practices in the department and in the company. Mandarin was the communication language (the mother tongue of the researcher and the interviewees) used in all the interviews to create better rapport for active participation and interaction (Tsang, 1999). All the interview data was digitally recorded with permission, except for interviews in two manufacturing companies, where filed notes were written down by the interviewer. The audio records were fully transcribed verbatim by the interviewer and checked for accuracy through repeated listening. Upon transcription completion and manual text mining, a member checking technique was applied to increase the validity of the study by sending the finalized transcriptions to the participants (Creswell, 2014).

In terms of data analysis, data from the semi-structured interviews was analyzed using thematic coding and analysis methods (Braun and Clarke, 2006; Lee, 1999) in the NVivo 12 software program. The data was analyzed and reported based on predetermined themes from the literature (Lee, 1999). The initial nodes in NVivo were created according to the main themes from the research questions, including knowledge requirements, knowledge sharing, knowledge reuse, and the impact of digitalization on the above-mentioned practices.

Publication IV applied a firm level analysis to investigate knowledge management practice in beginning-of-life (BOL) and middle-of-life (MOL) phases in the PSS context, which was represented by R&D and logistics, respectively. Six participants who were familiar with knowledge management practices in R&D from three large manufacturing companies represented the BOL phase, and three participants who were familiar with knowledge management in logistics from three logistics companies represented the MOL phase. In total, nine interviews were analyzed. In order to obtain a clearer comparison of knowledge management practices within and between the BOL and MOL phases, the two transcripts of each manufacturing company were merged into one. Therefore, six files representing six companies were eventually imported into NVivo, three manufacturing companies for the BOL phase (i.e., M1, M2, and M3) and three logistics companies for the MOL (i.e., L1, L2, and L3). A summary of the companies and participants in Publication IV is presented in Table 9.

Table 9. Information about the case companies and participants in Publication IV

	Company	Industry	Size *	Participant	Job title
Manufacturing	M1	printing	large	P1	senior supply chain manager
				P2	R&D manager
	M2	automobile	large	P1	R&D manager
				P2	senior R&D project manager
	M3	electronic measurement	large	P2	product planning master, former R&D engineer
				P2	channel manager, former R&D engineer
Logistics	L1	logistics	small	P1	customer service & customs manager
	L2	logistics	medium	P1	port & customs manager
	L3	logistics	small	P1	operations manager

In Publication V, knowledge management practices in six PLC sub-phases were analyzed in the PSS context, and from the PSS provider's perspective. Different PLC phases and sub-phases were represented by the relevant functional departments in the company, among which R&D, purchasing, and production were used to represent the beginning-of-life phase, and logistics, customer service, and sales were used to represent middle-of-life phase. A total number of twenty-seven interviews with managers in the corresponding departments were conducted from 7 manufacturing companies and 4 logistics companies. Another two interviews from manufacturing companies, one with the chief information officer and the other with the chief executive officer, were not included in the final data analysis through NVivo. Rather, the data was used to confirm the interpretations of other interviews as well as serving as triangulation to enhance the study's credibility. A summary of the companies and participants in Publication V is presented in Table 10 (on the next page).

3.2.3 Questionnaire survey

By studying a sample of a population, the researchers adopted a survey design method and intended to generalize the sample results to the population and provide a quantitative or numeric description of trends, attitudes, or opinions of that population (Creswell, 2014). In order to get more information on the usage of IT applications in the companies studied, a quantitative survey was used as a supplementary method in Publication V.

Table 10. Information about the case companies and participants in Publication V (Xin, Ojanen, and Huiskonen, 2020)

Company	*Industry*	*Size **	*Participant*	*Job title*	*PLC phase*	*PLC sub-phase*
C1	printing	large	P1	senior supply chain manager	BOL	Purchasing (PUR)
			P2	R&D manager	BOL	R&D (RD)
C2	automobile	large	P3	R&D manager	BOL	R&D (RD)
			P4	senior R&D project manager	BOL	R&D (RD)
			P5	procurement manager	BOL	Purchasing (PUR)
			P6	production manager	BOL	Production (PD)
			P7	customer service/quality manager	MOL	Customer service (CS)
C3	consumer electronics	large	P8	procurement manager	BOL	Purchasing (PUR)
			P9	product quality manager	BOL	Production (PD)
			P10	production manager	BOL	Production (PD)
			P11	logistics and customs manager	MOL	Logistics (LOG)
			P12	customer service manager	MOL	Customer service (CS)
C4	chemical	large	P13	senior sales manager	MOL	Sales (SAL)
			P14	production manager	BOL	Production (PD)
C5	electronics components	large	P15	logistics and customs manager	MOL	Logistics (LOG)
			P16	procurement manager	BOL	Purchasing (PUR)
			P17	sales manager	MOL	Sales (SAL)
			P18	customer service manager	MOL	Customer service (CS)
				chief information officer		
C6	electronic measurement	large	P19	product planning master, former R&D engineer	BOL	R&D (RD)
			P20	channel manager, former R&D engineer	MOL	Sales (SAL)
C7	biocheminstry	medium		CEO		
			P21	Procurement manager	BOL	Purchasing (PUR)
			P22	R&D manager	BOL	R&D (RD)
			P23	R&D manager	BOL	R&D (RD)
C8	logistics	small	P24	customer service & customs manager	MOL	Logistics (LOG)
C9	logistics	medium	P25	port & customs manager	MOL	Logistics (LOG)
C10	logistics	small	P26	operations manager	MOL	Logistics (LOG)
C11	logistics	small	P27	customer service & customs manager	MOL	Logistics (LOG)

* Size was determined using EU classification based on persons employed in the company: fewer than 10 → micro enterprises; 10-49 → small enterprises;

Questionnaire design

As the objective of the survey was to get descriptive information on the usage of IT applications in the company, the validity and reliability of the measurements was not the priority in the questionnaire design. Rather, the focus was on the list of the IT applications. Adapted from some literature on knowledge management systems, eleven IT applications were selected in the final list, including email, intranet, workflow systems, database management systems, search engines, document management systems, instant messaging, groupware systems, video conferencing, business intelligence systems, and decision support systems (Azyabi, Fisher, Tanner, and Gao, 2014; Alavi and Leidner, 2001; Choi and Lee, 2003; Hislop, 2009). A five-point Likert scale was used to measure the degree of usage of the IT applications (Churchill, 1992), where 1 = unknown application, 2 = known but not used, 3 = rarely used, 4 = regularly used, and 5 = intensively used.

Data collection and analysis

A questionnaire survey was used as a supplementary method in Publication V to get more information on the IT applications' usage. Purposive sampling was used to collect the data (Sandelowski, 2000) since the survey was conducted upon the completion of each interview. The interviewees were asked to fill in a short questionnaire, indicating that the sample size was limited to the number of interviews conducted. Similar to the data used in final case analysis in the same publication, the two survey responses from the chief

information officer and chief executive officer were excluded from the final quantitative data analysis. Therefore, twenty-seven questionnaires were used for the descriptive analysis using the IBM SPSS software package (Version 26). This is not only in line with the objectives of the questionnaire survey used in this study, but also consistent with the recommendations for data analysis with a small sample size (Creswell, 2014). A quantitative data analysis was carried out. The degree of usage of each of the eleven IT applications in different PLC sub-phases (departments) was compared through an ANOVA comparison of means. In order to show the significant difference between groups (i.e., in different PLC sub-phases) in detail, a post-hoc test of ANOVA was conducted for the comparison. The data analysis results of the survey are shown in Table 11.

Table 11. IT applications used in different PLC sub-phases

	R&D	*Purchasing*	*Production*	*Logistics*	*Customer service*	*Sales*	*Mean*	*Usage level*
emails	5	5	5	5	5	5	5	
intranet	5	5	5	4,67	4 ***	5	4,81	
workflow systems	5	5	5	3,67 *	5	5	4,7	intensively used
database management systems	5	5	5	3,83 ***	5	4 ***	4,63	
search engines	5	4,8	3,25 ***	4,83	4,33	4,33	4,52	
document management systems	4	4,8	4,5	4,33	4,33	4,67	4,41	
instant messaging	3	3,2	2,5	4,5 ***	4 ***	4 ***	3,52	regularly used
groupware systems	3,83	3,6	3,75	2,83	3	4,33	3,52	
video conferencing	3,5	3	2,5	3,17	3	3,67	3,15	
business intelligence systems	4 ***	3,2	2,25	2,33	3	3,67 ***	3,07	rarely used
decision support systems	3,5	2,8	2,5	2,83	3	3	2,96	

**** P<0,001 , ** P<0,01, * P<0,05 (Duncan alpha)*

3.3 Quality of the research

A piece of research should represent a logical set of conclusions, so it is important to judge the quality of the research based on multiple criteria (Yin, 2014). Usually, the quality of research is measured by its reliability, validity, and the generalizability of the results to a wider range of phenomena (Braun and Clarke, 2013). The more suitable corresponding term used to measure the quality of qualitative research is trustworthiness, which reflects the extent of credible and trustworthy of the data and the data analysis. The criteria adopted in this thesis to ensure trustworthiness were credibility, transferability, dependability, and confirmability, which were used in parallel to the corresponding quantitative criteria of internal validity, external validity (generalizability), reliability, and neutrality (Creswell, 2013; Lincoln and Guba, 1985).

Credibility

Credibility means the confidence of the data and its interpretation, in other words, how well the interpretations made from the data represent the research participants' (informants) perspectives. In this thesis, credibility was realized through numerous means. First, it was achieved through prolonged engagement and member checking. During the face-to-face interviews, the researcher interacted with the participants continuously to establish a trusting environment and relationship, which allowed the researcher to get deep insights from the participants. Regarding the member checking, the interview content was restated and verified by the researcher during the interviews to ensure the views of the participants were captured accurately, and instant corrections were made for any misunderstandings. Upon completion of the transcription and manual text mining, the polished transcriptions were sent to the participants to confirm the validity of the content (Creswell, 2014). Second, data triangulation was applied in this thesis to ensure a deep and complete understanding of the investigated phenomenon (Patton, 2014). Wherever possible, this thesis strove to collect data from different sources and of different types. Various types of data were used, including data from primary sources (i.e., interviews and surveys) and secondary sources (i.e., literature, press releases, company documentation and information from the company's website, and other publicly available information). Multiple key informants were selected in each manufacturing company so that the information from one interviewee could be confirmed by other interviewees (Golden, 1992). In addition, the extra two interviews conducted in Publication V were used to confirm the interpretations of the other interviews. Thirdly, the credibility of this thesis was ensured by the quality of the data sources. For the literature review articles, only peer-reviewed journal articles and conference papers were included, which addressed the quality of the reviewed publications. For the empirical articles, predefined protocols were used in the interviews to ensure the credibility of the results (Yin, 2014). Fourthly, peer scrutiny of this research enhanced the credibility of the results. The research results were presented at a total of five academic conferences, and all the individual publications have undergone a peer review process.

Transferability

Transferability refers to the applicability or generalizability of the research findings from the sample to other situations. Given the small sample size in most qualitative research, it is difficult to transfer the findings straightforwardly (Morrow, 2005). Therefore, it is important to provide proper information on the context of the research settings to allow other researchers assess the relevance and usefulness of the findings for them (Shenton, 2004). In this thesis, data collection from multiple companies made it possible to compare insights between cases and increased the generalizability and transferability of the results. The key informants were selected based on their relevance and familiarity with the research topic which increased the transferability of the results. In addition, in-depth descriptions of the case studies, including the research context, research process, participants and settings were provided to enable the readers to analyze and determine the applicability of the findings to their own premises.

Dependability

Dependability refers to the degree of information provided by the researcher to ensure the replicability of the research, including the logic, traceability, and documentation of the research (Eriksson and Kovalainen, 2016). In this thesis, a detailed research method section was provided in each individual publication to describe the research context and research process. For the empirical articles, all the interviews were recorded with permission, then transcribed and stored properly. For those interviews which could not be recorded, detailed field notes were made during the interviews. For the literature review articles, the systematic literature selection process was transparently showcased to increase the replicability of the study.

Confirmability

Confirmability refers to the quality of the results, that is the results should be based on the data gathered, and others should be able to easily understand the results through the linkage provided between the findings and conclusions (Lincoln and Guba, 1985). This implies that researchers must provide readers with a chain of evidence to logically draw the stated conclusions. The interviews were digitally recorded and transcribed verbatim to ensure the participants' narratives were accurately represented. In the empirical articles in this thesis, detailed data excerpts, such as direct quotations from the interviews, were used to establish a chain of evidence from the empirical data, thus providing evidence for the reader. Whenever possible, the findings were compared with the findings of other studies to confirm the interpretation of the findings, thus strengthening the confirmability of the thesis. In addition, the findings of all the individual publications were confirmed by the co-authors to provide additional conformability.

4 Summary of the publications and results

This chapter presents the primary findings of the thesis by summarizing the main findings and contributions made by each of the publications. The research results and research topics addressed in each of the individual publication are summarized in Table 12.

Table 12. Research results and research topics addressed in the individual publications

Publication	Research results and topics addressed
Publication I	▪ Analyzed the current state of empirical studies of product-service systems (PSS) through a systematic literature review of 70 peer-reviewed journal articles, including acceptance of PSS in academia and industry, evolution progress, research method used, and the focuses of these studies. ▪ Provided possible research directions/considerations for future empirical PSS studies.
Publication II	▪ Identified the impact of digitalization on product lifecycle management through a systematic literature review of 35 journal articles and conference papers. ▪ Provided suggestions for manufacturing companies to respond and remain competitive in the digital era.
Publication III	▪ Identified knowledge requirements, knowledge sharing and reuse practices throughout the product lifecycle (PLC) through a systematic literature review of 58 journal articles and conference papers. ▪ Raised propositions to academia on possible future research directions. ▪ Raised propositions to practitioners on how to facilitate knowledge sharing and reuse across PLC. ▪ Proposed an extended PLC model considering knowledge management in the PSS context.
Publication IV	▪ Investigated knowledge requirements, knowledge sharing, and knowledge reuse in manufacturing companies (representing the beginning-of-life, [BOL] phase) and logistics companies (representing the middle-of-life, [MOL] phase) in the PSS context from different stakeholders' perspectives through semi-structured interviews in three manufacturing companies and three logistics companies. ▪ Identified the impact of digitalization on the above-mentioned topics. ▪ Provided managerial implications to facilitate knowledge management.
Publication V	▪ Investigated knowledge requirements, knowledge sharing, and knowledge reuse in three PLC sub-phases in BOL (R&D, purchasing, and production) and three PLC sub-phases in MOL (logistics, customer service, and sales) from the PSS provider's perspective through twenty-seven semi-structured interviews in eleven companies and a supplementary questionnaire survey. ▪ Identified similarities and differences of knowledge requirements, knowledge sharing, and knowledge reuse within and between the BOL and MOL phases. ▪ Identified influencing factors of knowledge sharing from the knowledge sender's perspective and influencing factors of knowledge reuse from the knowledge receiver's perspective. ▪ Analyzed the impact of digitalization on the above-mentioned topics.

	▪ Provided guidelines for PSS providers to facilitate better knowledge sharing and knowledge reuse in the digital era.

4.1 Publication I: Empirical studies on product-service systems – A systematic literature review

4.1.1 Background and objectives

The awareness of sustainability is greater than before for the entire society. To deliver value to the customer and fulfill their needs by providing an integrated bundle of tangible products and intangible services (i.e., Boehm and Thomas, 2013; Roy and Baxter, 2009; Tukker and Tischner, 2006; Tukker, 2015), product-service systems (PSS) have the potential to embrace sustainability. Therefore, PSS has become an emerging topic for both researchers and practitioners. Although research related to PSS has been reviewed from various perspectives, in different fields and in special geographic areas (e.g., Baines et al., 2007; Boehm and Thomas, 2013; Lightfoot et al.,, 2013; Reim et al., 2015; Tukker and Tischner, 2006; Vasantha et a., 2012), to our knowledge, none of the existing review papers looked at empirical PSS studies as the focus. In order to understand the current state of the empirical studies on PSS, the objective of Publication I was to address this gap by conducting a systematic literature review.

4.1.2 Main findings

Through a systematic literature review of seventy peer-reviewed journal articles published between 2006 and 2016 in the online Scopus database, this study found that about 80 percent of the relevant studies had been published since 2012, which reflected the demand for empirical PSS research in the recent years. PSS has been widely studied in academia and related articles were distributed across more than thirty journals. In industry and practice, PSS has been widely applied globally, especially in Europe, as about two thirds of the studies were from Europe. However, it should be noted that more than half of the studies were related to product-oriented PSS, indicating PSS was not mature from the evolutionary perspective. Regarding research methods, qualitative case studies was employed by more than eighty percent of the articles reviewed, and about two thirds of them adopted a single case study approach. Based on the objectives and focuses of the PSS studies, seven themes were identified, including the PSS design approach, approaches facilitating PSS design, PSS transformation drivers, PSS status quo, PSS evaluation, PSS function, and PSS impact. Not surprisingly, more than forty percent of the studies were related to PSS design, especially the early phases of PSS design.

4.1.3 Main contributions

The systematic literature review in Publication I contributes to PSS development by providing possible research directions, or considerations, for future empirical PSS studies. With regards to the research method, increasing the number of quantitative PSS studies would be suggested to help to generalize and validate the findings as most existing studies were qualitative in nature. Regarding the research scope or the unit of analysis, a broader view should be taken to treat PSS as a system, rather than only focusing on a single entity. Related to the system, a lifecycle perspective is very important in the PSS context. However, only a few of the existing empirical PSS studies took this into account. Therefore, future PSS studies should think about the entire product lifecycle and integrate the viewpoints of different stakeholders.

4.2 Publication II: The impact of digitalization on product lifecycle management: How to deal with it?

4.2.1 Background and objectives

In order to be competitive in the ever-growing complex digital ecosystems, in addition to selling pure products, offering product-related services throughout the entire product lifecycle (PLC) is becoming a necessity for manufacturing companies (Herterich, Uebernickel, and Brenner, 2015), which means that manufacturers need to cooperate with multiple stakeholders throughout the PLC by utilizing digital means (Figay et al., 2012). As a strategy, product lifecycle management (PLM) becomes more important as its starting point and purpose is to manage the product-related information throughout the entire PLC efficiently so that competitive advantages can be achieved from more flexible and efficient business processes (Stark, 2011; Terzi et al., 2010; Wegst and Ashby, 2002). As a technological trend and ongoing transformation process, digitalization has impacted the whole society enormously (Li, Merenda, and Venkatachalam, 2009). For companies, digitalization has changed the organizational business model and provided new value-created opportunities, for example, by bringing heterogeneous resources together, observing and understanding the operations and results in real time, and blurring market boundaries (Hess et al., 2016; Parviainen et al., 2017). Then, what does digitalization bring to PLM and how should manufacturing companies respond? The objective of Publication II was to answer these questions by conducting a systematic literature review.

4.2.2 Main findings

Based on the online database Scopus, Publication II analyzed thirty-five journal articles and conference papers published between 1999 and 2017 with a focus on product lifecycle management (PLM) strategy and digitalization in industry. The study found that more than thirty percent of the articles in this review were published after 2015, which was consistent with the development of digitalization. In general, the study found that digitalization extended PLM to the entire product lifecycle (PLC) and allowed closed loop PLM in practice to improve product quality and enhance the company's business (Kiritsis, 2011). By categorizing PLC into beginning-of-life (BOL), middle-of-life (MOL), and end-of-life (EOL) (Kiritsis et al., 2003; Kiritsis, 2011; Stark, 2011), more detailed impacts of digitalization on different PLC phases were analyzed corresponding to the different objectives of the different PLC phases. From the PLM perspective, in the BOL phase, digitalization not only enhanced the development of product and process (Kuo and Wang, 2012; Patrick, 2008) which shortened the time to market of products (Affonso et al., 2013), but also improved energy management (Tao, Wang, Zuo, Yang, and Zhang, 2016). In the MOL phase, digitalization facilitated to reduce the through-life cost by using the data collected from the communication and interaction between products and components (Lerch and Gotsch, 2015) which enabled more efficient logistics and energy management (Främling, Holmström, Loukkola, Nyman, and Kaustell, 2013; Tao et al., 2016). When turning to the EOL phase, with the ability to help estimate the remaining value of the end-of-use products, digitalization increased the accuracy and efficiency of decision-making thus improving resource-saving recycling activities (Li et al, 2015).

4.2.3 Main contributions

The in-depth literature review in Publication II contributes to enhancing the current understanding of the impact of digitalization on product lifecycle management (PLM), thereby providing suggestions for manufacturing companies to respond and remain competitive in the digital era. Digitalization not only facilitates PLM by promoting the exchange of information between the stakeholders throughout the entire product lifecycle (PLC), but also bring challenges to managing information due to the various forms of data generated, the huge volumes of data created, and the security issues raised by the interconnection between various stakeholders in the physical world and cyberspace. The real benefits of digitalization can only be achieved when this information exchange is really fulfilled in practice. Therefore, it would be important to provide standardized data so that it is feasible for the relevant stakeholders to analyze and use the data from various domains in PLM. In addition, establishing stronger partnerships with the various stakeholders is essential for manufacturing companies to better manage resources, especially external resources. At the same time, the scope, depth, and manner of data sharing with other stakeholder or partners must be strictly defined to guarantee that the accessibility is only limited to the authorized parties. To deal with all these challenges, highly competent people will be even more crucial and indispensable for the company, especially those people with advanced problem-solving skills and a multi-disciplinary knowledge base. As such, to prepare in advance by providing appropriate training to the employees would be an option. Through such efforts, it would be possible to promote more efficient PLM and thus move towards a less resource intensive society.

4.3 Publication III: Knowledge management in product-service systems – A product lifecycle perspective

4.3.1 Background and objectives

Product-service systems (PSS) integrate tangible products and intangible services to create customer utility and generate value (Tukker, 2015) and can potentially move society towards sustainability because PSS takes into account the entire product lifecycle (PLC). Categorizing PLC into beginning-of-life (BOL), middle-of-life (MOL), and end-of-life (EOL) phases (Kiritsis, 2011; Stark, 2011), knowledge generated in each PLC phase will be used by various stakeholders, both within the same PLC phase and throughout different PLC phases (i.e., Baxter et al., 2009; Kim and Park, 2014; Sander and Brombacher, 2000), and this is especially true in the PSS context (Zhang et al., 2012). With different objectives and focuses in each PLC phase, the corresponding knowledge requirements and management are different as well. In the PSS context, identifying this difference is especially important because PSS requires the application of multiple-disciplinary knowledge throughout the PLC. However, the existing literature rarely investigated this in detail. Addressing this gap, the objective of Publication III is to look into the knowledge requirements and management in different PLC phases thus helping the various stakeholders of PSS to achieve better knowledge management and provide insights for researchers into the possible directions of knowledge management in the PSS context. In particular, knowledge requirements, knowledge sharing and reuse practices throughout the PLC are the focus of this study.

4.3.2 Main findings

Focusing on knowledge management in product-service systems throughout the product lifecycle (PLC), this study reviewed fifty-eight journal articles and conference papers published between 1995 and 2017 based on the online database Scopus. More than one-third of the studies were published between 2013 and 2017, which reflected the increasing trend of study in this area. Regarding knowledge requirements, this study found that although the knowledge required in different PLC phases might be generated from the same PLC phase, the focuses of their usage were not the same. In addition, use-oriented PSS looked forward to getting more knowledge from the middle-of-life phase. With regards to knowledge sharing, both codification and personalization strategies were adopted by the companies based on different objectives. However, person-to-person communication was still preferred by R&D personnel. Moreover, middle-of-life knowledge was mostly shared only within this phase due to non-uniformed knowledge representation and scattered knowledge storage. Concerning knowledge reuse, various models/frameworks were proposed with different focuses and from different points of view, targeting only one PLC phase or across different PLC phases. A variety of knowledge reuse models targeting the beginning-of-life phase were introduced and from different perspectives, whereas there were not many models targeting the middle-of-life and end-of-life phases and these had limited objectives or were from limited perspectives.

4.3.3 Main contributions

Publication III contributes to knowledge management in PSS by reviewing relevant studies from the product lifecycle (PLC) perspective and providing propositions to both academia and practitioners. To academia, this study proposed that it is crucial to identify and classify the knowledge requirements by different stakeholders throughout the PLC phases in future research. Moreover, it would be valuable to investigate knowledge reuse in middle-of-life (MOL) and end-of-life (EOL) phases to make the theory about knowledge management in PSS more comprehensive. In particular, the original equipment manufacturers' perspective should be considered for the knowledge reuse model targeting the EOL phase to achieve sustainability. To practitioners, this study proposed that the knowledge provided should be represented in standardized forms and appropriate manners to match the requirements in different PLC phases and facilitate knowledge sharing across the entire PLC. In addition, a balanced adoption of personalization and codification strategy should be determined depending on the organization's unique context, rather than following any fixed ratio.

Triggered by sustainability concerns and integrating lifecycle thinking in the PSS context, an extended product lifecycle (PLC) model considering knowledge management was proposed in this study. By incorporating raw materials extraction and material production, this model emphasized a close-loop information flow and will help to accomplish real sustainability in PSS (as shown in Figure 10).

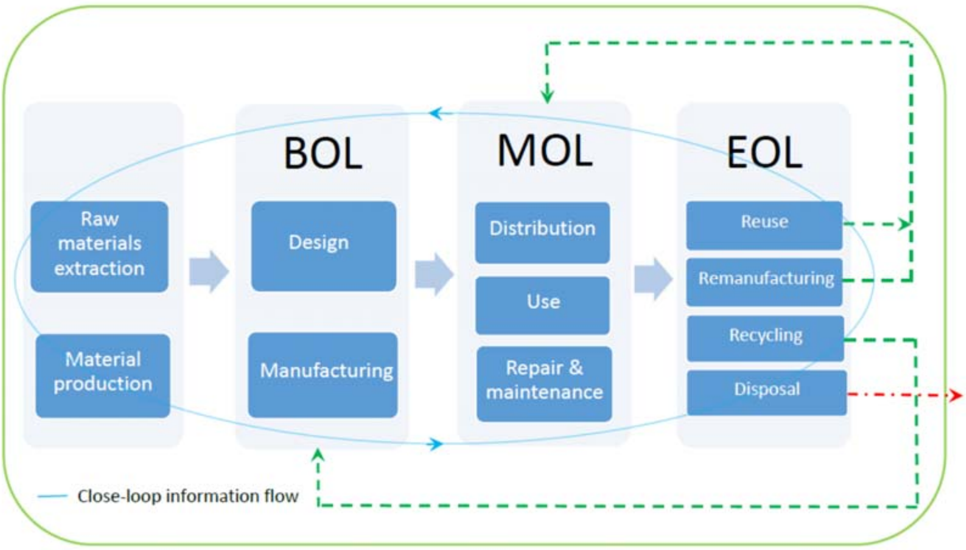

Figure 10. Extended PLC model considering knowledge management in PSS context

In addition to the contribution to academia and practitioners, some of the propositions in Publication III were planned to be investigated in PSS providers by conducting multiple case studies

4.4 Publication IV: Dealing with knowledge management practices in different product lifecycle phases within product-service

4.4.1 Background and objectives

Taking into account the emergence of widespread topics, for example, sustainability, digitalization, and product lifecycle management (PLM) together, product-service systems (PSS) have emerged as a business model to embrace sustainability from the environmental, economic, and social perspectives, with a focus on environmental sustainability (Geum and Park, 2011; Goedkoop et al., 1999; Tukker, 2004). Since the clarification of the concept, PSS has been widely applied globally and in a variety of research areas (e.g., Baines et al., 2007; Boehm and Thomas, 2013; Lightfoot et al.,2013; Reim et al., 2015; Tukker and Tischner, 2006; Vasantha et al., 2012). With the shift from providing pure manufacturing products with a certain functionality to offering availability of tangible and intangible value to the customers (i.e., Manzini and Vezzoli, 2003; Roy and Baxter, 2009), PSS involves a variety of stakeholders throughout the product lifecycle (PLC), i.e., the beginning-of-life (BOL), middle-of-life (MOL), and end-of-life (EOL) phases (Stark, 2011), and each phase has different knowledge requirements and knowledge management practices (e.g., Ahmed-Kristensen and Vianello, 2014; Filieri and Alguezaui, 2015; Ongondo and Williams, 2001; Perry, Pompidou, and Mantaux, 2014; Urwin and Young, 2014; Vezzetti, 2012; Vianello and Ahmed, 2012; Yang, Liu, Wang, and Shen, 2013). Being one of the most important sources of competitive advantage of the firm, knowledge becomes more important for the stakeholders in the PSS context because they need to intensively use knowledge from different PLC phases, which leads to more challenging management of knowledge (Zhang et al., 2012). Moreover, the opportunities and challenges brought by the on-going digitalization transformation has impacted the companies in different ways, which makes knowledge management even more complex (Xin, Ojanen, and Huiskonen, 2018). For these reasons, it is necessary to investigate knowledge management practice further in different PLC phases to facilitate better knowledge management for the stakeholders in PSS contexts, and to enrich PSS and knowledge management academic research, which is the starting ground of Publication IV.

The existing knowledge management studies have mostly focused on the beginning-of-life (BOL) phase and studies for the middle-of-life (MOL) phase have not been comprehensive (Cai et al., 2014). For those few studies of the MOL phase, the focuses were on one of the MOL sub-phases, e.g., use and support (Goh and McMahon, 2009; Thompson, 1999), and empirical studies on the other sub-phases in the MOL phase, e.g., distribution, were scant in the PSS context (Durst and Evangelista, 2018). Numerous manufacturing firms outsource their logistics with the intention of streamlining the value chains (Franceschini et al., 2003), which means that the investigation of knowledge management practice in the MOL phase inevitably involves logistics companies. Therefore, an investigation of knowledge management practices in the MOL phase, particularly in the distribution sub-phase (for example in logistics companies), will increase the understanding of appropriate ways of managing knowledge in manufacturing firms.

Addressing all the above-mentioned discussions, the objective of Publication IV is to investigate knowledge management in manufacturing companies (the beginning-of-life, BOL phase) and logistics companies (the middle-of-life, MOL phase) in the PSS context, especially focusing on knowledge requirements, sharing and reuse. In addition, the impact of digitalization will be examined to consider the opportunities and challenges raised in the digital era.

4.4.2 Main findings

The main results of this study came from semi-structured interviews in three manufacturing companies and three logistics companies in China. In the current study, the beginning-of-life (BOL) phase (particularly the design sub-phase related to R&D) was represented by these manufacturing companies, while the middle-of-life (MOL) phase (particularly the distribution sub-phase related to external logistic) was represented by the logistics companies. With regards to knowledge requirements, the results of this study demonstrated that a fair difference existed between the BOL and MOL phases. For example, the required expertise in the BOL phase focused on design and technology, whereas in the MOL phase the focus was on policy issues. The required customer knowledge in the BOL phase was related to customer needs and user experience, whereas during the MOL phase the focus became the characteristics of the customer's product. In addition, market knowledge was only used by the studied companies in the BOL phase, while industry knowledge was only used during the MOL phase. Corresponding to the knowledge required, during the BOL phase the studied companies acquired expertise-related knowledge through learning-by-doing and preferred person-to-person communication, whereas during the MOL phase such knowledge was acquired from the government and preferred through meeting organized by the government.

Regarding knowledge sharing, it was found that during both the BOL and MOL phases it was important and necessary in the current digital era to share knowledge. Knowledge was not only shared internally within the department and within the company, but also shared externally with customers. However, during the BOL phase knowledge was not shared with competitors due to confidentiality, whereas during the MOL phase knowledge was sometimes shared with competitors to gain mutual benefits. The most commonly adopted knowledge sharing mechanism in both the BOL and MOL phases was training. Unique mechanisms used in the MOL phase included job rotation and social media due to the characteristics of the job tasks in the MOL phase. The relevance of knowledge was the most significant factor that affected knowledge sharing, in both the BOL and MOL phases.

The studied companies reported that they reused knowledge in their daily work during the BOL and MOL phases and stressed its importance. During the BOL phase, knowledge reuse was reported by some companies to be one of their principles. However, the factors influencing knowledge reuse were different in the BOL and MOL phases. During the BOL phase, they were more related to the familiarity with the knowledge, and during the MOL phase they were more related to the standardization of the knowledge.

Under the on-going digital transformation, knowledge integration has become crucial as broader and more multi-disciplinary knowledge is required, which naturally calls for more highly competent employees. In addition, during the BOL phase, the safety and security issue of data protection was strongly emphasized as digitalization had led to vast amounts of available data and also made it easier for the data to be accessed.

One unsurprising finding from this study was that sustainability was highly stressed in the BOL phase, even though this topic was not included in the interview guideline. This awareness started from design and considered the entire PLC. However, a contradictory message related to this also arose from the BOL phase as in interviewees clearly indicated that the knowledge exchange between the BOL and EOL phases was very limited and they never improved product design by tracking or applying EOL knowledge.

4.4.3 Main contributions

Publication IV contributed to both PSS and knowledge management research. Firstly, this study shed light on PSS research by investigating the similarities and differences in knowledge management practices in the PSS context from different stakeholders' perspectives, and from a PLC perspective. Secondly, this study enhanced the understanding of knowledge management in manufacturing firms (BOL) by investigating knowledge management practices in logistics companies (MOL) in the PSS context. Thirdly, this study enriched the PSS literature by adopting a multiple case study approach to obtain a more comprehensive understanding of the status quo.

In addition to the theoretical contributions, some managerial implications were presented in this study to facilitate knowledge management and maintain company competitiveness in the PSS context in the digital age. Firstly, companies must clearly identify knowledge requirements in different product lifecycle (PLC) phases to ensure a correct understanding exists between the different PLC phases or between different stakeholders. This is a prerequisite for effective and efficient knowledge sharing and reuse. Secondly, companies should re-emphasize the importance of people, especially the importance of R&D personnel (Lerch and Gotsch, 2015; Terzi et al., 2010) and develop appropriate strategies to retain R&D experts. The experience and tacit knowledge obtained through learning-by-doing is more crucial for R&D and its accumulation takes time. Thirdly, companies should take action to strengthen external collaboration (Herterich et al., 2015) to facilitate the multi-disciplinary knowledge acquisition and application required in the digital era. Fourthly, companies should advocate standardization for different aspects, including but not limited to documentation and the interface between various stakeholders in the PSS context as knowledge sharing throughout the entire PLC can only be fulfilled by having widely recognized and must followed standards.

4.5 Publication V: Sharing and reusing knowledge for innovation and competitiveness in PSS

4.5.1 Background and objectives

Along with the trend of sustainability-oriented innovations (Adams et al., 2016), product-service systems (PSS) (Tukker, 2015), and emerging digital technologies and ecosystems (Clarysse, Wright, Bruneel, and Mahajan, 2014), the basis of competition has shifted from the physical product's functionality to the availability or performance of a bundle of product and service, i.e., the broader product system. Management of knowledge is even more crucial and challenging to the companies in this context as various forms of knowledge residing in different stakeholders along the product lifecycle (PLC) need to be integrated for the company to keep competitive. Therefore, as one of the actors in the system, manufacturing companies need to adopt appropriate knowledge management strategies/practices throughout the entire PLC to reap more value from knowledge management.

Knowledge sharing and knowledge reuse are the key processes in knowledge management (Bemret and Bennetz, 2003), which have long been investigated in the literature. However, if we categorize the product lifecycle (PLC) into three phases, that is the beginning-of-life (BOL), middle-of-life (MOL), and end-of-life (EOL) phase (Stark, 2011), the existing knowledge management studies on knowledge sharing and knowledge reuse have mainly focused on the BOL phase (design and manufacturing) (Baxter et al., 2009) and empirical studies targeting the MOL phase (external logistic, use, repair and maintenance) have not been comprehensive (Cai et al., 2014; Durst and Evangelista, 2018). As a PSS provider, ensuring the usefulness of their product along the PLC is crucial, which makes the MOL phase even more important than before. Thus, further investigating knowledge management practices, especially knowledge sharing and reuse in the MOL phase, will help PSS providers to set more appropriate knowledge management strategies and reap the fruit from their knowledge management efforts. In addition, the impact of the ongoing trend of digitalization on knowledge management, such as supporting communication (Treem and Leonardi, 2012), enabling information access (Kankanhalli et al., 2005), and facilitating and shaping the sharing and reuse behavior (Hislop, 2009; Leonardi et al., 2013; Von Krogh, 2012) should be investigated to get an integrated understanding of knowledge management.

The objective of Publication V is to investigate knowledge sharing and knowledge reuse in both the BOL and MOL phases to help companies, especially PSS providers, to better understand their knowledge management status quo, and adjust their management strategies to keep innovative and competitive in the digital era. This study also aims to complement the current knowledge management theory through a product lifecycle perspective in the PSS context. In this study because external logistics could be fulfilled by both the manufacturing firms themselves and third-party logistics companies (Franceschini et al., 2003), both manufacturing companies and logistics companies were the main targeted companies in this study.

4.5.2 Main findings

The main findings of Publication V were based on twenty-seven semi-structured interviews in eleven companies and supplementary questionnaire survey responses from the interviewees. Six product lifecycle (PLC) sub-phases were analyzed, among which R&D, purchasing, and production represented the beginning-of-life (BOL) phase, and logistics, customer service, and sales represented middle-of-life (MOL) phase. In this study, the analysis of knowledge sharing focused on the knowledge senders who initiated the knowledge movement from the sender to the receiver, and the analysis of knowledge reuse focused on the potential knowledge receivers who were inclined to seek and acquire knowledge from the senders. The main findings on knowledge management practices within single PLC phases and between the two PLC phases are presented as follows.

As the object of knowledge sharing and knowledge reuse, although the knowledge used/required were different between all the sub-phases under investigation, similarities were found not only within single product lifecycle (PLC) phases, but also between all the PLC sub-phases. The necessity to implement standardization and systemization in the work was demonstrated as process/procedure knowledge was required to be frequently used in all sub-phases. The commonly used expertise and product knowledge in all sub-phases on the one hand indicated the importance of this knowledge, on the other hand it also revealed that the focus of the requirement for the same type of knowledge was different corresponding with distinct job positions and responsibilities. It was also found that production knowledge and supplier knowledge were only used during the BOL phase, whereas commonly used customer knowledge in the MOL phase was only used in the R&D sub-phase of the BOL phase. Only expertise and process/procedure knowledge were considered equally important by all the interviewees during the different PLC sub-phases, while the degree of importance of other knowledge was not the same.

The findings on knowledge sharing focused on the sender's side. The scope and degree of knowledge sharing were different between different PLC sub-phases. For knowledge sharing within the company, the practices between the BOL phase and the MOL phase were fairly different. Except for the R&D sub-phase, which was the most extensive one and shared knowledge with all other sub-phases except logistics, while for the other two sub-phases in the BOL phases, knowledge was mainly shared within the same PLC phase (BOL). However, during the three sub-phases of the MOL phase knowledge was mostly shared with the BOL phase, rather than within their own PLC phase (MOL). This knowledge sharing pattern indicated the close cooperation between the sub-phases within the BOL phase, and relatively independent responsibilities of the sub-phases in the MOL phase. In addition, knowledge sharing between the MOL and BOL phases would smoothen the operation of the company. With regards to the knowledge sharing mechanism, mentor was the one who adopted it only within the same sub-phase. The mechanism selection corresponded to the characteristics of the job position, the knowledge involved, and the urgency level of the task, etc. For instance, job rotation and social media were the unique knowledge sharing mechanisms in logistics sub-phase. Confidentiality and non-relevance to the potential receiver were the two most impeding factors to knowledge sharing, while top management support and a sharing/learning culture were the two most facilitating factors.

Focusing on the receiver's side, knowledge reuse was embedded in their daily work. Both the scope of knowledge seeking, and the mechanisms adopted showed a similar pattern to knowledge sharing. The crucial role of R&D was revealed from the knowledge reuse pattern as all the sub-phases acquired and reused the knowledge from R&D. When seeking knowledge for the purpose of reuse, the most influencing factor was the usefulness of the knowledge. A source's credibility was a key concern for source selection, while the possibility to obtain the knowledge, the convenience of the mechanism, and the importance/urgency level of the task were the most influencing factors for the mechanism selection. In addition to this, although a knowledge repository could be found in all the companies in this study, the person-to-person mechanism was still preferred in all the sub-phases, whenever possible.

IT application was different in the different product lifecycle (PLC) phases and was consistent with the corresponding responsibilities of the employees during those phases. Although in general emails, intranet, and workflow systems were intensively used in all PLC sub-phases surveyed, the application of intranet systems was much lower in customer service compared to all other sub-phases. Digitalization will enable more knowledge reuse in the future. By reducing the associated money and time cost, digitalization made knowledge reuse easier, which accelerated new product development. By providing a comprehensive and convenient knowledge repository and platform, digitalization facilitated knowledge sharing and strengthened the cooperation between the PLC sub-phases. However, also challenges posed by digitalization, including but not limited to data security, large investments, and timely maintenance, need to be dealt with by the companies.

4.5.3 Main contributions

Publication V investigated knowledge sharing and knowledge reuse practices in different product lifecycle (PLC) phases (beginning-of-life [BOL], and middle-of-life [MOL]) and sub-phases (R&D, purchasing, and production in the BOL phase, and logistics, customer service, and sales in the MOL phase) from a PSS provider's perspective, and the impact of digitalization was also taken into account. The similarities and differences in knowledge management practices within and between BOL and MOL phases were identified in this study. In particular, this study investigated knowledge sharing from the knowledge sender's perspective and knowledge reuse from the knowledge receiver's perspective. Through this effort, Publication V extended the current knowledge management literature towards a more concrete, fine-grained understanding of knowledge sharing and knowledge reuse from the PLC perspective in the PSS context.

Based on the empirical findings, several guidelines for PSS providers were offered to facilitate better knowledge sharing and knowledge reuse in the digital era. First of all, the unique knowledge requirements in each product lifecycle (PLC) sub-phases should be clearly identified. Only the correct understanding of the knowledge requirements between the sender and the receiver will enable more efficient knowledge sharing and reuse between the different PLC phases and sub-phases. Secondly, a match should be made between the knowledge shared/sourced and the knowledge transfer mechanism used, and this is especially important for knowledge reuse. A variety of factors should be evaluated simultaneously but priority must be made based on the unique context. The factors include: knowledge and task characteristics, convenience of the mechanism, the sender's credibility, and the receiver's knowledge requirements, etc. Thirdly, it is important to create a culture/mechanism to retain competent employees in the company, and this is especially crucial in the digital age. Digitalization makes knowledge requirements broader and more in-depth, which thus leads greater requirements for the integration of multi-disciplinary knowledge. No matter how efficient knowledge sharing and knowledge reuse are in the company, it is still impossible to replicate a person's knowledge because of the tacit knowledge possessed. Therefore, competent people will be a crucial resource for the company. Fourthly, investment in knowledge management, such as building knowledge repositories and knowledge sharing platforms, should be strengthened whenever possible. In most of the companies studied, the development was based on incremental, rather than radical innovation, implying more knowledge reuse. As such, investment to facilitate knowledge sharing and reuse should be emphasized to facilitate knowledge sharing and reuse for future employees.

5 Discussion and conclusions

The focus of this thesis was on knowledge sharing and knowledge reuse strategies/practices in the product-service systems (PSS) context from a product lifecycle (PLC) perspective. By providing an integrated bundle of tangible products and intangible services, PSS has the potential to bring economic and ecological benefits. Transforming companies from being traditional manufacturers to PSS providers is not easy as the manufacturers need to collaborate with all the relevant stakeholders with different responsibilities throughout the entire product lifecycle (PLC). This indicates the requirements of integrating diverse knowledge, which inherently makes knowledge and its management ever more crucial and challenging. The two interrelated and inseparable knowledge management processes, i.e., knowledge sharing and knowledge reuse are considered to be more crucial in the PSS context due to their potential to overcome the rebound effects found in PSS. Based on this, the purpose of this thesis was to increase the understanding of knowledge sharing and knowledge reuse in the PSS context from a PLC perspective.

5.1 Answering the research questions

The main research question of this thesis was '*What are the knowledge management practices/strategies in (industrial) companies in the product-service systems context from a product lifecycle perspective in the digital era?*' Six sub research questions were defined to structure the research efforts and have been addressed through the findings of the individual publications. All the individual publications of the thesis played an important role to form the overall contribution of the thesis.

The first sub research question '*SQ1: What is the current state of empirical studies on PSS and what are the focuses of these studies?*' was answered by Publication I. Based on a systematic literature review of 70 peer-reviewed journal articles published between 2006 and 2016, Publication I confirmed that empirical PSS research has been in high demand in the past decade. With regards to the focuses of the empirical PSS studies, seven themes were identified based on the objectives and focuses of the studies, namely: the PSS design approach, approaches facilitating PSS design, PSS transformation drivers, the PSS status quo, PSS evaluation, PSS functions, and PSS impacts. Regarding the research method used, a qualitative case study was used by 84% of the studies, and about two thirds from them adopted a single case study method.

The status of PSS development could be summarized from three perspectives. First, being accepted as a research stream. The existing empirical PSS research shows that PSS had been widely accepted in academia as reflected by the distribution of journals with published articles, as well as being applied globally in practice as reflected by the geographic coverage of the publications. Second, from the evolution perspective, PSS research was found to be still in its early stages as more than half of the studies focused on product-oriented PSS. In addition, about 44% studies focused on PSS design. Thirdly, the concept has been researched in both developed and emerging economies. Empirical PSS studies were mostly from Europe (about two thirds of the studies) and Asia (about one fourth of the studies). In particular, more than forty percent of the studies in Asia were from China, indicating the emphasis of PSS research in the emerging economies. Publication I answered SQ1 and contributed to the PSS research by presenting a systematic literature review on empirical PSS studies. The review also provided considerations for future PSS research. More quantitative studies and multiple case studies should be done in the future to generalize and validate the existing findings. Additionally, researchers should focus on PSS as a system comprised of different stakeholders rather than a single entity. Thus, adopting a product lifecycle perspective and integrating different stakeholders' viewpoints would be valuable to enrich the PSS research.

The second sub research question '*SQ2: How does digitalization influence PLM in the PSS context when treating PLM as the implementation of a knowledge management strategy*?' was answered in Publication II. We analyzed 35 journal articles and conference papers published between 1999 and 2017 with the focus on product lifecycle management (PLM) strategies and digitalization in industry. It was found that from the data collection's perspective, digitalization enabled closed loop PLM by extending PLM to the entire product lifecycle (PLC) in practice. This way it facilitated access and reuse of more accurate and timely information and knowledge from different PLC phases and helped to improve product quality as well as enhance the firm's business opportunities (Herterich et al., 2015; Kiritsis, 2011; Terzi et al., 2010). The impacts of digitalization were different in the various PLC phases. During beginning-of-life (BOL) phase, digitalization enabled real time monitoring of the manufacturing process to enhance product and process development (Kuo and Wang, 2012; Patrick, 2008) and improve energy management (Tao et al, 2016), and facilitated reusing knowledge from the middle-of-life (MOL) phase to improve product design so that the time to market could be reduced (Affonso et al., 2013). During the MOL phase, digitalization could enable data collection from the communication and interaction between products and components (Lerch and Gotsch, 2015) to ensure the through-life performance and reduce the through-life cost through more efficient logistics and energy management (Främling et al., 2013), as well as predictive and preventive maintenance (Jun, Shin, Kim, Kiritsis, and Xirouchakis, 2009; Tao et al., 2016). During the end-of-life (EOL) phase, digitalization enabled the tracing, detecting, storing, and analyzing of the PLC data for each individual item. It could help to predict and estimate the quality and value of the end-of-use products, and consequently enhance the EOL decision-making and improve the EOL treatment performance (Chen, Yi, Zhu, Jiang, and Ju, 2017; Li et al, 2015). By answering SQ2, Publication II contributed to improving the current understanding of the impact of digitalization on PLM. From the knowledge management perspective, digitalization enhanced PLM by facilitating the knowledge exchange between various stakeholders throughout the entire PLC on the one hand, while on the other hand it brought challenges to knowledge management due to the various forms and huge volume of data generated and the security issues. Only with successful knowledge exchange, can the benefits of digitalization be achieved.

The third sub research question '*SQ3: What is the current state of the art of knowledge management practices in PSS from a PLC perspective?*' was answered in Publication III through a systematic literature review of 58 journal articles and conference papers published from 1995 to 2017. These findings indicated that research in this area has been increasing in recent years. Knowledge requirements differ according to product lifecycle (PLC) phases. In particular, R&D personnel, especially designers, had higher consideration of the product's lifecycle knowledge (Smith and Duffy, 2001), as well as the policies/regulations in different countries (i.e. Ongondo and Williams, 2001). Knowledge generated in a particular PLC phase could be used in different PLC phases with different focuses (i.e., Ahmed-Kristensen and Vianello, 2014). In addition, knowledge from the middle-of-life (MOL) phase seemed to be more crucial for use-oriented PSS (Roy et al., 2014). Although both codification and personalization strategies were adopted in knowledge sharing, person-to-person communication was still preferred by designers (Ahmed-Kristensen and Vianello, 2014). Moreover, MOL knowledge was mainly shared within MOL itself and with poor sharing between different PLC phases (Vianello and Ahmed, 2012). With regards to knowledge reuse, models/frameworks introduced at the beginning-of-life (BOL) phase were large in number and more comprehensive than models targeting the middle-of-life (MOL) or end-of-life (EOL) phases.

Through answering SQ3, Publication III contributed to knowledge management in PSS from the PLC perspective and provided propositions to both academia and practitioners. To academia, it proposed that (1) identifying and classifying the knowledge requirements of different stakeholders along the PLC phases would be important and valuable, and (2) investigating knowledge reuse in the middle-of-life (MOL) and beginning-of-life (BOL) phases would help to make the theory of knowledge management more comprehensive in the PSS context. To practitioners, the study proposed that (1) stakeholders in PSS contexts should provide knowledge in standardized forms and appropriate manners to fulfill the knowledge requirements in different PLC phases, thus facilitating knowledge sharing between different stakeholders or between different PLC phases, and (2) the adoption of personalization and codification strategies should be based on the unique context of the company itself rather than following any fixed ratio.

The fourth sub research question '*SQ4: What are the knowledge requirements, knowledge sharing and knowledge reuse strategies/practices in different PLC phases in the PSS context?*' was answered by Publication IV and V from different perspectives. Publication IV addressed this question from different stakeholders' perspectives (i.e., manufacturing companies and logistics companies). Manufacturing companies represented the beginning-of-life (BOL) phase (e.g., design sub-phase related to R&D) and logistics companies represented the middle-of-life (MOL) phase (e.g., distribution sub-phase related to external logistics). The authors found that the knowledge requirements were different for the BOL and MOL phases. Some knowledge (such as expertise) was used by all the companies but with different focuses, whereas some knowledge was only used in a particular product lifecycle (PLC) phase. For instance market knowledge was used only in the BOL phase and industry knowledge was only used in the MOL phase.

Knowledge sharing both within and beyond the company's boundaries (between the company and suppliers or customers) was important and necessary. In the BOL phase companies would not share knowledge with their competitors, but during the MOL phase, companies frequently shared knowledge with competitors to gain mutual benefits. Similarly, knowledge reuse was important and embedded in the daily work in both the BOL and MOL phases, and it was reported by some companies as a principle in the daily work in BOL phase. It should be noted that based on the company's innovation strategy, i.e., whether it is more radically oriented or incrementally oriented, the emphasis on the reuse of existing knowledge or new knowledge application was different, thus a balance was needed. With regards to knowledge transfer mechanisms, the most commonly adopted knowledge sharing mechanism was training in both the BOL and MOL phases, whereas job rotation and social media were used in the MOL phase only. Regarding knowledge seeking mechanisms, during the BOL phase expertise was acquired through learning-by-doing and person-to-person communication was preferred, whereas during the MOL phase such knowledge was acquired from the government and participating in meetings organized by the government was preferred.

By answering SQ4, Publication IV shed light on PSS research by investigating the similarities and differences in knowledge management practices in the PSS context from different stakeholders' perspectives and from a product lifecycle (PLC) perspective, and enhanced the understanding of knowledge management in manufacturing firms (i.e., representing the beginning-of-life [BOL] phase) by investigating knowledge management practices in logistics companies (i.e., representing the middle-of-life [MOL] phase) in the PSS context.

Publication V addressed SQ4 from PSS provider's (i.e., manufacturing company's) perspectives by considering both the BOL (i.e., R&D, purchasing, and production) and the MOL (i.e., logistics, customer service, and sales) phases. Through the case studies, we found that process/procedure knowledge was used frequently in all product lifecycle (PLC) sub-phases, indicating the necessity for standardization and systemization in the work. The focuses for the same types of knowledge were different based on particular job positions and responsibilities. Expertise and process/procedure knowledge were considered equally important in all PLC sub-phases. In contrast, other types knowledge had varying importance in the different sub-phases. Some knowledge was only used in the BOL phase (i.e., production knowledge and supplier knowledge).

With regards to knowledge sharing, the scope and degree were different in different PLC sub-phases, both within and outside the company. The authors found that the R&D sub-phase shared knowledge with all other sub-phases except logistics, while the other two BOL sub-phases mainly shared knowledge within the BOL phase. The three sub-phases of the MOL phase (i.e., logistics, customer service, and sales) mostly shared knowledge with the BOL phase, rather than sharing it within the MOL phase. The knowledge seeking scope of knowledge reuse was similar to that of knowledge sharing. R&D seemed to be the most important sub-phase as the knowledge from R&D was acquired and reused in all the other sub-phases. With regard to knowledge transfer mechanisms, mentor was the one that only used within the same sub-phase, and job rotation and social media were unique mechanisms in logistics sub-phase. In addition, the person-to-person mechanism was preferred in all the sub-phases, even though a knowledge repository existed in all the studied companies. Factors affecting the mechanism selection for both knowledge sharing and knowledge seeking (for reuse) were the knowledge involved, the importance/urgency level of the task, and the convenience of the mechanism. However, the characteristics of the job position affected the mechanism selection for knowledge sharing, whereas the possibility to obtain the knowledge affected the mechanism selection for knowledge seeking. By answering SQ4, Publication V extended the current knowledge management literature towards a more concrete, fine-grained understanding of knowledge sharing and knowledge reuse from a PLC perspective in the PSS context.

The fifth sub research question '*SQ5: What are the enablers and barriers to knowledge sharing and knowledge reuse in different PLC phases in the PSS context?*' was answered by Publications IV and V. From both publications, it was found that the ability of the sender, top management support and the sharing/learning culture were the most important facilitating factors for knowledge sharing, while confidentiality and non-relevance were the most prohibiting factors. Knowledge will not be shared if it breaches confidential limits or if the sender perceives it as irrelevant to the potential receiver. For knowledge seeking (for reuse), the most influencing factors were the usefulness of the knowledge and the credibility of the knowledge source (sender) for both the beginning-of-life (BOL) and middle-of-life (MOL) phases. In addition, familiarity with the knowledge was indicated for the R&D sub-phase as an important influencing factor, while standardization of the knowledge influenced knowledge reuse in the MOL phase.

The sixth sub research question '*SQ6: How does digitalization influence the above-mentioned requirements, strategies/practices, and enablers/barriers in the above-mentioned context?*' was answered by Publication IV and V. Both publications clearly indicated the benefits brought by digitalization, such as allowing more efficient and accurate feedback and tracing, promoting international cooperation, reducing time/money cost, reducing the workload, enabling more convenient data access and faster data analysis, providing better guidance for decision-making, and creating a better business environment. With regards to the knowledge requirements, the range of knowledge required became broader and cross-disciplinary knowledge became more important, which naturally increased the importance of knowledge integration as well as highly competent personnel. Documenting and archiving knowledge became easier with the help of standardization facilitated by digitalization, which essentially positively impacted knowledge sharing and reuse, for example, by providing a comprehensive knowledge repository and convenient knowledge sharing platform. Digitalization called for more knowledge reuse because of the requirement for more cross-disciplinary knowledge. At the same time, digitalization facilitated knowledge reuse due to its ability to reduce the money and time cost of the reuse, which finally led to faster new product development. Along with the benefits, digitalization brought challenges as well, such as issues related to data security, the large investments needed, and timely maintenance requirements.

The combined contribution of the five individual publications was related to the main research question: '*What are the knowledge management practices/strategies in (industrial) companies in the product-service systems context from a product lifecycle perspective in the digital era?*'. This constitutes the main contribution of this thesis from both theoretical and practical perspectives and will be elaborated in detail in the next section.

5.2 Contribution

This section discusses the theoretical contributions and managerial implications of the thesis. As the main theoretical background of this thesis lies in the research streams of product-service systems and knowledge management, the main contribution comes from these streams. These contributions are summarized in Table 13 and discussed in detail in the following sections.

Table 13. Contribution of the thesis

Research gap	Contribution of the thesis	Publication
Limited number of empirical PSS studies and no literature review focused on this area.	▪ This thesis contributes to PSS development by complementing the existing PSS review studies through a systematic literature review specifically focusing on empirical PSS studies. ▪ This thesis enriched the empirical PSS studies by investigating knowledge sharing and knowledge reuse practice/strategies in the PSS context, thus answers the call by Qu et al., (2016) for research to seek empirical knowledge management practices in PSS operations.	All publications
Incomprehensive understanding of the impact of digitalization on PLM in PSS context.	▪ This thesis reviewed the impact of digitalization on PLM for manufacturing companies in the PSS context by treating PLM as the implementation case of a knowledge management strategy. ▪ Digitalization was found to facilitate PLM by promoting the information exchange between the stakeholders throughout the entire PLC from the knowledge management perspective.	II
Lack of knowledge management studies in PSS from PLC perspective.	▪ This thesis extended the current knowledge management literature towards a more concrete, fine-grained understanding of knowledge sharing and knowledge reuse in the PSS context from a PLC perspective. ▪ The current study investigated knowledge sharing and knowledge reuse together and distinguished them by focusing on knowledge sharing from the knowledge sender's perspective and knowledge reuse from the knowledge receiver's perspective. ▪ Empirical investigation of knowledge sharing and reuse practices in different PLC phases and sub-phases brings clarity to the managerial implications of knowledge management in the PSS context.	III, IV, and V

	▪ The standardization and systemization of work was found to be important in all PLC sub-phases to guarantee the quality of work. ▪ This study enhanced the understanding of the influencing factors surrounding knowledge sharing and knowledge reuse by separating people-related factors (i.e., summarized in the MAO framework) and mechanism-selection-related factors (i.e., explained by the TAM).	
Challenges exist in finding suitable ways to make digitalization play a greater role in knowledge management.	This thesis investigated the impact of digitalization on knowledge requirements, knowledge sharing and knowledge reuse in different PLC phases in the PSS context empirically. It was found that: ▪ More knowledge reuse will be required in the future due to digitalization. ▪ Digitalization facilitated standardization thus made it easier to document and archive knowledge. ▪ Digitalization facilitated codified knowledge sharing and reuse by providing comprehensive knowledge repositories and convenient knowledge sharing platforms. ▪ Digitalization made knowledge reuse easier by reducing the associated money and time cost. ▪ Digitalization may not always facilitate knowledge sharing and knowledge reuse as person-to-person mechanisms were still preferred in the company. To deal with the challenges related to data security, large investments, and timely maintenance, the thesis suggested that the company should: ▪ Using both personalization and codification strategies to ensuring the right knowledge can be transferred to the right people. ▪ Emphasize the importance of competent people/personnel. ▪ Advocate standardization within and beyond the manufacturing firm’s boundaries. ▪ Invest not only on monetary rewards and staff training, but also on items such as knowledge repositories, knowledge sharing/reuse platforms, and data management.	II, IV, V

5.2.1 Theoretical contributions

Considering the lack of empirical studies, especially knowledge management related studies in the PSS context, this study investigated knowledge sharing and knowledge reuse strategies/practices in a product-service systems context from a product lifecycle perspective in the digital era.

Firstly, this thesis contributes to product-service systems (PSS) development by complementing the existing PSS review studies (i.e., Baines et al., 2007; Boehm and Thomas, 2013; Kjaer et al., 2016; Lightfoot et al., 2013; Nudurupati et al., 2016; Qu et al., 2016; Reim et al., 2015; Tukker, 2015; Tukker and Tischner, 2006; Vasantha et al., 2012). The systematic literature review in this dissertation specifically focusing on empirical PSS studies, thus contributes to PSS development by providing possible directions or considerations for future empirical PSS research. From the perspective of research methodology, increasing the number of quantitative PSS studies would be suggested to help to generalize and validate the findings because most of the existing empirical PSS studies were qualitative in nature. More specifically, single-case study was the dominating research approach. With regards to the research scope or the unit of analysis, researchers should focus on PSS as a system comprising of various stakeholders rather than a single entity. Relating to the system, a lifecycle perspective is crucial in the PSS context. However, only a very limited number of the existing empirical PSS studies took this into account. Therefore, future PSS research should think about the product lifecycle perspective and integrate the viewpoints of different stakeholders.

Secondly, this thesis enriched the empirical PSS studies by investigating knowledge sharing and knowledge reuse practice/strategies in the PSS context, thus answers the call by Qu et al., (2016) for research to seek empirical knowledge management practices in PSS operations. Conducting empirical case studies from different stakeholders' perspectives (that is, the PSS provider, manufacturing company, and the related logistics company) and from product lifecycle (PLC) perspective (that is, considering the beginning-of-life [BOL] phase, and the middle-of-life phase [MOL]), this thesis figured out the similarities and differences of knowledge sharing and knowledge reuse practice/strategies and the corresponding mechanisms in different PLC phases (i.e., BOL and MOL). In addition, it enhanced the understanding of knowledge sharing and knowledge reuse in manufacturing firms (BOL) by investigating knowledge management practices in logistics companies (MOL) simultaneously.

Thirdly, this dissertation extended the current knowledge management literature towards a more concrete, fine-grained understanding of knowledge sharing and knowledge reuse. As two interrelated and inseparable knowledge management processes, knowledge sharing and knowledge reuse are related to different focuses and needs (Kankanhalli et al., 2005; Watson and Hewett, 2006). However, little research has been conducted to study both knowledge sharing and reuse systematically (He and Wei, 2009). The current study not only investigated knowledge sharing and knowledge reuse together in the PSS context, but also distinguished them by focusing on knowledge sharing from the knowledge sender's perspective and knowledge reuse from the knowledge receiver's perspective. In addition, knowledge sharing and knowledge reuse are crucial in the PSS context as they can be used to overcome the rebound effects from the prolonged product life in PSS (Chierici and Copani, 2016; Goh and McMahon, 2009). The limited number of existing empirical studies on knowledge sharing and reuse in the PSS context were mainly focused on knowledge sharing and reuse during the BOL phase and with limited attention paid to the MOL phase (Baxter et al., 2009; Cai et al., 2014; Durst and

Evangelista, 2018). By investigating knowledge sharing and knowledge reuse practices in different product lifecycle (PLC) phases (the BOL and MOL phases) and sub-phases (R&D, purchasing, and production in BOL, and logistics, customer service, and sales in MOL) from the PSS provider's perspective, this thesis brings clarity to the managerial implications of knowledge management in the PSS context.

The standardization and systemization of work was found to be important in all PLC sub-phases to guarantee the quality of work. Most of the extant studies have focused on the importance and usefulness of using MOL knowledge in the BOL phase for current product improvement and future new product design (i.e., Hassanain et al., 2014; Igba et al., 2015; Roy et al., 2014). However, the current study indicated that seeking and reusing knowledge from the BOL phase, especially from the R&D sub-phase, was a prevalent phenomenon in both the BOL and MOL phases to increase the efficiency of work. With regards to knowledge sharing, the MOL phase was found to share knowledge mainly within MOL phase itself and there was poor sharing of knowledge with BOL phase in the case of oil industry (Vianello and Ahmed, 2012). However, the current study found that except for R&D sub-phase, the BOL phase mainly shared knowledge within the BOL phase itself and rarely shared knowledge with MOL phase. In contrast, the MOL phase mainly shared knowledge with the BOL phase, rather than sharing knowledge within the MOL phase itself, which contradicts the existing literature. This can be explained by the fact that the actors within the BOL sub-phases need to cooperate closely with each other to ensure that production is completed on time and to quality standards, whereas the responsibilities of each MOL sub-phase were relatively independent and they cooperated with BOL phase to smooth the operation of the company.

Fourthly, this study enhanced the understanding of the influencing factors surrounding knowledge sharing and knowledge reuse. Although certain motivators have similar impacts on both knowledge sharing (from the knowledge sender's perspective) and knowledge reuse (especially knowledge seeking from the knowledge recipient's perspective), such as the positive impact of trust and the negative impact of the effort required, there are different motivations for knowledge sharing and seeking as well (He and Wei, 2009). This thesis investigated the influencing factors of knowledge sharing and knowledge reuse by separating people-related factors (i.e., summarized in the Motivation-Ability-Opportunity framework [MAO]) and mechanism-selection-related factors (i.e., explained by the Technology Acceptance Model [TAM]). With regards to people-related factors: (1) For the motivation related factors, this study found that knowledge sharing was facilitated by intrinsic motivation, such as self-efficacy, which was consistent with the literature (Wasko and Faraj, 2000), but not significantly affected by extrinsic motivation. (2) For the ability related factors, this study found that knowledge sharing was facilitated by the knowledge sender's disseminative capacity and knowledge reuse (especially knowledge seeking) was highly influenced by the recipient's absorptive capacity, which was consistent with the existing literature (i.e., Parent et al., 2007; Reagans and McEvily, 2003). This impact was more significant for the personnel in R&D departments in the current research settings. (3) For the opportunity related factors, a learning culture in the company was found to facilitate knowledge sharing and reuse, which was consistent with the literature (Mueller, 2014). In particular, top management support was very important to motivate knowledge sharing in the company. With regards to the mechanism selection related factors: (1) Perceived usefulness affected the mechanism selection for both knowledge sharing and knowledge reuse. For instance, mentor (with a high degree of richness) was used within each product lifecycle sub-phase, and social media (high reach) was popularly used in the MOL phase, especially in the logistics sub-phase. (2) The impact of the perceived ease of use on mechanism selection was significant for both knowledge sharing and knowledge reuse. For instance, social media was used frequently in the logistics sub-phase because it was convenient and easy to use, as well as very fast. In addition, this study found that person-to-person mechanisms were still preferred in the company, especially in the R&D sub-phase. This to some extent reflectes that digitalization may not always facilitate knowledge sharing and knowledge reuse (Vuori et al., 2019).

Lastly, this thesis contributed to the knowledge management and PSS literature by investigating the impact of digitalization on knowledge management in the PSS context. Treating product lifecycle management (PLM) as the implementation case of a knowledge management strategy, this thesis reviewed the impact of digitalization on PLM for manufacturing companies in the PSS context. From the knowledge management perspective, although the impacts of digitalization were different during the various PLC phases, digitalization was found to facilitate PLM by promoting the information exchange between the stakeholders throughout the entire product lifecycle (PLC) (Herterich et al., 2015; Kiritsis, 2011). At the same time, digitalization brought challenges to knowledge management due to the various forms of data generated, the huge volume of data created, and the security issues. The benefits of digitalization cannot be achieved without successful knowledge exchange. Empirically, this thesis investigated the impact of digitalization on knowledge requirements, knowledge sharing and knowledge reuse in different product lifecycle (PLC) phases in the PSS context. It was found that digitalization facilitated standardization, which made documenting and archiving of knowledge easier. By providing a comprehensive knowledge repository and convenient knowledge sharing platform, digitalization facilitated codified knowledge sharing and reuse. Digitalization made knowledge reuse easier by reducing the associated money and time cost, and thus accelerated new product development. In addition, digitalization will require more knowledge reuse in the future because of the requirement for more cross-disciplinary knowledge in the digital era. Along with the benefits, digitalization brought challenges as well, including issues related to data security, large investments, and timely maintenance.

5.2.2 Managerial implications

Based on the findings about the current status of knowledge sharing and knowledge reuse practices/strategies in the interviewed companies, this study proposed several guidelines for PSS providers to facilitate knowledge sharing and knowledge reuse and remain competitive in the digital era.

Firstly, it is essential to identify the knowledge requirements in different PLC phases and sub-phases. Different types of knowledge were required in the different PLC phases and sub-phases, and with different focuses. Except for expertise and process/procedure knowledge, which were equally important throughout the entire PLC, the importance of other types of knowledge were not the same in different PLC phases. In addition, with the transition of the company from selling products (as a traditional manufacturer) to selling solutions (as a PSS provider), the importance of different types of knowledge changed accordingly. To facilitate knowledge sharing and knowledge reuse, the specific knowledge requirements in each PLC sub-phases should be identified, including the types, focuses and importance of knowledge required. By doing so, a correct understanding of the knowledge requirements will exist between both the sender and receiver, thus ensuring the right knowledge can be transferred to the right people. This can be achieved by using both personalization and codification strategies. Codification facilitates standardization, and thus reduces confusion about the meaning of the knowledge. Personalization, such as training, especially training organized by other functional departments, enables awareness of the knowledge requirements in other departments.

Secondly, it is important to advocate standardization. In the PSS context, products are dealt with within and beyond the manufacturing firm's boundaries and processed by different stakeholders. In addition, the volumes and forms of data are increasing significantly with the development of digitalization. From the manufacturing company's perspective, within the company it is important to provide standardized data (i.e., input data) and standardized archiving of documents so that the knowledge can be shared and reused between different departments with minimum confusion or misunderstanding; whereas beyond the company's boundaries, it is important to provide industry-recognized data and interfaces so that the relevant stakeholders can use and analyze the data from various domains. From a broader or higher perspective, the company should promote industry standards as only a widely recognized standard that every company must follow will realize smooth knowledge exchange in the PSS context.

Thirdly, it is critical to emphasize the importance of competent people/personnel. No matter how advanced the technology is, people are always indispensable, because the process is managed, controlled, implemented and realized by people. The development of digitalization has changed customer needs and even generated new ones. Within the same discipline/domain, the requirements for knowledge have become more in-depth, whereas cross-domain or even cross-industry customer needs require possible multi-disciplinary knowledge integration. The latter is much more complicated than in-depth knowledge in the same discipline. The competence or ability of people will affect knowledge sharing and reuse intentions and results, which to some extent depend on the disseminative capacity of the sender and the absorptive capacity of the receiver. In addition, even if the company has excellent processes/procedures and a standardized knowledge repository, it is still difficult to fully replicate an individual's knowledge due to the important tacit knowledge possessed by that person. Therefore, on the one hand, it is crucial for the company to recognize and emphasize the importance of highly competent personnel, which can be achieved through means such as higher recruitment requirements for new employees and by continuously organizing training. On the other hand, it is important for the company to create a culture/mechanism to retain competent employees in the company, which could be realized through means such as more appropriate performance evaluation and rewarding systems, improved task design, etc.

Fourthly, it is necessary to strengthen external collaboration. In the PSS context, it is impossible for a single company to provide a complete product-service offering to the customer, thus collaboration with other companies is essential. Long-term collaboration could motivate more knowledge exchange due to the accumulated reciprocal benefits, which has been demonstrated in various collaborations between manufacturing companies and their suppliers. For instance, the knowledge or innovation from a supplier could accelerate a manufacturing company's R&D process, while the knowledge from the manufacturing company could guide the R&D and production direction of the supplier. In addition, collaborating with external companies which have specialized in complementary domains could potentially generate cross-domain and cross-industry ideas to meet customers' needs through the reuse of external knowledge, which is one way to remain competitive in the ever-changing environment.

Fifthly, it is important match the knowledge shared/sourced and the mechanism used. An appropriate mechanism should not only enhance the efficacy of knowledge sharing and reuse, but also encourage people to share and reuse knowledge. To realize this, the job position, the knowledge characteristics, the task characteristics, the sender's credibility, the receiver's knowledge requirements, and the convenience of the mechanism should be considered simultaneously but the priority should be based on different contexts. For instance, if multi-department cooperation is required to solve an urgent problem, the most efficient mechanism will be to hold a meeting, no matter whether it is face-to-face or virtual, so that rich knowledge can be shared and discussed instantly. If an urgent problem can be solved by cooperation between two parties, a phone call plus digital flow (in the digital systems) would be more convenient and economical. If the matter is not urgent but focuses on in-depth and tacit knowledge transfer, mentor may be preferred.

Sixthly, but not lastly, it is important and necessary to invest. The benefits of knowledge management, digitalization, and PSS are not free. Capable personnel who are willing to share and reuse knowledge are a prerequisite for successful knowledge sharing and reuse. To fulfill knowledge sharing and reuse, the company must provide opportunities for employees to share and reuse knowledge, which involves various investments of the company. Due to the shorter PLC of the current physical products, more knowledge reuse will be required because incremental innovation will be preferred, and knowledge reuse could speed up the R&D and production processes as well as reduce costs. As such, investments in items such as knowledge repositories, knowledge sharing/reuse platforms, and data management systems will be necessary. With digitalization, the security related issues such as confidentiality, integrity, and data availability throughout the entire PLC have to be addressed to make sure that only authorized parties can access the data in an appropriate manner when needed. As such, investment in data protection is important and necessary, including but not limited to hardware, software, and personnel.

5.3 Limitation and suggestions for future research

Some limitations should be considered when interpreting the results of this study, which provides avenues for future research. First, the empirical data was collected from companies operating in China by interviewing the managers or senior staff in the department or in the company. Limiting the sample to the Chinese context may present limitations, because the environmental factors, which could to some extent represent opportunities in the Motivation-Ability-Opportunity framework, are not the same in different countries, for instance the development of digitalization. The influencing factors of knowledge sharing and reuse in one context may not be applicable to other contexts. However, this specific context can still provide fruitful insights as PSS related research has been increasing in China in the past decades (i.e., Tukker, 2015) and both industry and academia in China have been aware of the importance of PSS. Nonetheless, extending this research to other countries could enhance the generalizability of the results. Therefore, it will be meaningful to conduct studies in other countries, especially in developed countries, to compare the results with those from the emerging economy.

Secondly, the interviewees in this study were mostly managerial staff who were familiar with knowledge management strategies/practices in the departments and in the company, which also implies that their viewpoints would be different from general employees. Management support facilitates knowledge sharing and knowledge reuse, but knowledge sharing and reuse practices are fulfilled mostly by the general employees. Therefore, further study collecting data from different levels of employees in the same department would be valuable to make the results more comprehensive. In addition, choosing several informants in the same departments would increase the credibility in interpreting the results.

Thirdly, the companies interviewed in this study were from different industries but limited in number, which made it impossible to compare the difference between industries. Although the focus of this study is knowledge management in different product lifecycle phases rather than in different industries, it must be admitted that the focuses of knowledge management vary in different industries. For instance, a high-tech company may be more focused on new knowledge creation and may reuse internal and external knowledge for idea generation, whereas a mass consumer products oriented company may be more focused on reusing knowledge to improve production efficiency. This different focuses on knowledge management may have different influencing factors for knowledge sharing and knowledge reuse even in the same PLC phase. Therefore, further research extending the study into a particular industry and conducting interviews in several companies in that industry would enhance the credibility of the results. Additionally, extending the study to different industries to compare the results would enhance the generalizability of the findings.

Fourthly, due to time and resource constraints, only the beginning-of-life (BOL) and middle-of-life (MOL) phases in the product lifecycle (PLC) were considered in this study, without any specific concern for the end-of-life (EOL) phase. To realize ecological sustainability in PSS, the EOL phase is indispensable. Digitalization enables tracking and accessing data throughout the entire PLC, which makes knowledge sharing and knowledge reuse in the EOL phase more valuable than before. With increasing requirements for sustainability, it is thus meaningful and important to extend the current study into the EOL phase, thus investigating knowledge sharing and reuse throughout the entire PLC. It is believed that such findings could provide more guidelines to enhance knowledge sharing and knowledge reuse practices throughout the entire PLC.

Fifthly, there are limitations related to the research methodologies adopted in this study. The empirical data of this thesis was collected mainly through case studies following a qualitative research methodology. The objective of this study was to explore knowledge sharing and knowledge reuse strategies/practice in different PLC phases and to provide suggestions to enhance knowledge sharing and reuse, rather than theory building or hypothesis testing. Even though a qualitative research approach was considered to be most suitable for investigating the current topic, the utilization of alternative approaches could have been useful. For instance, surveying a large sample size of companies about the influencing factors of knowledge sharing and knowledge reuse might have generated a more systematic framework to guide practitioners in their knowledge management practices. Therefore, a quantitative study could be conducted in the future to obtain more testable and systematic guidelines for knowledge sharing and knowledge reuse.

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Empirical Studies on Product-Service Systems – A Systematic Literature Review

Yan Xin*, Ville Ojanen, Janne Huiskonen

Lappeenranta University of Technology, Skinnarilankatu 34, 53850 Lappeenranta, Finland

*Corresponding author Tel.: +358 29 44 64040; *E-mail address:* yan.xin@lut.fi

Abstract

The aim of this paper is to increase the understanding of empirical PSS research, and provide insights for future directions in PSS research. Based on an in-depth systematic literature review of 70 journal articles, it was found that PSS practices have been widely applied across various geographical and research areas. The majority of empirical research employed qualitative research method while large scale quantitative studies are still scarce. In addition, a large portion of product-oriented PSS studies demonstrate that PSS is still in its early development stage in terms of evolution. With regard to research themes, PSS design related studies are the focus of more than 40% studies.

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Keywords: Product-service systems; Literature review; Empirical studies

1. Introduction

The rising global population, accelerating technological development, increasing resource usage and intensifying environmental impacts make sustainability as the key issue for the entire society. With such a trend, product-service systems (PSS) have become an emerging issue in both academia and industry. As an 'integrated bundle of products and services which aims at creating customer utility and generating value' [1], PSS is one of the most effective instruments that moves society towards sustainability [2]. According to its evolution, the classical categorization of PSS includes product-oriented PSS, use-oriented PSS, and result-oriented PSS [3].

Since the clarifying of the PSS concept [4], PSS research have been reviewed by many scholars from different perspectives, including the establishment of key PSS domains [3], overview of the PSS design methodologies [5], contribution of knowledge production to PSS [6], and supporting framework for product-, use- and result-oriented business models [7]. PSS in different fields such as Information Systems, Business Management, and Engineering & Design [1] and special geographic area such as EU [8] have been reviewed as well. In addition, especially through lifecycle assessment, the challenges when evaluating PSS have been identified [9]. In summary, PSS research has progressed well [2] and PSS design seems to be still in its initial stages of development [5].

Similar to other theories, the real world PSS practices are important. However, none of the existing review papers specially focused on empirical studies in PSS. As empirical studies in PSS is still limited [10], and a better understanding of the existing studies will shed light on the future direction and contribute to PSS development. Therefore, this paper aims to present a systematic literature review (LR) about empirical PSS research in the existing publications, and thus provide an overview to the development routes of PSS research.

In section 2, we will describe the search strategy and present the descriptive analysis. The detailed review results based on the categorization of product-, use-, result-oriented PSS and others will be presented in section 3, and concluded with future directions in section 4.

2. Search strategy and descriptive analysis

Considering the aim, we limited the language to English and the search strings to 'product service system*', 'product-service system*', 'empirical*', 'operation*', and 'appl*' to identify journal articles published between 1995 and 2016 using online database Scopus. The initial 357 articles were then filtered on the basis of titles and abstracts, and reduced to 70 articles. As we focus on real world empirical studies, those articles with hypothesized, exemplar, or simulated cases were not included. These 70 articles were downloaded and analyzed in terms of the research objectives, methodologies, application status and findings. As no relevant articles were found before 2006, the main body of this systematic review comprises 70 peer-reviewed journal articles published from 2006 to 2016.

Figure 1 shows the distribution of publications over year. It shows that the majority of the papers were published since 2012 or later, which accounts for about 80% of all the papers reviewed. This may be due to the well processing of PSS development and the calling for empirical research [2].

Fig.1.Distribution of publications over year

The distribution of the articles by journal shows that the empirical studies in PSS are scattered across 33 journals, which demonstrates the wide acceptance of PSS. 14 journals with at least 2 articles in our review are listed in Table 1, and cover 73% of the articles. The Journal of Cleaner Production is the leading source with 11 articles, followed by Journal of Manufacturing Technology Management, International Journal of Operations and Production Management, and International Journal of Production Research.

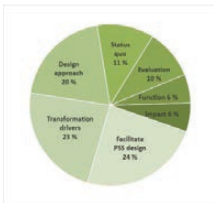
Table 1 Journals with at least two articles in the review

Journal	Numer of articles
Journal of Cleaner Production	11
Journal of Manufacturing Technology Management	6
International Journal of Operations and Production Management	5
International Journal of Production Research	5
CIRP Journal of Manufacturing Science and Technology	4
Business Process Management Journal	3
Expert Systems with Applications	3
CIRP Annals - Manufacturing Technology	2
Computers in Industry	2
Journal of Intelligent Manufacturing	2
Mathematical Problems in Engineering	2
Production Planning and Control	2
Service Industries Journal	2
Sustainability	2

With regard to the methodology used, qualitative case study approach dominates with 59 articles (accounts for 84% of all the papers), followed by quantitative surveys with 6 papers. The remaining 5 papers employed a combination of both methods. In addition, single case study articles account for 64% of the case study research (38 papers). This confirms that most of the existing literature on PSS were based on case studies and application of survey or large number of cases was scarce [2, 10].

Linking to the categorization of PSS, 36 articles fall into product-oriented PSS (51%), 12 articles fall into use-oriented PSS (17%), 16 articles fall into result-oriented PSS (23%), and the remaining 6 papers are mix, or specifically indicated by the authors as service-oriented. To some extent, the results indicate PSS is still in its early stage in terms of evolution.

Based on the aims and focuses of the papers reviewed, we divided them into 7 themes (Figure 2a) as PSS design approach, approaches facilitating PSS design, PSS transformation drivers (factors and approaches that initiate the product-service transition), PSS status quo, PSS evaluation, PSS function (extension or application of PSS concept), and PSS impact (including economic, environmental, and social impacts). Articles related to PSS design account for 44% of all the articles. This is not surprising as the design of a new PSS is one of the most challenging tasks for companies due to its rare existence in the market.



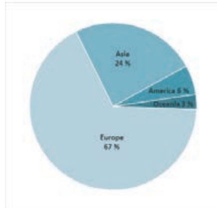


Fig. 2. Themes in the LR Fig. 2b. Distribution of publications over area

As normally the first author organizes the research, we identified the distribution of publications over area by analyzing the first author's affiliation (Figure 2b). European studies (including UK) dominate with 47 articles (67%), followed by Asia with 17 articles (24%). America and Oceania contribute to the remaining 6 articles. It should be noted that there is only one paper first authored by a researcher in US, indicating a lack of attention to PSS practice in US. For the studies in Europe, researchers in UK, North Europe, and Germany altogether contribute to 80% of the papers. In particular, studies in UK focus more on PSS transformation drivers (8 papers, about 44% of UK studies). For the 17 articles in Asia, the top three contributors are China (7 articles, 41%), Japan (18%), and Taiwan (18%). In particular, the studies in China focus on approaches facilitate PSS design (71% of the papers in China).

3. Empirical PSS studies

3.1. Empirical product-oriented PSS studies

In this LR, 36 papers belong to product-oriented PSS, and the top three themes involved are PSS transformation drivers (12 articles, 33%), approaches facilitating PSS design (10 articles), and PSS design approach (5 articles). We will discuss the findings in detail in terms of the research themes.

Under the 'PSS transformation drivers' theme, the transfer of PSS concept from academia to industry was more likely to be completed in the firms which had already used the service type of transaction and built the requisite capability to support this [11]. Limiting the uncertainty and complexity in service operations, realizing scale and pooling effects, deploying multi-purpose resources, using installed base data, and surpassing functional barriers were the strategic guidelines towards successful PSS [12]. In addition, PSS innovation capabilities should be developed through progression of routines over early PSS development stages [13]. Critical challenges have also been identified, such as embedded product-service culture, delivery of integrated offering, internal processes and capabilities, strategic alignment, supplier relationships [14]. Based on empirical results, useful frameworks facilitating the transition of PSS implementation and operation have been provided [15, 16]. With regard to activities that affect PSS transformation, the importance of co-design [17], tailored pricing scheme [18], having continuous feedback information [19], and appropriate operation configuration [20] have been addressed. Human resource [21] and facilities practices [22] were quite different from manufacturing firms thus should be considered with care.

Among our 10 reviewed articles about ‘approaches facilitating PSS design’ in product-oriented PSS, 60% focused on early PSS stages. Some approaches were from lifecycle perspective to enhance the designers’ awareness of the value contribution in PSS preliminary design [23], help designers to know how to adapt their future products used in PSS in a more beneficial way [24], and elicit and assess the customer’ requirements under vagueness in the early development PSS [25]. For sustainable PSS, the approach making the initial stage of searching for opportunities more productive and guided proved to be effective [26]. To increase the quality of early design decisions, web 2.0 tools can help to overcome knowledge sharing barriers between complex and cross-functional design teams [27], and an Internet of Things (IoT) enabled PSS adoption method could identify what should be monitored in the product in the early phase and assist the company in deciding which PSS strategy to be followed [28]. Approaches were also introduced to facilitate other PSS design stages. From strategy, tactic and support level, an integrative innovation management framework could ensure each stakeholder’s knowledge and expertise be shared among the network to lower the innovation cost and facilitate PSS design [29]. A Service Engineering Methodology can identify possible PSS solutions, as well as address the complexity of the performance of the service delivery of PSS offerings [30]. A mathematical PSS maintenance strategy model using multi-attribute utility theory enabled firms to achieve optimal efficiency in management model transformations [31]. A hybrid fuzzy methodology could evaluate the uncertainty of transitions from product-focused operations towards service-oriented operations and aid decision making [32].

A variety of ‘PSS design approaches’ addressing different aspects have been proposed. For instance, a Product-Service (PS) offerings classification model integrating business and green offerings could enable better design or re-design of PS business models, especially during the creation of PS offering’s portfolio [33], a service network design approach provided guidance for organizations to redesign dispersed networks for integrated PS delivery [34], a three-phase model collaborating research and stakeholder integration into PSS development contributed to knowledge about how to design, research and develop PSS, especially considering socio-ecological sustainability [35], and a product, service and organization framework could guide to create value for even more complex PSS design [36]. In addition to design method, marketing-oriented method was integrated as well to get feasible PSS solutions [37].

With regard to ‘PSS function’, PSS concept can be extended to create a new business model to transform, elevate, and revitalize traditional manufacturing industry so that manufacturers were more specialized in producing products and components while sharing and outsourcing manufacturing-oriented services from a service provider [38]. Providing a better analysis of the key criteria in measuring business performance, PSS concept can also be used to achieve customer satisfaction [39].

The ‘PSS evaluation’ models proposed to evaluate then compare the value of various potential PSS offerings had different focuses, e.g. focusing on customer value [40], on both customer and organization value [41], and on the value comparison with traditional business concept [42]. Only for evaluation, a maturity model was used to evaluate the maturity of new service development processes [43].

Under ‘PSS status quo’, in terms of model application, different function models proposed in the literature were interlinked insufficiently in mechatronic manufacturing firms [44]. However, a correct approach in the new PSS development process definition and the application of some tools of the existing methods were found to contribute to PSS for oil and gas equipment manufacturers [45]. In terms of value attributes, PSS companies in different regions had different value attributes [46].

3.2. Empirical use-oriented PSS studies

Empirical studies in use-oriented PSS were related to PSS design approaches (4 papers, about 33%), PSS status quo (3 papers), PSS evaluation (2 papers), PSS impact (2 papers), and approaches facilitating PSS design (1 paper).

Four PSS design approaches were introduced. A knowledge-based PSS design method could support the designers’ creation of design solutions by integrating knowledge accumulated in a knowledge base [47]. A four-step practical engineering method could enable effective human resources allocation in the PSS design process [48]. A product service supply chains (PSSC) model integrated the PSSC with multiple service concepts in a single service system to manage and coordinate PSSC [49]. Taking lifecycle into account, a multi-objective mathematical model could simultaneously optimize service decisions and end of life options by considering their environmental and economic impacts [50].

Under ‘PSS status quo’ considering PSS acceptance, bike sharing systems in China were widely accepted by commuters, urban dwellers and played multiple roles [51]. However, rental consumption, another type of use-oriented PSS, was not widely accepted by Taiwanese consumers because they were worried about situations related to the change of ownership [52]. Considering the value propositions in PSS, both tangible products and intangible activities were equally important in terms of how resources were optimally configured to co-create value with the customer [53].

Both PSS evaluation and impact for use-oriented PSS were related to carsharing systems. Evaluation model linking static impact-measurements to dynamic adaptation processes could better assess the sustainability impacts of carsharing systems to support policymakers enacting carsharing regulations in cities [54]. Another model considered both service providers and customers' perspectives to evaluate the feasibility of designing a carsharing system [55]. The launching of carsharing systems reduced total number of cars in the city, which constituted a potential for environmental gains [56, 57].

Under 'approaches facilitating PSS design', a customer satisfaction estimation method could enable designers to compare design solutions from the customers' viewpoint in the conceptual stage and therefore support iterative improvements of PSS design [58].

3.3. Empirical result-oriented PSS studies

The 16 empirical studies in result-oriented PSS were related to approaches facilitating PSS design (6 papers, about 38%), PSS design approaches (3 papers), PSS transformation drivers (3 papers), PSS function (2 papers), PSS evaluation (1 paper), and PSS status quo (1 paper).

Similar to product-oriented PSS, the approaches facilitating result-oriented PSS design also focused on early stages, i.e. specifying requirements for PSS to understand the interdisciplinary contexts to overcome the identified problems [59], pointing out the complexity of each potential new PSS idea and where to focus in the process [60], and focusing on the consumption side to guide the analysis of the practices elements, its configurations and how practices interlocked with one another [61]. Focusing on performance prediction, a simulation-based software tool could be used to compare the performance of different design options [62]. Considering inter-relationships, an assessment model could evaluate the interrelationships among time, quality, cost, stability and reliability of the service, and make a PSS platform more practical [63]. Taking sustainability in mind, a scheduling model could improve system response and robustness [64].

Two PSS design approaches were introduced to address co-development. An extended Kansei engineering method considered customer experience understanding and incorporation [65], whereas a Solution Oriented Partnership methodology took sustainability into account [66]. Another model even considered the emotional side to help designers create positive 'emotional chain reactions' for users [67].

With regard to PSS transformation drivers, to deliver performance-based industrial service contracts successfully, the key contributors related to provider, joint operation, sacrifice, and configuration for contract incentives and performance indicators were identified [68]. Considering policy, 'demand pull' national government policies could support PSS activity [69]. From risk management's view, matching different risks with appropriate options could guide the choice of the right strategies in different situations [70].

Under 'PSS function', applying PSS concept, design considerations and service requirements could be incorporated into the telehealth smartphone applications to change the traditional healthcare delivery model [71]. Extending the application of PSS concept to the development of synergistically sustainable community could open up the potential of PSS and co-produced services in sustainability improvement [72].

'PSS evaluation' taking lifecycle assessment into account to present a sustainability-oriented value assessment model that could provide comprehensive and consistent value assessment under different product-service design scenarios for design improvement, as well as for product-service plan comparison and selection [73].

In terms of PSS status quo, although the supplier relationships in 'performance-based contracting' were closer and longer term, the provider–sub–supplier relationships were not fully cooperative, which challenged the provider [74].

3.4. Other empirical PSS studies

Four studies in our study considered more than one category of PSS in a single research. Among them, two studies focused on PSS impact. From economic point of view, servitized firms generated higher revenues but lower % net profit compared to pure manufacturing firms [75]. From environmental and economic point of view, design, recycling, remanufacturing, reuse, maintenance, and holistic planning and operation in the integrated product service offering contributed to environmental and economic advantages [76]. One article focused on PSS transformation, which indicated that consumers' values could influence the acceptance, adoption and diffusion of collaborative consumption [77]. The remaining one focused on PSS status quo. It was found that although quality management became increasingly important for PSS, quality management practices were insufficient [78].

Two studies in our review were specified by their authors as service-oriented PSS, and both of them focused on PSS design approach. One studied provided a 4-stage service-oriented PSS development process which could guide service providers to develop PSS [79]. The other study proposed an ontology-based knowledge representation model which could develop web-based PSS through the reuse of knowledge unambiguously in maintenance, repair and overhaul services within the product lifecycle [80].

4. Conclusion

This paper presents a systematic review of empirical PSS studies published in peer-reviewed journals between 2006 and 2016. Originated in Europe, PSS practice have been widely applied across various geographical and research areas with an increasing trend. In particular, about two thirds of the existing empirical studies were written by authors affiliated in Europe, indicating a leading position of Europe in this topic. The majority of empirical research employed qualitative research method while large scale quantitative studies are still scarce. In addition, a large portion of product-oriented PSS studies demonstrate that PSS is still in its early development stage in terms of evolution.

Seven themes have been identified based on the aims and focuses of the papers. Among them, PSS design related studies capture the largest portion. Especially, more than half of the approaches proposed to facilitate PSS address the early development phases.

Based on the review findings, some considerations can be proposed for future empirical research. Firstly, findings from the empirical studies are often related to a single case study based on the insights of a limited number of key persons. To refine, validate and generalize the practical findings, more quantitative research will definitely be necessary. Secondly, being a complex system, PSS research should take the entire system into account. However, none of the existing empirical studies in our review had done this. Rather, the studies were conducted based on a project, a transformation process, a firm, or the PSS provider and its partners and suppliers at most. Therefore, unit of analysis selection in the future research turns to be pretty important. For instance, the entire supply chain might be a possible solution. Thirdly, a key factor for PSS design is the lifecycle perspective [81]. However, only 5 articles in our review took this point. In addition, none of them considered both customer and solution provider's points of view. Therefore, a complete detailed PSS design approach that not also considering both customer and solution provider's point of view, but also integrating the product and service components along the whole lifecycle should be more emphasized in the future. Lastly, only journal articles are included in our review. However, studies from other sources are important as well, and some of them are even more timely (such as conference proceedings). Therefore, a more comprehensive literature review including a large variety of sources would help to get more new insights.

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Publication II

Xin, Y. and Ojanen, V.

The impact of digitalization on product lifecycle management: How to deal with it?

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The Impact of Digitalization on Product Lifecycle Management: How to Deal with it?

Y. Xin, V. Ojanen
School of Business and Management, Lappeenranta University of Technology, Lappeenranta, Finland
(yan.xin@lut.fi, ville.ojanen@lut.fi)

Abstract - **This paper aims to create a comprehensive understanding on the impact of digitalization on product lifecycle management, and provide suggestions for manufacturing companies to achieve competitiveness in the digital age. Based on an analysis of 35 journal articles and conference papers, it was found that digitalization closes the product information loop and extends the traditional PLM to the whole product lifecycle, which makes Closed Loop Lifecycle Management possible. To achieve competitiveness, actions related to partnership, standardized and industry-wide accepted data, security, and people should be considered by the manufacturing companies.**

Keywords - **digitalization, product lifecycle management (PLM), product lifecycle (PLC)**

I. INTRODUCTION

Digitalization is one of the most significant on-going transformations of contemporary society and the most significant technological trend faced globally [1]. It has impacted every aspect of organizational and social activities profoundly [2]. To gain competitive advantage in the digital business ecosystem with growing complexity, manufacturing companies are required to offer product-related services in addition to selling tangible products throughout the product lifecycle (PLC) [3]. At the same time, the complexity of the products and their environments are increasing as well, which leads to a necessity to use digital means to model the product with multi-discipline teams distributed in different companies throughout the PLC [4]. Integrating internal and external data of the company, digitalization enables a better real time view on operation and results, and improves business process efficiency, quality, and consistency [5].

As a strategic weapon, product lifecycle management (PLM) enables companies to provide additional values to customers to gain competitive advantage [6]. By managing product data generated throughout the PLC, PLM makes the business processes more efficient, flexible and effective [7]. It enables a company to reduce product-related costs and improve product quality [8, 9], and it increases customer satisfaction directly and increases market share indirectly by shortening the time-to-market and providing more complex product [10, 11].

With digitalization, what have been and will be changed for PLM? Will these changes make PLM easier or more difficult? How can manufacturing companies be well prepared for such changes? These are the target questions for this study. To answer these questions, an in-depth literature review was conducted, and some suggestions were provided.

In section 2, we will clarify the definitions used in this study. The search strategy and brief descriptive results will be described in section 3. Section 4 will present the detailed review results, and section 5 will be concluded by some suggestions for manufacturing companies.

II. DEFINITIONS

Different definitions of digitalization and PLM can be found in literature. To make it clear and consistent, the definitions we used are presented in this section.

Digitalization is an on-going process and an open concept that has not been fully defined [12]. In the production mode, digitalization can be defined as designing products in a digital form, composing and exercising components virtually before really producing the product, and maintaining the relationship between product, users, and the producing company [13]. More focusing on business, Gartner defines digitalization as "*the use of digital technologies to change a business model and provide new revenue and value-producing opportunities*" [14]. In general, digitalization concerns the changes that digital technologies can bring about in a company's business model, products, processes and organizational structure [15], which is the concept we adopted in this article as it matched with our research context well.

Although different interpretations of PLM can be found in the literature, the ideas implied are the same, i.e. to manage product efficiently through all phases of its lifecycle [16, 17, 18]. In this study, PLM is a business strategy used by manufacturers to support the full PLC and accelerate business performance through a combination of process, organization, methodology, and technology [8]. It is an integrated approach of managing the product-related information along the entire PLC that includes people, processes/practices and technology [17, 19].

Following an easy-to-use model, this study categories PLC into three mains phases, i.e. beginning-of-life (BOL), middle-of-life (MOL), and end-of-life (EOL) [16, 17, 20, 21]. BOL includes design and manufacturing to generate the product concept and physically realize the product. The product is within the manufacturing firm's boundaries during this phase. MOL includes distribution (external logistic), use and support (repair and maintenance). The product is in the hands of the final customer during this phase. EOL takes account of reuse, recycling, remanufacturing, and disposal. It starts when the product cannot satisfy its users.

III. SEARCH STRATEGY

Considering the objective of the study, we limited the language to English and the search strings to 'digitalization', 'digit*', 'lifecycle', 'life cycle', 'IoT', and 'information technology' to identify journal articles and conference papers published between 1990 and 2017 using online database Scopus. The initial 281 articles were then filtered on the basis of the relevance of the titles and abstracts, and reduced to 28 articles. As we focus on digitalization and PLM in manufacturing companies and treat PLM as a strategy rather than a software package, those articles that did not meet the requirements were not included. These 28 articles were downloaded and analyzed in terms of the research objectives and findings. To complement these articles, the relevant citations in these articles were downloaded and analyzed as well, which added 7 more articles. As no relevant articles were found before 1999, the main body of this systematic review comprises 35 peer-reviewed journal articles and conference papers published from 1999 to 2017.

The majority of the papers were published since 2010 or later, which accounts for about 71% of all the related papers. In particular, 11 papers were published from 2015 to 2017, which accounts for 31% of all the papers. This is in line with the increasing propagation of digitalization since 2014.

IV. RESULTS

Within a closed silo of information management, PLM traditionally focuses on collecting the physical product data [22], and product manufacturers are responsible for the BOL phase in PLM [16]. As such, product information content and flow during MOL and EOL phases is largely incoherent and incomplete. This information gap in the PLC limits the manufacturer's capacity to provide holistic products and services [7].

However, the application of information technology could greatly reduce the difficulty of PLM [23]. By tracking the products through its PLC and linking the products to their manufacturer, the radio frequency identification (RFID) technology and Internet of Things (IoT) close product's information loop, as a result the accurate, real-time, and complete product information can be available throughout the whole PLC [21, 24]**.** As products are equipped with sensors and connectivity, it is possible and even convenient for the manufacturers to collect product data in the MOL and EOL phases and use such data to improve the product in the future [4]. With the IoT technology, all the things along PLC can be equipped with embedded intelligent devices, such as the raw material, component, machine, product and facilities. By doing so, energy parameters connected to the manufacturing process or in-service stage can be acquired in real time, the critical information about the usage and condition of an individual item can be collected, and the detection and take-back of the end-of-use products are facilitated [25]. Now with the cloud-based system, designers can perform 2-D and 3-D modeling, and even collaborative design remotely via a web browser or a mobile device [26].

By closing the product's information loop, digitalization makes Closed Loop Lifecycle Management (CL2M) possible [27, 28, 29]. CL2M addresses the collection of entire PLC information as it can help to improve design, manufacturing, use and EOL handling of products continually [27, 28, 29]. As a result of this, product quality can be improved, and the business opportunities will be enhanced [28]. Closed-loop PLM contributes to the modernization of industry by improving the product information quality and ease of access to information at all PLC phases [7]. Consequently, operations of MOL and EOL can be streamlined by using the product design and production related information in BOL. The BOL decisions made by designers and engineers will be better with the help of the more easily provided MOL and EOL information [7]. In a word, a CL2M allows all the actors playing a role during PLC to track, manage and control product information at any phase of its lifecycle at any time and at any place [30].

In each phase of PLC, the PLM objectives are different [22]. The BOL phase targets at improving the product design and production quality, whereas the MOL phase concerns the reliability, availability and maintainability improvement of products. As such, the impact of digitalization on PLM in different PLC phases should be different. Consequently, we investigate the impact of digitalization on PLM in BOL, MOL, and EOL, respectively.

A. The Impact of Digitalization in the BOL Phase

BOL includes design and manufacturing, with different focus. Product design focuses on finding solutions for given problems, whereas manufacturing focuses on concretizing a decision taken by others [7]. From the PLM's perspective, the manufacturing process can be monitored and measured in real time, the reasons for complicated quality problems can be found before they turned into issues, and the maintenance activities can be supported with the help of digitalization in BOL [5]. The impacts can be described in detail as follow.

Firstly, digitalization enhances products and process development [9, 31]. Sensor technologies can provide real-time status information of the product to improve the manufacturing process [32]. Through virtual factory, a company can monitor and control the manufacturing process in real time, and prepare for risks [5]. With virtual prototyping, system planners can respond to the changes in manufacturing process quickly, improve the flexibility and efficiency of tooling and process design recursively, and consider human-machine interaction with regards to usability, comfort, and safety in BOL phase [31]. With 3-D simulation tying all the way to the actual physical resources in the factory, the designers can design with the knowledge and context of the manufacturing processes and the currently available resources, thereby generate fast and precise modeling of product development processes [9].

Secondly, digitalization helps to reduce the product time to market [10]. Product design is crucial as 85% of the defects arising during manufacturing are related to the decision-making in design phase [10]. Using an information system in a digital factory, unexpected problems taking place during PLC upstream phases can be avoided, and therefore save time in the product design project, and finally reduce the product time to market [10]. Utilizing a tangible/graphical user interface (GUI) and augmented reality (AR) in EOL, the number of paper drawings needed can be reduced and the phase of design revision can be speed up, therefore realizing 'concurrent engineering' and shortening the time to market [33].

And thirdly, digitalization can support better energy management in BOL phase [25]. With IoT, better energy management can be achieved through optimizing raw material procurement, simulation and testing of product, and setting the efficient working way of manufacturing equipment in design phase. In production phase, this can be achieved though better monitoring and controlling the production processes. For instance, test data is generated by automatic equipment during the PLC, then technologists or designers can make decisions from analyzing correlation of test data connected with different kinds of influence factors and choose the most energy-efficient product design [25].

B. The Impact of Digitalization in the MOL Phase

From the product development's viewpoint, researches mostly focus on the BOL phase, and the information for the MOL phase such as distribution, use and support are incomplete [34]. Due to the requirements to optimize the through-life cost or increase the availability of high value or long life products, manufacturers are expected to not only guarantee product performance over the contracted period, but also provide the maintenance service [35], which makes PLM in the MOL phase to be much more important.

Traditionally, the owner of products changed from manufacturer to customers when the products are transported from the factory and delivered to customers. When the machines or equipment are used by the end users in their premises, it is difficult to collect and analyze the relevant data [5]. Thus it is difficult for the manufacturer to improve product and optimize operation by using product usage data, and it is also difficult for the customers to master the product with high efficiency [25]. With the help of digitalization, technically it is feasible to connect products to the internet and assign them an IP address, so that they can communicate and interact with each other, with other components, and even with remote controllers [36]. Therefore, it enables us to cope with the limitation through efficient transport planning, optimized warehouse management, comprehensive customers' energy use guide, and predictive and preventive maintenance [25, 37].

The impact of digitalization on PLM in the MOL phase can also be reflected from the through-life cost reduction. One of the most prominent benefits of digitalization is to make preventive maintenance possible, which can be scheduled to reduce the risk of unplanned failures, reduce the inventory level for spare parts, and even minimize the inventory cost by planning the availability of spare parts across a geographic location [35].

Using Intelligent Product refrigerator as an example, it was demonstrated that digitalization could enable energy efficiency and proactive maintenance during MOL phase [32]. Abnormal conditions affecting the energy efficiency can be detected in near real-time thus can be corrected timely, and the need for instance spare parts can be known with the help of remote monitoring thus can be prepared without delay. More importantly, the spare parts needed and the fix time required can be determined in advance to avoid potentially repetitive visits [32].

C. The Impact of Digitalization in the EOL Phase

Due to the rapidly depleted natural resources and the unintended environmental consequences and social problems brought by manufacturing industries, now appropriate strategies have to be considered and developed to deal with the end-of-use products [38], which is exactly what PLM in the EOL phase deals with, i.e. reuse, recycling, remanufacturing, and disposal. Currently, the primary focuses of PLM are BOL and MOL phases, with little emphasize on the EOL phase. In order to make PLM a close loop and reduce the negative impacts of the end-of-use products on environment and human, the EOL phase has to be addressed [7].

Moving from BOL to MOL and EOL along the entire PLC, the product information flow becomes less and less complete, which leads to complicated decision-making processes in EOL [21]. However, the real-time PLC data of each individual item can be traced, detected, stored, and analyzed with the help of digitalization, in particular IoT [38]. Thus, the critical information related to the end-of-use products, especially the quality and remaining value of those products can be predicted and estimated, the uncertainty in the status of those products can be mitigated or eliminated, and therefore the resource-saving recycling activities can be enhanced [21, 24, 32, 38].

Using a RFID based disassembly decision-making system as an example, the impact of digitalization on PLM in the EOL phase can be clearly presented [39]. At present, when recycling companies receive the products, it is hard for them to obtain accurate PLC information.

Using such a system, the lifecycle information can be kept up-to-date to guarantee recycling firms get accurate and timely lifecycle information under any circumstances, thereby the decision-making cost can be reduced, and the accuracy and efficiency of decision-making can be increased. Consequently, the recovery efficiency can be improved, environmental pollution can be minimized, and recovery profits can be maximized.

V. CONCLUDING SUGGESTIONS

The impact of digitalization on PLM is on-going, and the manufacturing companies have to take some actions to make themselves competitive in the digital age. Based on the impact, some suggestions for the manufacturing companies are discussed below.

A. Partnership

Currently, many actors interacting with the product during MOL and EOL phases only perform their respective activities, with little information exchange with other actors [7]. However, digitalization promotes holistic information exchange among different parties including designers, manufacturers, customers and recoverers, which will involve more interactions among them [7]. In such emerging complex networked organizations, interchanging, sharing, and managing internal and external resources will be more challenging, and establishing partnerships with other companies who specialized in complementary domains turns to be essential [3]. For instance, when IT and data are becoming an integral part of the product, teaming up with software companies or partners who are expertized in equipping products with sensor technology and connectivity will be very valuable to the manufacturers [4]. Therefore, a stronger partnership between all of these parties will be essential in the future [35].

B. Standardized and industry-wide accepted data

PLM requires efficient handling of an enormous amount of data [33]. Throughout the different phases of PLC, products are disposed not only within the manufacturing firm, but also in a distributed, mobile, and collaborative environment beyond the firm's boundaries [34]. In addition, along with digitalization, the complexity of products, processes, value creation networks and IT environments are growing increasingly, the volume of data is turning to be extremely huge, and the forms of data are developing to be incredibly various, which make managing all that information even more difficult [24, 40]. From the PLM software providers' point of view, providing an information platform covering entire PLC with a flexible and configurable pattern to support unified management of distributed and heterogeneous product data turns to be crucial [34]. From the manufacturing firms' point of view, it is very important to provide standardized and industry-wide accepted PLM data models to support the interlinked data analysis, and to model links between data from different domains [40].

C. Security

With digitalization, manufacturing firms and the relevant parties will be increasingly interconnected in both the cyberspace and the physical world. The security issues such as confidentiality, integrity, and availability of data through the PLC have to be addressed since the data can be attacked by not only hackers, but also competitors [26, 41, 42]. The whole new product design can be stolen by the competitors only because of a small stolen part of data [24]. Therefore, it is very important for the firms to guarantee that only the authorized parties can access the data when needed and in an appropriate manner.

D. People

No matter how advanced the technology and PLM are, people are always indispensable as the processes are managed, controlled, implemented and realized by human beings [7]. Because of digitalization, the requirement for people with complexity, abstraction, and problem-solving skills will increase, and the need for people with multidiscipline knowledge will surge as well [36]. To be prepared for this, providing special training could therefore be an option for the companies.

In the future, PLM is expected to ensure a less resource intensive society through enabling improved traceability of product and in logistics, improvement in material recycling, and optimization of resources usage throughout the PLC [7]. Manufacturing companies should take actions on the suggested areas and be well prepared for this.

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Publication III

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Knowledge Management in Product-Service Systems – A Product Lifecycle Perspective

Yan Xin*, Ville Ojanen, Janne Huiskonen

Lappeenranta University of Technology, Skinnarilankatu 34, 53850 Lappeenranta, Finland

* Tel.: +358 29 44 64040; *E-mail address:* yan.xin@lut.fi

Abstract

The current paper aims to investigate the knowledge management practice in PSS based on literature, and presents propositions for both academia and practitioners from the perspective of product lifecycle. In particular, we look at knowledge requirement, knowledge reuse, and knowledge sharing throughout the entire product lifecycle. Our findings suggest that more appropriate knowledge representation manners and standard knowledge representation form, the identification and classification of the most important knowledge for different stakeholders, and balanced application of personalization and codification strategy will be very important for companies in PSS domain to manage knowledge. Trigging by the increasing concern of sustainability in PSS context, we propose a product lifecycle model integrated raw materials extraction and material production, therefore making a more integral close information loop in PSS.

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Keywords: Product-service systems; Knowledge management; Product lifecycle

1. Introduction

Currently, sustainability is among the key issues for the society. In moving the society towards sustainability, Product-service systems (PSS) are among the most potent implements [1]. One commonly accepted definition of PSS is an 'integrated bundle of products and services which aims at creating customer utility and generating value' [2]. In general, it can be categorized into three types as product-oriented, use-oriented, and result-oriented PSS [3]. Under the on-going transformation to digitalization, the rapid advancement of information technology (IT) enables a company to approach the real-time information of the product over the entire product lifecycle (PLC) accurately and completely [4], therefore reduce the difficulty of product lifecycle management (PLM) [5].

Following an easy-to-use model, the current study categorizes PLC into three main phases including beginning-of-life (BOL), middle-of-life (MOL), and end-of-life (EOL) [6,7]. Design and manufacturing are included in BOL phase to generate the product concept and physically realize the product. The product is within the manufacturing firm's boundaries during this phase. Distribution (external logistic), use, and support (repair and maintenance) constitute MOL phase. The product is in the final customer's hands during this phase. EOL phase takes account of reuse, recycling, remanufacturing, and disposal. It starts when the product cannot satisfy the needs of its users (not matter they are the initial purchasers, or the second-hand owners of the products). Focusing on manufacturing firms, only PLC will be discussed in this study. Although service lifecycle as such will not be covered, we will define the product lifecycle relatively broadly, and the relevant integrated services have been included, for instance the use, repair, and maintenance of the product in MOL phase.

Knowledge generated in different PLC phases are very important for the entire PLC. The BOL engineering knowledge can not only be applied by manufacturing companies to various customer applications, but also help to improve their MOL services such as maintenance and repair [8]. The MOL information is a vital source for designers in BOL phase [9], especially the knowledge concerning component failure,

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operating conditions, maintenance, and reliability [10]. For instance, the service experience from the previous similar products is very important for both current product improvement and future products development as product flaws can be systematically corrected [11,12], and this is especially true in PSS scenario [13,14]. The MOL knowledge will also be beneficial for the MOL phase itself as it can enhance the quality of the provided service, and improve the consistency of the service as well [15]. Moving towards environmental aspects, the EOL knowledge will assist the Reduce and Redesign in the next lifecycle [16]. Therefore manufacturers who collect the EOL phase products, recover the products returned, and use them as resources could to some extent reduce the unexploited sourcing [17]. Because the product return flows are characterized by the uncertainties related to timing, quantity, and quality [18], dealing with product recycling is challenging for manufacturers [17]. Available accurate EOL product information definitely can facilitate the product recovery decisions [19].

Knowledge management can be defined as 'explicit strategies, tools and practices, applied by the management that seek to make knowledge a resource for the organization' [20]. In general, knowledge management aims to capture and store the past experience and information and reuse them to solve the new problems, including both new product development and enhancement of the existing products [21]. Knowledge range required in PSS design is broader because not only products are considered in the design space, but also service has to be taken into account as an essential component, [22]. In the sustainability oriented PSS scenario, the intensive use of knowledge from multiple disciplines makes knowledge management even more crucial and challenging than ever [13].

As a business strategy, product lifecycle management (PLM) concerns various product stakeholders over the entire PLC. As a technology solution, PLM enables knowledge creation, transformation and sharing along the entire PLC by establishing various tools and technologies. The combination of the above two perspectives leads to treat PLM as a knowledge management system to support different PLC phases [23]. Knowledge requirement and knowledge management practice (such as knowledge reuse and knowledge sharing) in each PLC phase will be different. In order to better manage knowledge in such case, the focus on knowledge management in each phase should be different as well. However, this had rarely been concerned in detail in the existing literature, especially in PSS context. Therefore, this study intends to investigate knowledge management across the entire PLC phases to help the stakeholders along the PLC phases reusing and sharing knowledge better, and provide insights for academia on the future directions for knowledge management in PSS. In addition, trigging by the increasing concern of sustainability in PSS context, a complete close-loop information flow is necessary for all the stakeholders. In response to this, we propose a product lifecycle model integrated raw materials extraction and material production, consequently trying to make the information loop in PSS more integral.

Search strategy will be described in section 2. Based on literature review, propositions related to knowledge requirement, knowledge reuse, and knowledge sharing throughout the entire PLC phases will be developed in section 3 through 5. In section 6, a proposed new PLC model in PSS context will be presented. Conclusion and future research plan will be discussed in section 7.

2. Search strategy

In view of the objective of the study, we first used online database Scopus to identify relevant journal articles and conference papers published between 1990 to 2017 with the search strings as 'product-service system*', 'product service system*', 'knowledge', 'knowledge management', 'lifecycle', and 'life cycle', and limited the language to English. However, the searching results only provided limited number of relevant articles. Focusing on PLC perspective, we revised the search strategy. The entire PLC was divided into three phases as mentioned previously, and several stages were included in each phase. Based on this, we identified relevant articles in each stages of PLC using search strings 'knowledge' and 'knowledge management'. The initial 1164 articles were then filtered on the basis of the relevance of the titles and abstracts, and reduced to 58 articles. We downloaded and analyzed these 58 articles in terms of the research objectives and findings. The earliest article in our final list was published in 1995, and only three papers were published before 2000. Therefore, 58 peer-reviewed journal articles and conference papers published from 1995 to 2017 were used in this study to formulate the propositions. In particular, 21 of them were published in the past 5 years, which account for about 36% of all the papers.

3. Knowledge requirement

The stakeholders in different PLC phases have different requirements for knowledge. For instance, in the BOL phase, the designer's main objective is to find a set of technical specifications to solve the problem through the analysis of customer requirement [24], which implies both customer and technical knowledge are needed by designers. In general, both tacit and explicit knowledge are included in customer knowledge, while explicit knowledge is the main body of technical knowledge. At the same time, the entire PLC has to be considered by the designers as an inseparable component of the design process in new product design [25]. Furthermore, they should also consider the policies/regulations in different countries. For instance, in order to decrease the percentage of disposing EOL mobile phones into landfills, a variety of voluntary takeback schemes are existing in different countries [26,27,28]. They have different characteristics, requirements, and performance. Designers and manufactures should take this in mind to design and produce the right products targeting at different countries.

Although both designers and service staffs emphasized the relevance of MOL knowledge (especially in-service information), their focus were different. Process knowledge and component-level knowledge of the equipment was the former's interest to improve the product development, while knowledge about the systems' overview was more emphasized by the latter to provide more efficient support service [15].

In some industries, MOL knowledge turns to be especially important because of the high maintenance cost [14]. For instance, in the aerospace industry with prevailing leasing model which is a classic use-oriented PSS case, in addition to reliability and low fuel consumption, the most important design objective for new product design (such as engine) turns to be overall lifecycle costs reduction, especially to have low and predictable maintenance costs. Therefore, their requirement of knowledge will be more concentrated on the MOL phase of the existing products to guarantee the engine health and minimize the maintenance cost of the high-value components [8,29].

From the above discussion, it is clear that the required knowledge in different PLC phases may be generated from the same PLC phase, but focusing on different aspects. In addition, companies with use-oriented PSS business model will require more knowledge generated in MOL phase. Therefore, the propositions related to the different knowledge requirements are presented as follows:

P1a: Knowledge should be represented in appropriate manners to meet the different requirements raised by the stakeholders in different PLC phases.

P1b: Future research on PSS knowledge requirement should focus on identifying and classifying the most important knowledge required by companies with different PSS business models.

4. Knowledge reuse

Knowledge reuse aims at retrieving previous knowledge and experience and applying it in the right manner to solve the current problem [30]. Analyzing similar projects from past makes it possible to transform a new product or new project into a re-engineering of an existing product partially [24]. Knowledge reuse is especially a normal practice for R&D people to speed up the development process as most of the product development projects are indeed incremental redesign of existing products [31]. In the current PSS environment, the collaborative design scenario makes it even more critical for a company to reuse the knowledge from different product lifecycle phases to support the product development and achieve competitive advantage [8,15]. Along the PLC, a variety of models/approaches have been developed/proposed to facilitate knowledge reuse.

<u>In BOL phase</u>

Knowledge reuse models/approaches/frameworks for different knowledge's types have been proposed for BOL phase. For instance, using historical process data during production, a method was proposed for robust design improvement by estimating the variance of a new product's performance early in BOL, especially in the design phase [32]. To encourage innovative design by novice designers, a knowledge reuse framework based on a knowledge map with extracted explicit design knowledge and implicit knowledge on design case was proposed [33]. To support SMEs operating in an engineer-to-order business model reusing their engineering projects knowledge in design and planning phase, a knowledge framework for advanced manufacturing was defined [34]. A quantitative approach to capture service damage knowledge in MOL phase and to make it available for designer and manufacturer was proposed to encourage MOL knowledge reuse [14]. Within a collaborative multidisciplinary aerospace manufacturing environment, a method enabling the share and reuse of machining knowledge to accelerate the process of design-make was developed [35]. Integrating a semantic-based visualized wiki system with a core visualized search module, a framework to reuse the empirical lesson-learned knowledge in product design was proposed [36], through which design engineers can conveniently share their knowledge and reuse others' experience to shorten the problem-solving time.

Some models are related to knowledge representation/codification in BOL phase. To improve in-service knowledge reuse in product design and consequently design more reliable and serviceable products, techniques for codifying and classifying in-service records were developed [37]. A multi-level knowledge representation model integrated with a simulation tool was presented to facilitate knowledge representation and management by integrating the knowledge elements into a graph representation effectively, therefore supporting collaborative work of distributed designers [30].

Knowledge reuse models related to knowledge linkage have also been proposed. To meet the requirements of engineering design in the design phase, a method facilitating design knowledge reuse was reported by considering the interaction between two types of models - design process and product data [38]. To improve the reuse of knowledge in products' digital design process, an ontology-based knowledge management method and reuse strategy was introduced to link structure and design knowledge [39]. Linking design strategies with a recycling process, a proposed solution makes it possible for the designer to consider the materials behavior's characterization, and the limits, constraints and opportunities of recycling process in a sustainability-oriented product design [40]. In order to effectively and efficiently apply the product usage data in the new PSS development or current PSS improvement, an approach supporting the analysis of usage related data sets and their linkage to product design parameters was proposed [41].

Sustainability and PLC have also been addressed in some models. From a PLM perspective, a knowledge reuse framework providing both manufacturing and service knowledge to designers was developed to support product development in PSS design scenario [8]. Focusing on concept development in consumer package goods industry, an operative knowledge management methodology integrating the Theory of Inventive Problem Solving (TRIZ) and Quality Function Deployment (QFD) was developed to reuse previous solutions and designs adopted in other products or fields with similar situations in the PLM database, thereby reducing the design and plant setup costs, and even helping to realize a packaging design with completely recyclable materials [42]. Through interviewing experts and conducting a case study in a heavy construction machinery company, a proposed knowledge management and reuse framework based on ontology enables designers in PSS design to access the entire PLC knowledge (especially usage and maintenance knowledge in MOL phase) efficiently was approved, therefore improving the maintenance service from design phase [13]. From the viewpoint of a PSS provider, a framework was developed to use product in-service data adequately in the BOL phase to improve the through-life product performance [43].

In MOL phase

There are only a few models aiming at knowledge reuse in MOL phase, which have been proposed earlier. A proposed model based on product characteristics during operation can be used to predict products status in the future and enable a real-time predictive maintenance [44]. In order to improve the logistics performances, a knowledge management system based on RFID was developed. Through such a system, the logistics operators can get the right process knowledge at real time [45]. Based on Bayesian inference, a maintenance knowledge reuse framework was established to support decision making of maintenance service [46].

In EOL phase

The knowledge reuse model proposed for EOL phase were mostly related to environment concerns and from the recyclers' perspective. Recycling and remanufacturing are integrated components of sustainable manufacturing [47]. Using item-level information that was generated through RFID tags, a knowledge-based framework was proposed from a recycling/remanufacturing perspective to consider quality improvement issues relating to repair & refurbishment and EOL recycling [47]. Using this framework, the process of sorting and the following processes for recycling of EOL products can be operated more accurately, therefore minimizing the pollution that generated unnecessarily by mis-operation [47]. Taking into account critical product parameters and key performance indicators of business, a knowledge-based framework was developed to support the recyclers' decision making in EOL phase [48]. Mainly using MOL phase information such as maintenance management and condition monitoring, a framework was developed to support product life extension decision in EOL phase, as it can determine the cost and carbon footprint of life extension process [49].

Across different PLC phases

Product design knowledge, especially recycling-oriented product characterization can link product design (BOL) and recycling systems design (EOL). With such knowledge, recyclers can analyze product characteristics to adapt their recycling process. In addition, they can communicate with manufactures to indicate the product characteristics with positive or negative impact on recycling, thus provide recommendations for product design improvement [50]. Tracking and managing product data through its entire PLC by using RF tagging in component level, a RFID-based modular lifecycle data management system was proposed, which can help manufactures to achieve optimal product planning with considering remanufactured components, and help recyclers to choose the most appropriate recovery option by handling the quality uncertainty problem [17]. In an ideal situation, iterative feedback loop with some forms should exist between each PLC phase, therefore the knowledge or lessons learned from the later phases could be used to improve the decision making in the early phases. As found in literature, the feedback loop within BOL phase (i.e. between design and manufacturing) works well, while the loop between MOL and BOL is less formal [43]. In a drilling equipment company who provided machineries for the oil industry, a model facilitating the reuse of MOL knowledge (service knowledge) across the entire PLC was proposed [15].

The above literature summarized a variety of knowledge reuse models/frameworks across the PLC phases. Some of them are only targeted for one particular phase, while some of them are focused on knowledge reuse across different PLC phases. They are proposed from different perspectives, and with different focus. For instance, most of the knowledge reuse models are targeted at BOL phase and from different perspectives, whereas models in MOL phase are mainly focused on improving maintenance performance, and model in EOL phase concern environmental effects and are from the recyclers' perspective. Therefore, the propositions related to knowledge reuse in PSS are:

P2a: Future research should focus on facilitating knowledge reuse in MOL and EOL phase.

P2b: In the PSS context, knowledge reuse model in EOL phase should also consider the original equipment manufacturers' viewpoint to realize sustainability more effectively and efficiently.

5. Knowledge sharing

Knowledge sharing is another challenge for knowledge management in PSS. Some studies indicate that an easy-to-use knowledge repository with codified knowledge will enhance knowledge sharing [51], which makes codification strategy as the main knowledge sharing strategy. However, it was also found that even with formal knowledge repositories, engineering designers still prefer to contact the senior service staffs directly to get the necessary knowledge [15]. In addition, high knowledge complexity makes people-to-people interactions as a favored knowledge sourcing method [52]. For instance, in the vehicle industry, people-to-people interactions are preferred by R&D people when solving complex problems [53]. In such situation, collaborative activities should be emphasized by the company, rather than only focusing on codification approach to share knowledge [54]. In a word, codification strategy which codifies and stores knowledge in databases will increase knowledge reuse and sharing volume, whereas personalization strategy emphasizing person-to-person contacts could improve the communication of knowledge tied to the person, and building networks of people turns to be crucial [54].

Due to the difficulty of retrieving and reusing knowledge through the non-uniformed knowledge stored in the exiting scattered repositories, MOL knowledge transfer/sharing primarily occurred within the individual PLC phase, and the knowledge transfer across different PLC phases was poor [55]. In addition, knowledge sharing between designers and recyclers is necessary for designing recycled composite products. To facilitate such product design, experts in material and mechanical characterization should also be included to enrich the material level knowledge for both designers and recyclers [40]. Therefore, with regards to knowledge sharing in PSS, we propose that:

P3a: In the company, it is necessary and complementary to have a knowledge sharing strategy including both personalization and codification, and a balance is needed based on the context.

P3b: A standard form of knowledge representation should be encouraged to facilitate knowledge sharing across the different PLC phases.

6. An integral PLC

The ever rapid advancements in ICT not only positively affect the society, but also makes obsolescence of electronic products within a short time frame which leads to tremendous increased quantities of Waste Electrical and Electronic Equipment (WEEE) [56]. WEEE could be treated as a metal resource as it contains valuable metals in high amounts such as cooper, tin, aluminum, gold, and silver [57].

Quoted first in the Swedish government's report, extended producer responsibility (EPR) claims that collecting, recovering, and reusing obsolete products are the original equipment manufacturers' responsibility. In addition, they are also on their own responsible for the disposal of those products [58]. After that, several regulations and directives were adopted in EU to improve the chemicals information flow and enhance the management of chemicals. To promote collecting and recycling of electrical and electronic equipment (EEE), EU legislation [59] entered into effect in January 2003. To restrict the use of hazardous substances in EEE, another EU legislation [60] took effect in February 2003. In an effort to ensure '*information on chemicals throughout their life cycle, including, where appropriate, chemicals in products, is available, accessible, user friendly, adequate and appropriate to the needs of all stakeholders*', the Strategic Approach to International Chemicals Management (SAICM) was proposed in 2006 [61]. At the same year, Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) containing a number of provisions to improve information flow of chemicals was enacted [62].

In practice, however, the treatment results of EOL products are not as expected. For instance, the mobile phone consumption globally increases enormously and it leads to a large volume of waste generated from mobile phone [63]. To be consistent with the principle of producer responsibility, a number of mobile phone manufactures implement their own take-back systems during 2008 and 2009, such as Sony Ericsson, Nokia, and Motorola [57]. But results from a literature review of articles dealing with mobile phones published during 1999–2015 indicate a low recycling rate of mobile phone in both developing and developed countries [63]. Remanufacturing was claimed to spread worldwide in the auto parts sector [64], but empirical results from the EOL vehicles' recycling in Sweden implied a low functional recycling rate for most of the scarce metals despite the high overall recycling rates of materials in general [65].

To improve the footprint of environment in EOL, especially in the recycling phase, actions should be taken as early as possible. For instance, one option is to eliminate the hazardous and undesired substances from the products even during the design phase of those products [57]. In order to accomplish this, a dependable understanding of the content of substance in the products is a necessity [57]. If the treatment decisions of the EOL products have to be made by the recyclers who are not the original equipment manufacturers, the product information in BOL and MOL phases turns to be necessary [48]. However, in practice, this knowledge are not always available, nor is there any guarantee for the quality [48].

The main goals of lifecycle thinking (LCT) are to reduce resource usage and emissions to the environment of the product, and improve its social-economic performance through its PLC. From this perspective, PLC begins with raw materials extraction and ends up with final disposal [61]. Moreover, the chemical related knowledge (for instance which chemicals are being used, how to use, handle, and recycle or dispose them) from the producers of chemicals, formulations, and materials will help product designers to design a more sustainable product [56]. An adapted waste hierarchy regarding treatment methods of EOL products was presented by adding remanufacturing between the reuse and recycling in the original framework [48,66]. Among them, remanufacturing is considered as a suitable EOL strategy for life extension to cut down the overall environmental burden from the product [49]. Based on the discussion above, and related treatment methods of EOL products with BOL and MOL phases, we developed a more complete PLC (as shown in Fig. 1.) with regards to knowledge management and PLC in PSS context. In addition, a close-loop information flow was emphasized in this frame considering raw materials extraction and material production. Based on this, we proposed that:

P4: In PSS, raw materials extraction and material production should be added to the PLC, although the companies in these categories might not necessarily be the suppliers of the manufacturers.

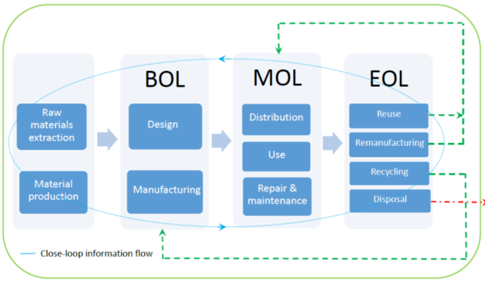

Fig. 1. An integral PLC in PSS context

7. Conclusion and future research

In the current study, some propositions based on a review of 58 journal articles and conference papers are presented with regards to knowledge and knowledge management throughout the entire PLC phases, and a new PLC model under PSS context is developed.

With respect to knowledge requirement, our findings suggest that in order to meet the knowledge requirements raised by the stakeholders in different PLC phases, more appropriate knowledge representation manners are needed. In addition, to fulfill the above requirements, the identification and classification of the most important knowledge for different stakeholders turns to be crucial. Concerning knowledge reuse, insufficient existing studies for knowledge reuse in MOL and EOL phases implies a necessity to conduct more research in these particular phases. Regarding knowledge sharing, both personalization and codification strategy should be adopted by the companies depending on the context. Moreover, to facilitate knowledge sharing across the entire lifecycle, a standard knowledge representation form should be stimulated. Integrating lifecycle thinking in PSS domain, our findings suggest that the previous PLC should be extended to include raw materials extraction and materials production. By doing so, a close-loop information flow could be emphasized to achieve real 'sustainability' for the PSS.

Only journal articles and conference papers are included in the current study to formulate propositions. However, some studies from other sources, such as findings from the relevant projects, may be more timely. Therefore, future studies with a more comprehensive literature including recent projects outputs would help to enrich the insights. In addition, with the transition to PSS for many manufacturing companies, especially the manufactures of long-life complex products, management of knowledge retention should be taken into account in future studies due to its increasingly importance and difficulty. Moreover, the on-going digitalization transformation will raise great opportunities and challenges to the companies from different aspects. Consequently, these impacts on knowledge management in PSS context should be further investigated in future studies.

Based on the current results, we are planning to investigate these propositions in PSS providers through a series of in-depth case studies. By doing so, we hope to have a more fine-grained understanding of knowledge management practice in PSS, especially through the PLC perspective. Therefore, different stakeholders along the PLC phases can be guided to better manage knowledge in PSS context, and academia can get some insights for future research directions about knowledge management in PSS.

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Publication IV

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Dealing with Knowledge Management Practices in Different Product Lifecycle Phases within Product-service Systems

Yan Xin*, Ville Ojanen, Janne Huiskonen

LUT University, Yliopistonkatu 34, 53850 Lappeenranta, Finland

* Tel.: +358 29 44 64040; *E-mail address:* yan.xin@lut.fi

Abstract

Through semi-structured interviews in six companies, the current paper investigates the knowledge management practices in product-service systems from product lifecycle perspective. Knowledge requirements (types/sources), knowledge sharing, and knowledge reuse in both beginning-of-life and middle-of-life phases are our focus. Similarities and differences on knowledge management practices were found in the two phases. Our finding suggests that in the current digital era, in order to keep competitive, the knowledge requirements in different PLC phases should be clearly identified, the importance of people should be re-emphasized, external collaboration should be strengthened, and standardization should be advocated in the company.

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Keywords: Knowledge management; Product lifecycle; Beginning-of-life; Middle-of-life; Product-service systems

1. Introduction

Sustainability, digitalization, and product lifecycle management (PLM) are popular topics for both academia and industry. Considering all of them together, product-service systems (PSS) integrating bundle of products and services to create customer utility and generate value have become an emerging issue [1]. Originated in Europe, the application of PSS have been worldwide and across various research areas. However, existing PSS literature has mostly been based on case studies, especially single case studies [2, 3]. Therefore, multiple case studies or even large scales quantitative research would contribute to both industry and academia for PSS.

The objective of knowledge management is to capture and store the past experience and information and reuse them later to deal with new problems [4]. Along the product lifecycle, including beginning-of-life (BOL), middle-of-life (MOL), and end-of-life (EOL) phase [5], knowledge management is naturally distributed to the different stakeholders in PSS. However, BOL phase is the focus among the existing researches, and MOL phase is still not comprehensive [6]. Therefore, further investigation of knowledge management practices in MOL phase would shed light on the PSS research, especially in the current digital era

In response to the discussion above, the current study aims at investigating the knowledge management practices further in the PSS context, including both BOL and MOL phases. Therefore, our research questions will be: What are the knowledge management practices in both BOL and MOL phases under the PSS context? What are the impacts of digitalization on the above mentioned knowledge management practices? How to deal with this? In particular, we will focus on both the similarity and difference of knowledge management between these two phases. By doing so, we hope that companies can get more insight on their own knowledge management status quo, and keep competitive through better knowledge management in the ever changing digital era.

Section 2 will explain the theoretical background of this study. In section 3, research method will be described and the

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detailed data analysis results will be presented in section 4. Conclusion and suggestions will be discussed in section 5.

2. Theoretical background

Knowledge management not only focuses on creating new knowledge, but also aims to capture and store the past experience and leverage them within and around the company through knowledge sharing and knowledge reuse [4, 7]. Essentially, different stakeholders in sustainability oriented PSS are actors along the entire product lifecycle, from BOL (design and manufacturing), MOL (external logistics, use, and support) to EOL (reuse, recycling, remanufacturing, and disposal) [5]. As an indispensable resource, knowledge turns to be even more important for these companies to enhance the competitiveness in PSS context because knowledge from different PLC phases, no matter focusing in one particular area or multi-disciplinary, will be used intensively by them. Consequently, knowledge management will be more challenging for these companies [8]. In order to have a better understanding on knowledge management practices in these companies, we therefore focus on knowledge sharing and knowledge reuse practices based on the existing literature.

The benefit of using MOL knowledge in BOL phases, and vice versa, had been investigated in earlier studies. For instance, the engineering knowledge from BOL phase helped the service staffs in MOL phase to improve maintenance and repair [9], whereas the use-related, or in-service knowledge from MOL phase helped designers and engineers in the BOL phase to improve future product development [10, 11]. However, as an important sub-phase in MOL, the knowledge management practices of external distribution (logistics) had rarely been empirically explored in the PSS context [12]. The ever-increasing competition made many manufacturing companies outsource their logistics to streamline the value chains [13]. Therefore, exploring knowledge management practices in logistic companies will in turn help to understand the knowledge management in manufacturing companies better, especially help to understand the possible knowledge sharing and knowledge reuse between these two types of companies. This is the main reason why we decided to choose logistics company to represent the MOL phase of PLC in the PSS context. For the BOL phase, R&D was chosen as the representative in our study because it is very knowledge-intensive [14] and is well known as the most important stage in PLC.

Based on the discussion above, this study therefore focuses on knowledge sharing and knowledge reuse in BOL phase (R&D as representative) and MOL phase (logistics as representative) in PSS context. Being the object of knowledge management, the knowledge requirements, especially types/sources of knowledge used in these two PLC phases will be involved as well. Considering the opportunities and challenges that may raise due to the on-going digitalization transformation, the impact of digitalization on knowledge management will also be investigated [15].

3. Research method

3.1. Study design and setting

The empirical study was conducted in manufacturing companies and logistics companies in Beijing, China. Semi-structured interviews were used in this study because the data collection process was flexible and the relevant topics could be ensured to be covered in each interview [16, 17].

3.2. Sample and recruitment

Key informants were purposively selected based on their relevance with our research topic. The participants in manufacturing companies were familiar with knowledge management of R&D to represent EOL, whereas the participants from logistics companies were familiar with knowledge management in logistics to represent MOL. Email invitation was sent to each participants, clearly outlining the purpose of the research and how data would be used.

3.3. Data collection

In order to fulfill ethical research practice standards, informed consent was obtained from participants before conducting each interview [18]. Identifiable details were excluded to protect confidentiality, but the job titles were remained [18, 19]. In addition, the participants were made aware that they were free to withdraw from the study before, during, and after data collection [18].

Nine semi-structured interviews of six companies in Beijing were conducted between July and October 2018, as shown in Table 1. The manufacturing companies were in in different industries, ranging from traditional (printing) to high-tech industry (electronic measurement), and were relatively big concerning staff number, with at least 100 employees in Beijing. The participants were R&D staff, former R&D staff, or staff who are quite familiar with R&D and communicated frequently with R&D department. In contrast, the logistics companies were relatively small, with less than 100 employees in Beijing. The participants were in charge of logistics operation in the company.

Table 1. Profile of the company and interviewee

	Company	Sector	No. of employee	Interviewee	Length of interview (minutes)
Manufacturing	M1	printing	500~999	(P1) senior supply chain manager	120
				(P2) R&D manager	80
	M2	automobile	100~499	(P1) R&D manager	70
				(P2) senior project manager	80
	M3	electronic measurement	1000+	(P1) product planning master, former R&D engineer	90
				(P2) channel manager, former R&D engineer	80
Logistics	L1		1~49	customer service & customs manager	75
	L2		50~99	port & customs manager	45
	L3		1~49	operations manager	60

The length of the interviews ranged from 45 to 120 minutes. During the interviews, participants were asked about the questions around knowledge management strategies/practices in the company from their perspectives, including knowledge requirements (types/sources of knowledge used), knowledge sharing, knowledge reuse, and the impact of digitalization on knowledge management (see Appendix). Upon permission, all the interviews were audio recorded, except for the two interviews conducted in the second manufacturing company (M2), and one interview conducted in the third manufacturing company (M3, P1), which were written down by the interviewer. The audio records were fully transcribed by the interviewer, and checked for accuracy through repeated listening.

3.4. Data analysis

Data were analyzed using NVivo data analysis tool (Version 12). To make the comparison within and between the two phases (EOL and MOL) more clearly, the two transcripts for each manufacturing company were combined into one. Therefore, finally six files representing six companies were imported to NVivo, three representing EOL in manufacturing companies (M1, M2, and M3) and three representing MOL in logistics companies (L1, L2, and L3). The initial nodes were created in NVivo based on the main themes from the research questions, i.e. knowledge requirements, knowledge sharing, knowledge reuse, and impact of digitalization on knowledge management.

4. Results

Data analysis results following the interview guidelines, i.e. knowledge requirements (types/sources), knowledge sharing, knowledge reuse, and the impact of digitalization on knowledge management will be shown in this section. Although not listed in the initial interview guidelines, result related to sustainability will be included as all R&D staff emphasized this.

4.1. Knowledge requirements

Table 2. Knowledge used types/sources

	L1	L2	L3	M1	M2	M3
customer knowledge	√		√	√	√	√
industry knowledge			√			
market knowledge				√	√	√
supplier knowledge			√		√	
expertise	√	√	√	√	√	√

During the interviews, different types of knowledge were mentioned (see Table 2). Among them, expertise is the only type of knowledge that was indicated in each interview. However, the types of knowledge that were defined as expertise were quite different between the two groups of people. For the R&D people, expertise was mostly related to design, development, technology, and manufacturing process. For the logistics people, it was mostly related to import & export, insurance, and policy & legal aspects. One logistics staff (L1) even clearly indicated that design knowledge and development knowledge were completely irrelevant. Because of this difference, their sources were different as well. Professional background was a must for the R&D people, and they accumulated their expertise through self-learning, through learning by doing, and also acquired from employees in other departments. In contrast, except for learning by doing, most of the logistics people got expertise from government and even from the competitors. Sometimes, expertise acquired from competitors are more useful as they are more relevant (L1). That probably was the reason to explain why the R&D staff believed that it was not difficult to get the relevant knowledge for their work (M2 and M3). Whenever it was difficult, most of the time they could get the knowledge from other channels, especially through person-to-person communication (M3). However, the logistics staffs expected that the government could organize more special meetings so that they can get more timely updates.

Customer knowledge was also indicated by most of the companies. Similar to expertise, the focus of the two groups was different. The R&D people paid more attention to market demand, customer needs, and their using experience, for the sake of new product development and future product improvement. Therefore, these knowledge were mostly acquired from the report or feedback from other departments, such as marketing, sales, and quality. However, the logistics people paid more attention to the features of the customers' products, because they wanted to fulfill the transportation and legal requirements and at the same time lower the risk involved. Therefore, they usefully got this knowledge from customer directly. In addition, sometimes customers even actively emphasized their special requirements because they also wanted to minimize their own risk (L1 and L3).

Market knowledge was the knowledge mentioned only by R&D staff, and all R&D staff indicated this as they need to have sufficient market knowledge to analyze their competitors. Usually, they got this knowledge from conference & exhibitions, customers, and suppliers (M1, M2, and M3). In particular, all R&D staff emphasized the importance of attending conference & exhibitions. Industry knowledge was the knowledge mentioned only by logistics staff, and only by one of them because the customers were from a variety of industries.

> *'Every industry is different. For example, oil and pharmaceutical industry, they are very different. Petroleum equipment may be very expensive, but it is very strong and heavy. Therefore, you have to consider the overweight and over length for transportation, as they are not regular goods. Especially when it is urgent and airfreight is necessary, the limitation of weight and length of aircraft makes the transportation extremely challenging. However when you need to deliver vaccines, your focus then have to change to hygiene, safety, and temperature. In addition to customer requirements, industry standard must be met for this particular industry.' (L3)*

Supplier knowledge was mentioned once by R&D staff and by logistics staff, respectively. The R&D staff focused on new materials and innovations from suppliers to apply them to their own product development faster (M2), whereas the logistics staff focused on the suppliers' transportation capacity because sometimes their own fleet cannot meet customer requirements (L3).

All these knowledge mentioned by the interviewees were considered as equally important by them. Only one exception was that one R&D staff clearly indicated that customer knowledge was the most important one when they conducting SWOT analysis (M2). Also, only R&D staff indicated that if they could get some knowledge more, they could achieve better performance, but they could not get them currently (M1, M2, and M3). For instance, some knowledge from other industries, such as new materials, could help them accelerate the R&D process and launch the product to market faster. In addition, when searching for knowledge to solve a problem, there was a prioritization of the order to decide where is the starting point, including but not limited to own capability, familiarity level with the knowledge and with the person, and geographical location.

'When we cannot solve the problem internally, external knowledge sourcing turns to be as prior.' (M1)

'For instance, the searching priority is person or document depending on the familiarity level with the knowledge and with the person. When the knowledge is considered as unfamiliar, searching or enquiring from person first is quite common, even though there might be existing standard repository there.' (M3)

'Of course we want to search within our department first because we are sitting in the same office.' (L3)

4.2. Knowledge sharing

All the interviewees believed that knowledge sharing was important and necessary. Knowledge was shared within the department, within the company, with branch office, with supplier, with customer, and even with competitor, as shown in Table 3.

Table 3. Knowledge sharing scope – share with whom

	L1	L2	L3	M1	M2	M3
branch office					√	
supplier				√	√	
customer	√	√		√	√	√
competitor	√	√	√			
within the company	√	√	√	√	√	√
within the department	√	√	√	√	√	√

Knowledge sharing within the department and within the company was mentioned by all the interviewees, indicating its acknowledgement by both R&D and logistics staff and its importance for them. Indicating by most interviewees, knowledge was also shared with customers as they can develop together, and grow together. However, only R&D staff shared knowledge with branch office and supplier, and only logistics staff shared knowledge with competitor. Especially, all the R&D staff clearly indicated that they would not share their knowledge with competitors because of confidentiality and professional ethics. In contrast, the logistics staff mentioned that they would like to share their successful experience with their competitors as all of them were in the same system and this kind of sharing was a win-win strategy. They even share their knowledge with their competitors frequently and mutually through unofficial social media group built by them. With regards to branch office, the three interviewed logistics companies were relatively small and do not have branches yet.

Knowledge sharing could be implemented through different mode, as shown in Table 4. Most of them were quite common modes and we will not explain them in detail here, such as training, meeting, and intranet. The only point we want to emphasize here is job rotation and social media, as only logistics staff mentioned them. As we discussed earlier in the previous section, professional background was a must for R&D staff and this could not be shared simply through job rotation. However, the basic knowledge required for a qualified logistics staff could be learned through job rotation, and it was especially important for knowledge sharing within the department. Job rotation made everyone have a better understanding of the whole process and lead to better personal development and better team management (L1, L2). It ensured each task could be completed by a backup person, which was especially important for small logistics companies.

Table 4. Knowledge sharing modes

	L1	L2	L3	M1	M2	M3
conference and exhibition			√		√	√
internet					√	√
intranet	√		√	√	√	√
job rotation	√	√				
meeting	√		√	√	√	√
training	√	√	√	√	√	√
social media	√		√			
person to person			√	√	√	√

Table 5. Influencing factors of knowledge sharing

	L1	L2	L3	M1	M2	M3
confidentiality	√			√	√	√
level of sender and receiver	√	√				√
relevance of knowledge		√	√	√	√	√
top management support	√			√		√

Factors affect knowledge sharing were also explored in the interviews. The most important influencing factors are shown in Table 5. It is quite clear that relevance of knowledge was the most common factor as mentioned by most of the interviewees.

'For instance the experience of dealing with non-standard case sometimes is only for special case and the knowledge is rarely relevant to other cases.' (L3)

'We will not share the product related knowledge to our branches because it is not relevant, and only management knowledge or some process knowledge will be shared.' (M2)

Confidentiality was another common influencing factor, and especially mentioned by all the R&D staff. In order to strengthen confidentiality, one possible solution is knowledge fragmentation.

'For instance, the instruction for manufacturing process was divided into several sections, and each person can only access the section that he/she needs for his/her own job with permission. All the individual sections are automatically linked together when necessary, however only the relevant people can access with certain permission.' (M1)

Top management support will not be explained in detail here, but the level of sender and receiver should be emphasized. Sometimes the effectiveness of knowledge sharing can be determined, because if the corresponding knowledge was not obtained, the shared person will not be able to perform his/her job (L1). However, knowledge sharing sometimes is subjective, and one of the difficulties in knowledge sharing is control.

'From the human's perspective, it is very difficult to control to what extent a person willing to share his/her knowledge with others.' (M2)

'Knowledge sharing depends on person. The judgement for the importance level of the same knowledge varies among different people, and this is especially true for ordinary R&D personnel. They do not share some knowledge only because they presume the knowledge is too simple and treat it as common sense, without considering the receivers' background.' (M3)

'It is also very difficult to control to what extent a person want to share others' knowledge.' (L1)

4.3. Knowledge reuse

All the interviewees agreed that knowledge reuse was necessary, and would be even more important in the digital era.

'Reuse of knowledge can increase efficiency'.' (L1)

'Knowledge reuse is a principle in our company, and this is especially true for R&D. Knowledge reuse exists in all R&D phases and activities. ' (M2)

'Most (of our work) is the reuse of knowledge. And with advancement of informatization, the proportion will only increase, and not decrease. This is because technology is innovating gradually, or with some jumping, but customer application is only a combination of different fields, or cross functional, and most of them are knowledge reuse.' (M3)

Some influencing factors of knowledge reuse were mentioned by the interviewees. The R&D staff emphasized the distance or familiarity of knowledge.

'Even though there is existing code for a specific function already, some software engineers still prefer writing the codes by themselves to fulfill the function if they are familiar with the knowledge required. However, they will more likely choose to use the ready-made code if they feel the knowledge required for coding is unknown or not familiar with it.' (M3)

The logistics staff emphasized the standardization, or universal level of knowledge. The possibility of reuse would be very low if the knowledge was only related to a very special case.

'The most reused knowledge will be the standard one, no matter it is case, code, or process. Some knowledge is rarely reused because of its particularity. It maybe only used in one special case, and has no reference value for other cases or processes. However, this kind of knowledge was still stored in our company in case for future reference.' (L3)

However, it was also indicated that a balance is needed between the reuse of exiting knowledge and the application of new knowledge as this might be related to different innovation orientation of the company, i.e. more radical oriented with less knowledge reuse or more incremental oriented with more knowledge reuse.

4.4. Impact of digitalization on knowledge management

Each interviewee talked about the impacts of digitalization on their company, such as more convenient, more efficient, better decision making, better cooperation, better business environment, and less cost. With regards to the impact of digitalization on knowledge management, some general points can be summarized from the interviewees. With the increasing amount of data available, safety and security of data protection should be emphasized.

'Data access must be set with strict permissions, even within the company.' (M3)

'Informatization allows us to get the knowledge faster, but it also means that others can more easily acquire the knowledge we have. Therefore, it is necessary to ensure the confidentiality of the corresponding knowledge.' (M2)

Due to informatization, the range of knowledge required will be broader and much of the knowledge from other fields becomes necessary, and knowledge integration is very important.

'Customer needs are increasingly diverse, and many of these demands come from the development of IoT. Therefore, we need a lot of knowledge in different fields, and we must integrate them organically into new product development and implement new functions to meet these new demands.' (M3)

Related to the range of knowledge required, the requirement for people also higher than before. A person with multi-disciplinary and integrated knowledge will be more important to the company (M3).

Although the impact of digitalization was emphasized by all the participated companies, the impact varies across the companies and also varies within one company. For instance, digitalization was acknowledged to greatly improve the efficiency of co-design and cooperation, but its impact on distinguishing product fault was not obvious.

'Sometimes the impact is not obvious. For instance when looking for the cause of a product fault I always need to see the physical product, as I need to distinguish whether the fault was caused by the product itself or due to the customer's misuse.' (M2).

4.5. Sustainability

Sustainability was not included in the original interview guidelines. However, the R&D participants highly emphasized this point. All the R&D staff clearly indicated that they considered sustainability for the entire product lifecycle. For instance,

'Taking a book as an example, we will consider its entire lifecycle, including how it will be dealt with after being read by the last reader. How we can print it more reasonable that not only meet the reader's needs, but also minimize the manufacturing cost, and at the same time be responsible for

the environment and society.' (M1)

Consisting with existing literature [20], sustainability started from design, including design of lighter and smaller products to fulfill the same function, design for the more environmental-friendly manufacturing process, and more strictly raw material selection. For instance,

'We tried to design smaller and lighter product, thus reducing the amount of raw materials used. Of course, the product must achieve the same function, and even better.' (M2)

'We tried to keep only the key functions and delete all those functions that seems magic but in fact unnecessary. By doing so, raw material consumption was reduced, and the manufacturing process became simpler.' (M3)

'In the design of the production process, we must consider making the production process as simple and easy as possible, and also consider minimizing the pollution caused in the production process.' (M1)

'Ingredients of each component need to be registered, especially chemical ingredients. Only certified by the system, this component can be used.' (M2).

'Supplier selection is very strict. Only the suppliers who have the environmental certificate and fulfill the governmental requirements will be selected by us.' (M1)

Although sustainable development is indispensable, no case company improves the design of their existing products by tracking the processing record of the end-of-life products. In fact, none of the case companies tracked the processing of their EOL products. Similarly, no procedure or instructions exist in the case companies to send the design information to recycler to assist the end-of-life processing. Usually the products will be handed over to a specialized company, and this was the current situation for all manufacturing companies in our study.

'Before handing over to the other companies, we will provide various maintenance records that have been done for the equipment, but that's all.' (M1)

In order to make sustainability more effective and feasible, standardization and supervision were emphasized. For instance,

'It is better to put it into policy (but there is no existing one). The process of tracking needs to be standardized in the industry. Each company only needs to follow the standards.' (M3)

'Sustainability is the responsibility of each stakeholder, but for us, we mostly care about our own benefits and prefers doing the things that we are familiar with. The sustainability of an industry, or the whole society, should be supervised by a specialized agency.' (M1)

5. Conclusion and suggestions

The current study investigated the knowledge management practices in different product lifecycle phases, i.e. BOL and MOL, by conducting interviewees in manufacturing companies and logistics companies. It was found that knowledge requirements are quite different between these two phases. Although both expertise and customer knowledge were mentioned by both phases, their focuses were different. For expertise, BOL was more focused on the knowledge related to design and technology, whereas MOL was more focused on policy. For customer knowledge, BOL was more focused on customer needs and their using experience, whereas MOL was more focused on the features of the customer's product. Besides these two types of knowledge, market knowledge was used in BOL only, and industry knowledge used in MOL only. Related to the types of knowledge used, the sources of the knowledge also turned to be different. Conference & exhibitions, learning-by-doing, and person-to-person were the main sources for BOL, whereas government was the main source for MOL. The importance and necessity of knowledge sharing was also acknowledged by both BOL and MOL. They shared knowledge within the department, within the company, and the customer. However, BOL would not share with competitor, and MOL would not share with supplier or branch office. Training was the most commonly used knowledge sharing mode for both BOL and MOL. However, job rotation and social media were only used in MOL. Among the factors affecting knowledge sharing, relevance of knowledge was the most influencing one. Knowledge reuse was important for both BOL and MOL, and it was even a principle for BOL. The more familiar with the knowledge, the more knowledge will be reused in BOL. The more standardized of the knowledge, the more knowledge will be reused in MOL. In the digital era, the broader and diversified knowledge base turns to be very important. Safety and security of data protection was the most concern in BOL. Although not listed in the interview guideline, sustainability was highly emphasized in BOL. The consideration for sustainability across the entire product lifecycle and started from design. However, the exchange of knowledge with EOL was still rare.

Based on the findings from the study, some managerial implications are discussed for better knowledge management in the digital era under PSS context.

Firstly, knowledge requirements in different PLC phases should be clearly identified. Although the same type of knowledge might be referred by both BOL and MOL staff, the focus of their requirements were different [21]. Therefore, in order to share knowledge more effectively and efficiently, i.e. share the right knowledge to the right people, a correct understanding of the knowledge requirements from both the sender and receiver have to be identified.

Secondly, the importance of people have to be re-emphasized, especially for BOL, or more specifically, for R&D people [22, 23]. The characteristics and quality of people will not only influence knowledge sharing and knowledge reuse intention, but also knowledge sharing result. The importance of learning-by-doing makes experience and tacit knowledge even more important for R&D, which will lead to extremely costly for company to replace a R&D expert

Thirdly, external collaboration should be strengthened [24]. More and more knowledge application was multi-disciplinary, and across different industries. External collaboration is the only feasible way to make the company keep competitive. If the relevant knowledge could be acquired faster, the R&D process could be accelerated and shorten the time to market.

Fourthly, but not lastly, standardization should be advocated. Standardization will not only for documentation, but also for the interface between different stakeholders along the PSS, and for the whole industry. Only standardized documents could be shared and reused more, only standardized interface could allow the efficient and effective data sharing between different stakeholders, and only a widely recognized standard that everyone must follow could realize the knowledge sharing in the entire PSS.

There are some limitation in the current study, which should be address in the future. First, the transcripts were only checked by the interviewer due to time limitation. A double check should be conducted for further analysis. Second, the participated logistics companies in this study were relatively small, which may not represent the full status quo of the logistics industry. More interviews from larger logistics companies would be helpful to increase the reliability of the results. Last, R&D and logistics were the only sub-phases for BOL and MOL, respectively. To have a better understanding of the knowledge management practices in BOL and MOL, interviews from other sub-phases would be necessary.

Appendix. Interview guidelines

Types/sources of knowledge used:

- Which type of knowledge is most important/useful from your point of view?
- Which source of knowledge is most important/useful from your point of view?
- How do you get them? Are they difficult to get?
- What other types/sources of knowledge are also needed but you do not have?
- If there is such knowledge, is it because of not knowing where the knowledge is, or due to the difficulty of accessing and acquiring it?
- If you are informed where the knowledge is, do you know how to access and acquire it?

Knowledge sharing:

- Have you shared knowledge only within your department or across the company? Why and how (for instance, codification or personalization)?
- Have you shared knowledge with other companies? If yes, why and how?
- Is knowledge sharing useful/effective in the current situation? Why?
- What factors have motivated you to share knowledge or prevented you from sharing knowledge?
- Which department/company is the one that you want to share the most and least? Why?

Knowledge reuse:

- Have you reused knowledge from previous products/projects? Why and how?
- Do you want to reuse more in the future? Why?
- If you want to reuse more, what knowledge will be the most important one from your point of view?

Impact of digitalization:

Has digitalization affected knowledge management in your company? Why and how?

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Sharing and reusing knowledge for innovation and competitiveness in PSS

Yan Xin*

LUT University, School of Engineering Science, Yliopistonkatu 34, 53850, Lappeenranta, Finland.
E-mail: yan.xin@lut.fi

Ville Ojanen

LUT University, School of Engineering Science, Yliopistonkatu 34, 53850, Lappeenranta, Finland.
E-mail: ville.ojanen@lut.fi

Janne Huiskonen

LUT University, School of Engineering Science, Yliopistonkatu 34, 53850, Lappeenranta, Finland.
E-mail: janne.huiskonen@lut.fi

* Corresponding author

Abstract: Through twenty-seven semi-structured interviews in eleven companies and supplementary questionnaire survey responses by the interviewees, the current study investigates knowledge used, knowledge sharing (focusing on sender), and knowledge reuse (focusing on receiver) from product lifecycle perspective in the product-service systems context. Both beginning-of-life (represented by R&D, purchasing, and production) and middle-of-life (represented by logistics, customer service, and sales) phases were our focus. The impact of digitalization on knowledge management was also an aspect explored in this study. Similarities and differences were found between and within the two phases. Our finding suggested that in order to be competitive in the digital era, a consistent understanding of knowledge requirement from both sender and receiver should be identified, a match between the knowledge shared/sourced and the mechanism used should be made, a culture/mechanism to retain competent people in the company should be emphasized, and investment on knowledge repository should be strengthened.

Keywords: knowledge sharing; knowledge reuse; product lifecycle; digitalization; product-service systems

1 Introduction

How to efficiently lead and manage innovations and transform the creative ideas to business and societal value has captivated the attention of researchers and managers already for decades. Currently, we are witnessing the era, when the contemporary phenomena like sustainability-oriented innovations (Adams et al., 2016), product-service systems (PSS) (Tukker, 2015), emerging digital technologies and ecosystems (Clarysse et al., 2014) build the foundation for potentially drastic changes in innovation management. Along with this trend, the basis of competition shifts from the functionality of a discrete product to the performance of the broader product system, and the single firm is only one of the actors. The requirements of integrating diverse knowledge relating to economic, social and environmental considerations across the entire product lifecycle (PLC) inherently brings complexity to innovation, and makes knowledge and its management even more crucial and challenging to the company (Adams et al., 2016). Although companies in various industries have invested in KM initiatives and gained benefits, many companies are still struggling with reaping the value from KM (Rao, 2012). In order to be competitive, taking an appropriate knowledge management strategy/practice across the entire PLC phases become a necessity.

Being identified as the key process for successful knowledge management (KM), knowledge sharing and knowledge reuse (Bemret and Bennetz, 2003) have been investigated in research articles for decades. However, to our knowledge, few of them concern KM in the PSS context through the PLC perspective. Especially, if PLC was divided into beginning-of-life (BOL), middle-of-life (MOL), and end-of-life (EOL) phase (Stark, 2011), the existing studies were mainly focused on BOL phase, whereas the studies on MOL phase were not comprehensive (Cai et al., 2014). From the PSS providers' perspective, they must support their customers and ensure the usefulness of their product along the PLC. Therefore, investigating KM practice further in MOL phase would not only enrich the PSS research, but also refine the KM research.

In response to the discussion above, coupled with the fact that the majority studies in the existing PSS literature were conducted through the single case study method (Tukker, 2015), the current study aims at investigating knowledge sharing and reuse under the PSS context from PLC perspective through the multiple case study method. In particular, both BOL and MOL phases will be included. Under the ongoing trend of digitalization, a proliferation of technologies was adopted to support communication (Treem and Leonardi, 2012) and shape the sharing and reuse behavior. Considering the opportunities and challenges brought by the digitalization transformation, the impact of digitalization on KM will be investigated as well. Therefore, the corresponding research questions addressed in this study are: What are the main knowledge requirements for PSS providers in different PLC phases? What are the knowledge sharing and reuse strategies/practices in that context? How does digitalization influence the above-mentioned strategies/practices? Are the answers of the three questions raised above similar or different in different PLC phases? By replying to these questions, we intend to complement the current KM theory through PLC perspective and hope that companies can have a better understanding on their own knowledge sharing/reuse status quo, and keep innovative and competitive through better KM strategies.

Theoretical background will be explained in section 2. Research design and methodology will be described in section 3. Section 4 will present the data analysis results and discussion. Finally, section 5 will discuss the conclusion and suggestions.

2 Theoretical background

Knowledge sharing, reuse, and transfer

'Knowledge is of little value if not supplied to the right people at the right time' (Teece, 2000, p. 38). Many discussions around KM have focused on how knowledge is transferred, shared, and used (reused) in the company, which are broadly concerning the movement of knowledge, but with different emphasis, from different perspectives, and intertwined with each other (Majchrzak et al., 2004; Szulanski, 1996). Knowledge transfer emphasizes the efficacy of knowledge movement from the sender/producer to the receiver/consumer between the predetermined sender and receiver, knowledge sharing emphasizes the sender's contribution to knowledge from a supplier's perspective, whereas knowledge reuse focuses on the demand of knowledge from a consumer's perspective (Gray and Meister, 2004; Majchrzak et al., 2004; Szulanski, 1996). In addition, knowledge can be used/reused without being shared or transferred when the re-user uses his/her own knowledge. To narrow down the research focus in the current study, knowledge sharing and knowledge reuse will be emphasized, as knowledge transfer can be treated as one stage in both knowledge sharing and knowledge reuse processes and covered by both processes (Majchrzak et al., 2004; Markus, 2001; Szulanski, 2000). To make the study clearer, by considering the different emphasis of the above-mentioned knowledge movement, the definition of knowledge sharing, knowledge reuse, and knowledge transfer used are described as follow:

- Knowledge sharing is the process in which the sender contributes his/her knowledge to the receiver and initiate the knowledge movement from the sender to the receiver. The focal actor is the knowledge sender.
- Knowledge reuse is the process in which the receiver seeks and acquires the knowledge from the sender, initiates the knowledge movement from the sender to the receiver and applies the knowledge received. The focal actor is the potential knowledge receiver.
- Knowledge transfer is the knowledge movement from the sender to the receiver. The focus is the mechanism used to facilitate the knowledge movement.

Knowledge management in PSS context from PLC perspective

Targeting at sustainable development, companies should consider the entire PLC, and this applies to KM as well. In general, PLC can be categorized into three mains phases including beginning-of-life (BOL), middle-of-life (MOL), and end-of-life (EOL) (Stark, 2011). In BOL phase, the product is within the manufacturing firm's boundaries. Design and manufacturing stages are included to generate the product concept and realize the product physically. MOL phase consists of product distribution (i.e. external logistics), use (consumption), and support (i.e. repair and maintenance). It implies that the product is out of the manufacturing firm's boundaries and used by the customer. When the users' needs cannot be satisfied by the product, it turns to EOL phase, which involves reuse, recycling, remanufacturing, and disposal.

In the PSS context, various stakeholders play their roles along the PLC phases with different KM requirements and strategies. However, to our knowledge, most existing literature on knowledge sharing and reuse focuses on BOL phase (Baxter et al., 2009), and rarely explore them in MOL phase empirically (Cai et al., 2014; Durst et al., 2018). To streamline the value chains, manufacturing companies are currently in a trend of outsourcing their logistics (Franceschini et al., 2003), which implies that external logistics could be fulfilled not only by the logistics department in the manufacturing firms, but also by the third-party logistics companies. Therefore, in order to have a better understanding of knowledge sharing and reuse in both BOL and MOL phases, both manufacturing and logistic companies will be our targeting companies in the PSS context. In particular, in BOL phase, R&D will represent design, and purchasing and production (normally under the umbrella of supply chain) will represent manufacturing. In MOL phase, logistics (both logistics company and logistic department) will be the representative of external logistics, and customer service represent support. For the majority manufacturing companies, the sales department is indispensable. Because they communicate closely with customers and are familiar with the use of products on the customer's side, the sales department is included in this study and categorized under the MOL stage.

Impact of digitalization on knowledge sharing and reuse

Digitalization has been one of the major changes during the past decades, which has not only had influence on the means of communication, but also enabled access to enormous information sources (Kankanhalli et al., 2005a and 2005b). For instance, ICT facilitates knowledge sharing through internet and facilitates knowledge seeking through search engines (Hislop, 2005). Social media changed the way of sharing and collaboration and has been viewed as an informal KM tool Von Krogh, 2012) because it helps the potential knowledge receivers to be aware of the knowledge possessed by the knowledge sender (Leonardi et al., 2013).

3 Research design and methodology

By considering the objectives of this research, the nature of the research questions, and the lack of extensive theories in the research field, qualitative case study methodology was adopted as the dominant methodology. In particular, semi-structured interviews were used for data collection because they allow immediately clarification of the terminology involved and circumventing misunderstandings (Parkhe, 1993). Quantitative survey was adopted as a supplementary method to get more information. The sample size was limited to the number of cases as the questionnaire was answered by the interviewees right after each interview. Therefore, only descriptive results from the survey were used.

Key informants were selected purposefully by considering their relevance with the research topic, and they were managers in their own functional department who are familiar with KM practices in the department and in the company. Before conducting the interview, invitation was sent to the participants through email to outline the research objective and how the collected data would be used. Informed consent from each participant was obtained to fulfill the ethical research practice standards (Heath et al., 2012).

Between June and October 2018, a total number of twenty-nine face-to-face on-site interviews were conducted in seven manufacturing companies and four logistics companies in Beijing and Tianjin, China. Different PLC phases and sub-phases were represented by the relevant functional departments in the company in the current study, as indicated before. No matter which industry the company is in, the functional departments perform the similar responsibilities. Therefore, industry difference was not taken into consideration.

The length of each interview ranged from 40 to 120 minutes. The list of companies and participants is presents in Table 1. Questions around knowledge management strategies/practices in the department/company were asked during the interviews, including types of knowledge used, knowledge sharing/reuse practice, and the impact of digitalization on the above-mentioned topics. All the interviews were digitally recorded upon permission, except for the interviews in two manufacturing companies. Right after each interview, a short questionnaire survey was filled in the interviewee to rate the IT application in the company, which would be used to supplement the information on digitalization in the company.

Table 1 Summary of the companies and the participants

Company	*Industry*	*Size **	*Participant*	*Job title*	*PLC phase*	*PLC sub-phase*
C1	printing	large	P1	senior supply chain manager	BOL	Purchasing (PUR)
			P2	R&D manager	BOL	R&D (RD)
C2	automobile	large	P3	R&D manager	BOL	R&D (RD)
			P4	senior R&D project manager	BOL	R&D (RD)
			P5	procurement manager	BOL	Purchasing (PUR)
			P6	production manager	BOL	Production (PD)
			P7	customer service/quality manager	MOL	Customer service (CS)
C3	consumer electronics	large	P8	procurement manager	BOL	Purchasing (PUR)
			P9	product quality manager	BOL	Production (PD)
			P10	production manager	BOL	Production (PD)
			P11	logistics and customs manager	MOL	Logistics (LOG)
			P12	customer service manager	MOL	Customer service (CS)
C4	chemical	large	P13	senior sales manager	MOL	Sales (SAL)
			P14	production manager	BOL	Production (PD)
C5	electronics components	large	P15	logistics and customs manager	MOL	Logistics (LOG)
			P16	procurement manager	BOL	Purchasing (PUR)
			P17	sales manager	MOL	Sales (SAL)
			P18	customer service manager	MOL	Customer service (CS)
				chief information officer		
C6	electronic measurement	large	P19	product planning master, former R&D engineer	BOL	R&D (RD)
			P20	channel manager, former R&D engineer	MOL	Sales (SAL)
C7	biocheminstry	medium		CEO		
			P21	Procurement manager	BOL	Purchasing (PUR)
			P22	R&D manager	BOL	R&D (RD)
			P23	R&D manager	BOL	R&D (RD)
C8	logistics	small	P24	customer service & customs manager	MOL	Logistics (LOG)
C9	logistics	medium	P25	port & customs manager	MOL	Logistics (LOG)
C10	logistics	small	P26	operations manager	MOL	Logistics (LOG)
C11	logistics	small	P27	customer service & customs manager	MOL	Logistics (LOG)

* Size was determined using EU classification based on persons employed in the company: fewer than 10 → micro enterprises; 10-49 → small enterprises; 50-249 → medium-sized enterprises; 250 or more → large enterprises (Eurostat, 2016)

The digital records were fully transcribed verbatim by the interviewer. Data from the semi-structured interviews were analyzed by the thematic coding and analysis methods and NVivo was used (Version 12). The initial nodes in NVivo were created based on the main themes in the research questions, i.e. knowledge requirements, knowledge sharing/reuse, and impact of digitalization. Data from the questionnaire survey were analyzed by using IBM SPSS (Version 26). Transcripts from two interviewees and the corresponding questionnaire survey from them were excluded in the above analysis due to their position (one was chief information officer in C5, and the other one was chief executive officer in C7). Rather, they served as supplementary materials to confirm the findings from other interviews and was a kind of triangulation to increase the credibility of the study.

4 Results and discussion

In this section, data analysis results from both the semi-structured interviews and the questionnaire survey will be presented and discussed following the interview guidelines.

Knowledge requirements

Different types of knowledge were used/required in PLC sub-phases (as shown in Table 2).

Table 2 Types of knowledge used/required in in PLC sub-phases

	R&D	*Purchasing*	*Production*	*Logistics*	*Customer service*	*Sales*
expertise	✓	✓	✓	✓	✓	✓
process/procedure knowledge	✓	✓	✓	✓	✓	✓
product knowledge	✓	✓	✓	✓	✓	✓
production knowledge	✓	✓	✓			
supplier knowledge	✓	✓	✓			
customer knowledge	✓			✓	✓	✓
market knowledge	✓					✓
industry knowledge				✓		

Expertise, process/procedure knowledge, and product knowledge were used by all PLC sub-phases. The use of process/procedure knowledge in all the PLC sub-phases interviewed implies the importance of standardization and systemization of work, no matter in which PLC sub-phases. Even in the most knowledge intensive R&D, it was also very important to guarantee the quality by using R&D standard operating procedure (C7/P22).

Although all sub-phases used expertise and product knowledge, their focus were not the same. Regarding expertise, the focus of R&D were design, development, and technology, the focus of production were production management, product quality control, and equipment maintenance, whereas the focus of logistics was more related to transportation, import & export, and policy & legal issues. With regards to product knowledge, the focus of R&D was how to realize the functions of the product, the focus of purchasing was the detailed requirement of the product, the focus of production was the production process of the product, the focus of the logistics was the characteristics of the product, and the focus of the sales was the performance and advantages of the product. Even in the same sub-phase, the requirement for the same type of knowledge is different according to the job position, or the responsibility.

> "All this expertise related knowledge is important for us. However, according to job position, the emphasis is different, and the degree of importance will be different." (C5/P15)

Production knowledge and supplier knowledge were only used during the BOL phase, whereas industry knowledge was mentioned only by logistics. All the sub-phases in MOL use customer knowledge, and in BOL only R&D uses it. This difference derived from their different responsibilities and focuses of work. The BOL phase focuses on how to design, develop and realize the physical product, which requires comprehensive knowledge of product and supplier. In contrast, the MOL phase focuses on how to ensure satisfying customers' requirements by using the product, which requires in-depth understanding of the customers. Even within MOL phase, focuses of customer knowledge were different. Logistics focuses on the customers' requirement about delivery time and delivery modes, customer service focuses on the customers' usage experience, and sales focuses on the customers' requirement and expectation of the product performance. It should be emphasized that customer knowledge is also important for R&D, which is the only sub-phase uses that knowledge in BOL in the companies interviewed. R&D people not only paid attention to customer needs for the purpose of product development, but also concerned the customers' feedback so as to improve the product (C3/P12).

Market knowledge was used in R&D and sales with different objectives. In R&D, it was used to answer what new products should be developed to satisfy customer needs or create new customer needs. Therefore, the focuses were market trend, technology trend, and competitors' information etc. In sales, it was used to answer how to satisfy customer needs with the existing products. Therefore, the focuses were the historical sales of their own products and the competitors' products. With regards to industry knowledge required by logistics, the focus was on knowing the industry standard of the product to better arrange the transportation (C10/P26).

Both expertise and process/procedure knowledge were considered as equally important by all the interviewees, although people in different position (division of labor) may have different focuses for these two types of knowledge (C1/P2, C4/P13). Except for these, the importance of other knowledge was different according to the PLC sub-phases. For instance, production people considered production knowledge as the most important one, whereas the customer service people took customer knowledge as the most important one. In addition, the importance of different types of knowledge changed according to the transition of the company's strategy from being as a manufacturer to a PSS provider.

> "With the transition of the company from selling product to selling solution, the importance of different types of knowledge changed accordingly. The

importance level changed from product knowledge first to customer knowledge first." (C6/P20)

Knowledge sharing

Knowledge sharing was important and necessary, which was clearly emphasized by all the interviewees. Knowledge was not only shared with the same department (i.e. within one PLC sub-phase), within the company (i.e. across different PLC sub-phases), but also with external companies (i.e. across different PLC sub-phases and across the company's boundary). The scope of knowledge sharing from each PLC sub-phases is shown in Table 3.

Table 3 Knowledge sharing scope (share with whom) and mechanism

Knowledge sharing with …		BOL			MOL		
		R&D	*Purchasing*	*Production*	*Logistics*	*Customer service*	*Sales*
BOL	*R&D*	training, mentor, meeting, public folder, intranet by permission	meeting, informal discussion, email, intranet by permission	e-flow, email, phone, meeting on-site discussion		e-flow, regular report	email, phone, informal discussion
	Purchasing	meeting, training on-site discussion, informal discussion, email, intranet by permission	training, mentor, meeting, public folder, intranet by permission	e-flow, email, phone, meeting on-site discussion, regular report			
	Production	meeting, training on-site discussion, informal discussion, email, intranet by permission	e-flow, email, meeting	training, mentor, meeting, public folder, intranet by permission	e-flow, email	e-flow, regular report, email, phone	
MOL	*Logistics*			e-flow, email	training, mentor, meeting, social media, job rotation, public folder, intranet by permission		
	Customer service	meeting, training, informal discussion, email, intranet by permission				training, mentor, meeting, public folder, intranet by permission	
	Sales	meeting, training, informal discussion, on-site discusison, email, intranet by permission					training, mentor, meeting, public folder, intranet by permission
External	*Other branches*	intranet by permission, email, video conference		intranet by permission, email, regular report video conference			
	Supplier	supplier training, supplier visit, meeting, email (on demand), project team	email, phone, e-flow supplier visit	email, report			
	Customer	customer visit, face-to-face, email, project team			email, report, phone	report, email, phone, informal discussion	customer visit (mutual) customer training document
	Other				email, report, phone, social media, informal discussion		

All the interviewees indicated that they shared knowledge within the department and within the company, but with different scopes and degree. It implies that the importance of knowledge sharing had been acknowledged by all PLC sub-phases interviewed. With regards to scope, R&D shared knowledge with all the PLC sub-phases, except logistics.

R&D also shared knowledge with supplier and customers frequently for innovation (C1/P2).

> "With the development of product, R&D turns to know the suppliers very well. When some new raw materials are needed, R&D may know which supplier is more suitable and contact the supplier directly, rather than through purchasing department. They even help the suppliers design, so that suppliers can produce the new raw materials faster and better to fulfill our company's requirements for new product development." (C3/P8)

In contrast to R&D, the other two sub-phases in BOL mostly shared knowledge within BOL phase, and rarely with MOL phase. The only exception was production's knowledge sharing with logistics. However, this sharing was automatic through the e-flow in the company, rather than actively initiated by production. Different from the knowledge sharing scope for the BOL sub-phases, the MOL sub-phases mostly shared knowledge with BOL phase, rather than shared within MOL. This pattern of knowledge sharing scope and direction reflects the relationship between the different PLC sub-phases. BOL sub-phases needs to cooperate closely with each other to ensure that production was completed on time and on quality. In contrast, the responsibilities of each MOL sub-phase were relatively independent. They cooperated with BOL to smooth the operation of the company.

With regards to the mechanism, i.e. the knowledge transfer mechanism defined in this study, most of them were commonly used by the interviewees, such as training, meeting, public folder, intranet, and e-flow, etc., as shown in Table 3. Among all the mechanisms, mentor was commonly used by all the PLC sub-phases when sharing knowledge within the same sub-phase only. This is particularly important for sharing knowledge with new employees (C6/P20). In logistics, two special mechanisms, i.e. job rotation and social media (i.e. WeChat) were used, which was not mentioned by other sub-phases. This could be explained by the characteristics of the job (most of the time on-site) and the knowledge used. The necessary knowledge for a qualified logistics staff were more related to policy and procedure, which was more convenient to share and learn through job rotation and learning-by-doing (C8/P24). In addition, many tasks fulfilled were on-site, and social media was a very fast and convenient mechanism to share information.

> "For example, the new policies that must be implemented imminently, we will share it immediately in the department and in the company. Due to the high demand for timely update, we usually choose to push the information in WeChat group immediately from on-site, and then organize meeting." (C11/P27)

In addition to the knowledge characteristics, the urgency level of the task also influenced the mechanism selection. The urgent task would prefer faster, and person-to-person mechanism, such as phone (C5/P18).

> "In case of unexpected emergent problems happened in production or R&D, telephone communication is priority to solve the problem. If it is not urgent,

> management software will be used to communicate and solve the problem." (C7/P21)

Factors prohibited knowledge sharing were related to confidentiality and non-relevance. The knowledge will not be shared if beyond the confidential limit, nor will it be shared if the sender perceived it as irrelevant with the potential receiver.

> "The only obstacle/hindrance of knowledge sharing is confidential. For example, the product failure mode and measures are not disclosed to public, so it is impossible to share. This is mainly to protect against competitors." (C2/P4)

> "It is not necessary to share such information with other departments as it is not relevant." (C3/P10)

Regarding how to facilitate knowledge sharing, top management support and the sharing/learning culture in the company were emphasized.

> "R&D staffs are willing to share their knowledge with others although they may be in different fields. This is attributed to the learning culture of the company, from top to down." (C7/P23)

Knowledge reuse

In the current study, knowledge reuse focuses on knowledge sourcing (i.e. acquiring from which sender) and the mechanism used, from the receiver's perspective. Knowledge reuse was not only necessary, but also embedded in the daily work, as indicated by all the interviewees.

As shown in Table 4 (next page), the scope of knowledge seeking in the different PLC sub-phases were quite similar to the scope of the knowledge sharing, and the mechanisms used were similar as well. The importance of R&D was clearly reflected here, as all the sub-phases seek knowledge from R&D and reused it. When the knowledge needed was not within the company, searching external knowledge was necessary and automatic.

> "It is now an open society. External knowledge sourcing is necessary. For us, usually external knowledge sourcing is for cross-boundary knowledge because they are more professional in their professional fields. By using these cross-boundary or multi-disciplinary knowledge, we can speed up the R&D process." (C1/P2)

Table 4 Knowledge sourcing (from which sender) and mechanism

Sourcing knowledge from ...		BOL			MOL		
		R&D	*Purchasing*	*Production*	*Logistics*	*Customer service*	*Sales*
BOL	*R&D*	training, mentor, meeting, public folder, informal discussion intranet by permission	training (organized by R&D), intranet by permission, meeting, email, phone informal discussion	training (organized by R&D), intranet by permission, meeting, email, phone informal discussion	training (organized by R&D), intranet by permission, email, informal discussion	training (organized by R&D), intranet by permission, meeting, email, phone informal discussion	training (organized by R&D), intranet by permission, meeting, email, phone informal discussion
	Purchasing	intranet by permission, sharing platform, email, informal discussion	training, mentor, meeting, public folder, informal discussion intranet by permission	e-flow, email, phone, meeting			
	Production	e-flow, report, meeting, email, informal discussion, intranet by permission	e-flow, meeting, report, email, informal discussion, intranet by permission	training, mentor, meeting, public folder, informal discussion intranet by permission	e-flow	e-flow, email, phone	
MOL	*Logistics*			e-flow	training, mentor, meeting, social media, job rotation, public folder, informal discussion, intranet by permission		
	Customer service	e-flow, regular report, email, phone				training, mentor, meeting, public folder, informal discussion intranet by permission	
	Sales	report, email, phone, informal discussion					training, mentor, meeting, public folder, informal discussion intranet by permission
External	*Other branches*			intranet by permission, email			
	Supplier	supplier visit, joint project meeting, informal discussion, document from supplier, co-innovation system	supplier visit, e-flow, informal discussion, co-innovation system				
	Customer	training organized by customer, document, customer visit			report, email, phone	report, e-flow, email, phone	customer visit, phone, email
	Government / Regulatory authority	official website search			official website search, official wechat account/ group, training organized by government, phone		
	Logistics in other company, transportation capacity provider				WeChat, report, email, phone, informal discussion		
	Other	conferences, exhibitions, 3rd party report					3rd party report

The point needs to be emphasized in BOL was knowledge sourcing of R&D and purchasing. Both sub-phases seek in-depth knowledge from supplier, such as the supplier's innovation, because it could be used in their own R&D to speed up the process and have better material selection (C2/P3, C5/P16). In addition, conferences and exhibitions were very important sources of knowledge for R&D, but it was not mentioned by any other sub-phases (C6/P19). The point needs to be emphasized in MOL was knowledge souring of logistic. Government / regulatory authority was the most important external knowledge source for them, but rarely used by other sub-phases. This was consistent with the expertise required in logistics, i.e. policy related knowledge.

> "Suppliers will also develop new materials, such as lighter, smaller, and cheaper materials. This innovation from suppliers can be used on our own innovation. Like the new material I mentioned just now, it is possible to use it and make our own products lighter and smaller." (C2/P3)

> "The official platform provides by the government (for us, mostly Customs) is very important for us because they provide timely information on new policy/regulation. Based on this, we can response promptly. In addition, any confusion about the new policy/regulation can be asked on the platform and get the appropriate answer." (C5/P15)

The mechanism selection of knowledge sourcing during the knowledge reuse process was impacted by many factors, such as the sender's credit, the possibility of getting the needed knowledge, and the importance and urgency level of the task.

> "We prefer to get the latest policy from the official website because it is accurate (no fake) and fast." (C11/P27)

> "We want to search within our department first because we know the possibility of finding the needed knowledge is higher." (C10/P26)

> "According to the degree of importance and urgency, sometimes multiple confirmation will be required. In such case, a combination of multiple ways will be needed for knowledge sourcing." (C4/P14)

However, in the companies interviewed, no matter whether there was comprehensive knowledge repository or not, person-to-person mechanism was still preferred by the interviewees as most knowledge needed could be obtained through this mechanism (C6/P9).

> "Even if there are documents ready for check, they are still more inclined to communicate with people directly to search the knowledge." (C1/P2)

Knowledge reuse is good. However, rigidly following the procedure sometimes also implies less flexibility. Therefore, a balance needs to be made between proceduralization and practicality when reusing knowledge (C3/P8).

> "The knowledge is inherited by the company through years' accumulation. Using/applying them in daily work will definitely reduce risk, but it also means less flexibility." (C6/P19)

The impact of digitalization

All the employees agreed that digitalization made changes in the companies. Digitalization promoted international cooperation (C2/P3), decreased the workload (C10/P26), reduced time cost (C2/P4), provided better guidance for decision-making (C1/P1), made data analysis faster (C4/P14), allowed more efficient and accurate feedback and tracing (C5/P18, C7/P21), and created a better business environment (C9/P25). In order to have an idea of the most commonly used IT applications (Azyabi et al., 2014; Alavi and Leidner, 2001; Hislop, 2005), the survey results are shown in Table 5.

Table 5 IT applications in PLC

	R&D	*Purchasing*	*Production*	*Logistics*	*Customer service*	*Sales*	*Mean*	*Usage level*
emails	5	5	5	5	5	5	5	intensively used
intranet	5	5	5	4,67	4 ***	5	4,81	
workflow systems	5	5	5	3,67 *	5	5	4,7	
database management systems	5	5	5	3,83 ***	5	4 ***	4,63	
search engines	5	4,8	3,25 ***	4,83	4,33	4,33	4,52	
document management systems	4	4,8	4,5	4,33	4,33	4,67	4,41	regularly used
instant messaging	3	3,2	2,5	4,5 ***	4 ***	4 ***	3,52	
groupware systems	3,83	3,6	3,75	2,83	3	4,33	3,52	
video conferencing	3,5	3	2,5	3,17	3	3,67	3,15	rarely used
business intelligence systems	4 ***	3,2	2,25	2,33	3	3,67 ***	3,07	
decision support systems	3,5	2,8	2,5	2,83	3	3	2,96	

***** P<0,001, ** P<0,01, * P<0,05 (Duncan alpha)**

1= unknown application, 2= known but not used, 3 = rarely used, 4 = regularly used, 5 = intensively used

Although the sample size of the survey was small, it still provided some descriptive information. Not surprisingly, emails, intranet, workflow systems, database management systems, and search engine were intensively used in the PLC sub-phases surveyed. However, compared to other sub-phases, the usage of intranet was lower in customer service, and usage of search engine was lower in production, which was consistent with the responsibility of those sub-phases. Consistent with our interview results, instant messaging was used in MOL, especially in logistics.

The impact of digitalization on knowledge types, knowledge sharing, and knowledge reuse was also investigated. Digitalization made cross-disciplinary knowledge more important, which indeed means more knowledge reuse. Digitalization facilitated standardization, which was very useful for documenting and archiving of the relevant knowledge. In addition, it facilitated codified knowledge sharing by providing comprehensive knowledge repository and convenient knowledge sharing platform. Furthermore, digitalization facilitated knowledge reuse by decreasing the money and time cost of knowledge reuse, and finally lead to faster new product development.

> "In the future, there will be more and more cross-discipline and integration of knowledge, which are reuse of knowledge. There will be more reuse of existing knowledge, and new products will be produced through different new combinations." (C6/P20)

> "Informatization promotes standardization, including the standardization of production data, the standardization of equipment maintenance, etc., which is good for documentation." (C1/P2)

> "Now it is more convenient and efficient for knowledge sharing. Knowledge sharing changed from using paper, fax to using public folders, platforms, intranet, etc." (C3/P9)

> "The efficient knowledge accumulation (i.e. stored in the system, or public folders for future reference) with the help of digitalization significantly reduce the cost of time and money for knowledge reuse, thus speed up the new product development process." (C7/P22)

However, digitalization also raised challenges. With digitalization, the faster and more convenience access to the external knowledge means that other companies can also quickly and easily acquire knowledge from our side. Therefore, information security turns to be more important and more difficult than ever, which should be paid attention to by all the companies (C5/P15). In addition, the convenience and expeditiousness brought by digitalization is not free. High investment is needed, and timely maintenance is required, which are not easy for any company.

> "Security becomes more important than ever. Data access must be set with strict permissions, even within the company." (C6/P19)

> "The cost of the system is high, and system maintenance is very difficult. Once there is a problem in the system, the down time of the production line is longer than the traditional way." (C3/P10)

> "If there is update lags in the system, there will be negative effect. Therefore, the maintenance of the system is very important to keep it up to date." (C5/P17)

5 Conclusion and suggestions

Through conducting semi-structured interviews and supplemented by small scale questionnaire survey in both manufacturing and logistic companies, this study investigated knowledge sharing and knowledge reuse practices in different PLC sub-phases, as well as the impact of digitalization on those practices. More specifically, sub-phases R&D, purchasing, and production represented BOL phase, and sub-phases logistics, customer service, and sales represented MOL phase. It was found that knowledge requirements were different between all the sub-phases. However, similarities could be found within BOL and MOL. For instance, production knowledge and supplier knowledge were only used during the BOL phase. By contrast, the commonly used customer knowledge in MOL was used by only one sub-phase in BOL (i.e. R&D). From the sender's perspective, knowledge sharing scope and degree were different between the PLC sub-phases. Within the company, R&D shared knowledge with all the sub-phases except logistics, whereas purchasing and production's knowledge sharing mainly occurred within BOL. Quite different from BOL, sub-phases of MOL mostly shared knowledge with BOL, rather than within MOL. With regards to the mechanism used, mentor was only used within department, and job rotation and social media were only used in logistics. It was also found that the mechanism selection was influenced by the characteristics of the job position, the knowledge involved, and the urgency level of the task. Confidentiality and non-relevance were the two barriers for knowledge sharing. From the receiver's perspective, the scope of knowledge seeking and the mechanisms used in the different PLC sub-phases were quite similar to those in knowledge sharing. Knowledge sourcing of R&D and purchasing reflected the importance of applying supplier's innovation to speed up the company's own new product development, whereas knowledge sourcing of logistics reflects the importance of knowledge sender's credit. One important finding from this study was that person-to-person mechanism was still a priority even if there were existing convenient knowledge repository in the company. Some IT applications were intensively used, such as emails, intranet, and workflow systems, whereas decision support system was rarely used. With the existing IT applications, digitalization not only facilitated knowledge sharing and reuse, but also raised challenges such as information security and timely maintenance.

Based on the findings from the empirical study, some managerial implications will be discussed to promote better knowledge sharing/reuse in the digital era under PSS context and from a PSS provider's perspective. Firstly, practitioners should clearly identify the specific knowledge requirements in each PLC sub-phases and make sure that the correct understanding exists from both the sender and the receiver to enhance knowledge sharing/reuse efficacy. Secondly, a match should be made between the knowledge shared/sourced and the mechanism used. To achieve this, the job position, the knowledge characteristics, the task characteristics, the sender's credit, the receiver's knowledge requirement, and the convenience of the mechanism should be considered simultaneously but by making priority based on different context. For instance, if multi-department cooperation is required to solve an urgent problem, the most efficient mechanism will be meeting, no matter face-to-face or virtual, so that rich knowledge can be shared and discussed. If the urgent problem can be solved by the cooperation between two parties, phone call plus e-flow would be more convenient and economical. Thirdly, the importance of competent people/personnel should be emphasized. The development of digitalization changes customer demand and even generates new customer demand. In the same field/area, the requirement of knowledge changed to be more in-depth. In addition, the cross-field/area customer demand means the requirement for multi-disciplinary knowledge integration. This is much more complex than in-depth knowledge in the same field/area. All these call for competent personnel in the company. In addition, even if the company has excellent processes/procedures and excellent knowledge storage, it is still difficult to completely replicate a person's knowledge because of the important tacit knowledge possessed by the person. Therefore, creation of a culture/mechanism to retain the competent employee in the company turns to be extremely important. Fourthly, but not lastly, investment on knowledge repository should be strengthened if possible. Knowledge will be reused more due to the incremental, rather than radical innovation in most companies. The investment is not only limited to the hardware, but also includes the maintenance of the system, the standardization of data (e.g. input data), and the archiving of the documents. All of these will facilitate the future employees to master and reuse knowledge faster with the help of easy searching.

Finally, the limitation in the current study should be address for future research. First, case study approach was adopted, which is helpful to get in-depth understanding of the topic investigates. However, it also decreases the generalization of the result due to the limited number of interviews. Further study could be conducted by using large sample survey to generalize one or more selected research areas in this study. Secondly, the companies interviewed were from different industries, which made the PLC sub-phases in our study could only be represented by the functional departments in different industries. A future study with more companies in the same industry would be valuable to better compare knowledge sharing/reuse in different PLC sub-phases.

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