Circular Economy in the Digital Age – How Information Systems Can Advance Sustainable Consumption and Production

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Roman Zeiß, M.Sc.

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Goch

Referent:	Prof. Dr. Jan Recker
Korreferent:	Prof. Dr. Wolfgang Ketter
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Four challenging but enlightening years flew by. As I write these lines, I am not sure I yet grasp what it means to finally close this chapter. What I do know for sure, however, is that I am incredibly grateful to have been part of a wonderful research community for a while, both in Cologne and beyond. People who know me know that a PhD in Cologne was never my first choice. But it was the best second choice I have ever made, because there were some people who made this journey unforgettable:

Patricia, you made me pursue my dream of a PhD. You accompany me everywhere, walking next to me or in my heart. I am at loss for words to describe my luck of knowing you. And yes, I copied those last two sentences from the acknowledgements of my Master's thesis, but they are just as true as they were five years ago.

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While I spent the years cobbling together a few sentences, more important things happened. Patricia can now call herself Dr. My niece Ida mastered the transition from elementary to secondary school. And my nephew Noah managed to see the light of day. Well done—to you and to everyone who supported you. I realize that the support I have received from these same people and many others should not be taken for granted. While we are all busy with our own lives, we should never forget to help other people be happy. Therefore, my final shout-out goes to my parents who have dedicated their lives to making sure that my siblings and I are happy: Mama und Papa, vielen Dank für eure uneingeschränkte Unterstützung seit mehr als 30 Jahren. Ich habe euch lieb.

Abstract

Our current economic practices are ecologically unsustainable. We take resources out of the ground, use them up, and dispose of them faster than our planet can regenerate them. This 'linear economy' leads to both depletion of resource deposits and uncontrollable waste streams. Alternatively, scholars, policymakers, and practitioners have begun to embrace the concept of a circular economy, which aims to minimize the input of virgin resources and output of waste and emissions from economic activities by narrowing, slowing, and looping material flows. However, implementing more circular economic practices remains challenging and cumbersome.

As many identified challenges point to an underlying information problem, digital technologies—artifacts embodied in or enabled by information and communication technologies—are being touted as potential drivers of a circular economy. However, the relationship between digital technologies as part of larger information systems and a circular economy remains largely unexplored.

In this dissertation, I present four studies that examine the relationship between digital technologies and a circular economy. In the studies, we explore (a) the potential of Information Systems scholarship to contribute to circular economy research, (b) information flows relevant to the implementation of circular economy principles, such as reuse, repair, or recycle, (c) the digitalization of waste management firms, which are a core circular economy industry, and (d) changing control structures in digital product aftermarkets that may impact repair and remanufacturing services.

The insights from this dissertation extend the body of knowledge on information systems and environmental sustainability from digital technologies for energy efficiency to digital technologies for resource efficiency in support of sustainable production and consumption.

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List of Abbreviations

AI	Artificial intelligence
AIS	Association for Information Systems
AMCIS	Americas Conference on Information Systems
ARP	Authorized repair service provider
AvaL	Austausch von auftragsbezogenen Leistungsdaten
CE	Circular economy
COVID-19	Corona virus disease 2019
CPS	Cyber-physical systems
DfE	Design for environment
eANV	Elektronisches Abfallnachweisverfahren
ECIS	European Conference on Information Systems
EfbV	Entsorgungsfachbetriebeverordnung
EMIS	Environmental management information system
ERP	Enterprise resource planning
ICIS	International Conference on Information Systems
IRP	Internal repair service provider
IS	Information systems
MMIS	Matchmaking information system
OEM	Original equipment manufacturer
OS	Operating system
PACIS	Pacific Asia Conference on Information Systems
PLC	Product life cycle

PSD	Persuasive systems design
PSS	Product-service system
RFID	Radio-frequency identification
SMIS	Sensemaking information system
TSIS	Task-supporting information system
URP	Unauthorized repair service provider
VC	Value chain
XML	Extensible markup language
ZUGFeRD	Zentraler User Guide des Forums elektronische Rechnung Deutschland

Chapter 1

Introduction

This chapter sets the stage for my dissertation on 'Circular Economy in the Digital Age.' I motivate my work and provide an overview of the research questions guiding the four studies that form the main body of my dissertation. I end with a structural outline of my work.

1.1 Motivation

Our current economic behavior is ecologically unsustainable. We extract natural resources from the ground, consume them, and dispose of them in landfills or incineration plants. This linear 'cradle-to-grave' approach may be economically viable, but it is expected to cause uncontrollable waste streams (Forti et al. 2020) and a depletion of natural resources (Meadows et al. 1972). Consider waste from electrical and electronic equipment (i.e., e-waste): In 2016, humanity generated nearly 45 million metric tons of e-waste worldwide. This is equivalent to more than six kilograms per capita. By the end of 2021, e-waste is projected to be the fastest-growing part of the global domestic waste stream (United Nations University 2017). At the same time, we are overstretching the capacity of the Earth's natural resources. In 2019, Earth Overshoot Day—the illustrative calendar date on which humanity's resource consumption for the year exceeds Earth's capacity to regenerate those resources—was in late July, the earliest date ever. In 2020, the date was moved to late August in the wake of the COVID-19 pandemic outbreak.

A circular economy (CE) is considered a promising alternative that has the potential to replace the linear 'cradle-to-grave' approach with a circular 'cradle-to-cradle' approach (Geissdoerfer et al. 2017). It is *an economic model with the objective to minimize virgin resource input as well as waste and emission output of economic activities by narrowing, slowing, and looping material flows* (Bocken et al. 2017). I define material flows as processed physical entities, including raw materials, components, and products, that move through the economic value chain from extraction to landfill or incineration. The CE concept is commonly known as the sustainability paradigm '**reduce**, **reuse**, **recycle**' (Kirchherr et al. 2017): The *narrowing* of material flows can be realized through more resource efficient production and consumption practices that **reduce** overall resource use. Material flows can be *slowed* through new forms of consumption practices that **reuse** idle or discarded products and components. The *looping* of material flows can be achieved through waste recovery practices that **recycle** materials from discarded products and components. In this way, economic value generation shall be decoupled as much as possible from consumption of virgin resources.

Despite advances in scientific discourse (Ghisellini et al. 2016) and announcements in policy (European Commission 2015; United Nations Environment Programme 2015) and business (H&M 2019; IKEA 2020; Philips 2017), the transition towards a CE remains challenging and slow—if not even reversing. While in the European Union the share of secondary materials in total materials processed increased only slightly, globally it decreased (de Wit et al. 2020; Mayer et al. 2019). On the one hand, demand for materials outpaces progress in material recovery practices. On the other hand, materials are embedded in long-term stock, such as buildings or infrastructure, rendering them unavailable as secondary material feedstock for the time being.

If leveraged appropriately, digital technologies—artifacts embodied in or enabled by information and communication technologies (Lyytinen et al. 2016)—promise great transformative potential in a CE transition (French and Shim 2016; Kristoffersen et al. 2020). One enabling factor of a CE that is often emphasized but little explored is the provision and use of information (Antikainen et al. 2018; Bressanelli et al. 2018; Nobre and Tavares 2017). Economic actors need information about the supply, demand, and condition of materials to apply circular principles (Wilts and Berg 2017). For instance, uninformed producers are unaware that their product design is hazardous or difficult to recycle. Similarly, uninformed consumers are unaware about reusable components in things they consider waste. Simultaneously, we are living in times of unprecedented data availability, where technological advances in software and hardware are adding additional intelligence to products and services (Yoo et al. 2010). These developments hold the potential to connect material with information flows along value chains (Zhang 2016).

Despite this vague notion of a relationship between digital technologies and a CE, corresponding investigations are largely lacking in information systems (IS) research. Although a research area on *IS and environmental sustainability* has emerged in the IS discipline over the past 15 years, the broad range of phenomena studied (Sedera et al. 2017)—including *sustainable business* (Hanelt et al. 2017; Seidel et al. 2013), *energy* (Ketter et al. 2016a; Loock et al. 2013), and *mobility* (Flüchter and Wortmann 2014; Watson et al. 2011)—has not yet shown any substantive links to the CE concept and its focus on circular material flows for more *sustainable production and consumption*.

I believe it is the right time for IS scholarship to join the scientific conversation on CE. The IS discipline, whose mission is to study how digital technologies can be designed and used in human enterprise (Grover and Lyytinen 2015), is known for helping solve grand challenges (Adepetu et al. 2014; Ketter et al. 2016a). In times of increasing digital penetration of our everyday lives, which I call the digital age, I consider it an opportune and societally urgent moment to analyze and develop impactful and scalable IS solutions to the overuse of natural resources by our current economic system.

My goal in this dissertation is therefore to explore the CE in the digital age and examine the relationship between digital technologies and CE from an IS perspective. In doing so, I extend the knowledge of information systems and environmental sustainability from digital technologies primarily serving energy efficiency to digital technologies for resource efficiency that support sustainable production and consumption.

1.2 Research Questions

My thesis comprises four separate but interrelated studies, all published either in peer-reviewed journals or in conference proceedings. The *first study* explores the potential of IS scholarship to contribute to the growing body of knowledge on CE. Despite our observation that the CE transition is often a challenge of effective information provision and use, we note a lack of substantive research on CE in IS scholarship. We, therefore, ask the following research question:

Research Question 1: *How can IS scholarship contribute to CE research?*

We conducted a structured, interdisciplinary review of the literature on the relationship between IS and CE. Based on our synthesis and interpretation, we developed directions for future IS research that emphasize a shift from optimizing linear processes for efficiency (i.e., narrowing material flows) to circular processes that extend the life of materials through circular material flows (i.e., slowing and looping material flows). The proposed directions aim to provide new insights into how IS can help understand and enact circular material flows.

The *second study* provides a conceptual foundation for analyzing and designing IS for a CE. Building on the complexity perspective outlined in the synthesis of our literature review from study 1, we conceptualize IS as information brokers that support the complex application of CE principles, such as reduce, reuse, and recycle, by providing appropriate information. We ask the following research question:

Research Question 2: *What information flows are required for the application of CE principles?*

We taxonomized CE principles based on their underlying material flow networks and identified four classes of information flows that enable these principles to function properly. With this taxonomy, we continue the introduction of the CE idea and its central principles to IS scholars by expanding the conceptual lexicon we began in our study 1. We describe the components of material flow networks that underly CE principles, identify the information flows that support material flow networks, and discuss four roles that IS can play in providing these information flows. In doing so, we intend to facilitate solution-oriented IS design research on digitally enabled CE solutions.

Following the contribution of study 2 on the design of IS artifacts for a CE, the *third study* focuses on the adoption of such artifacts in a specific industry relevant to CE: waste management, a sector which handles waste from origin to disposal or recycling. As outlined in study 1, waste management plays a key role in the application of the recycle principle with a focus on closing the loop of waste materials on the one hand and secondary resources on the other. We are seeing it increasingly being targeted by digital technology providers that promise more effective and efficient operations, for instance, through smart bins, semi-autonomous trucks, or artificial intelligence-based material recognition. However, little is known about the current extent of digitalization in waste management. Available studies focus on firms' digitalization intentions, but largely neglect the degree of actual adoption of digital technologies and do not differentiate digitalization along the various steps of the waste management value chain. Therefore, we pose the following research question:

Research Question 3: *What is the status-quo of digitalization by private and public waste management firms in Germany?*

We present a descriptive, cross-sectional survey that captures the current digitalization efforts and strategies of German waste management firms. We analyzed their levels of digitalization along different stages of the waste management value chain and examined their digitalization goals, approaches, and transformation measures. We identified implementation challenges that partly explain, why actual adoption of advanced digital technologies lags behind intentions reported in 2016 and 2017. Our findings point to previously ignored research opportunities, such as the digital transformation of established, largely non-digital infrastructures.

The *fourth study* takes a critical look at the repairability of digital products. With the advent of digital products, we observe a qualitative shift in the way original equipment manufacturers (OEMs) control the aftermarket. Digital technologies allow products to be monitored, accessed, and modified long after they are sold. This is important to understand because these capabilities can encourage discriminatory and anti-competitive conduct in aftermarkets, which could limit the ability to repair defective digital products. This in turn has implications for the longevity of these products and the CE strategy to slow material flows through reuse, repair, and remanufacture. We, therefore, ask the following research question:

Research Question 4: *How do digital products enable aftermarket control?*

We conducted a longitudinal embedded case study of Apple's iPhone repair aftermarket to develop a new theory of how digital product capabilities enable and change modes and means of product aftermarket control. We show how aftermarket control has evolved from a regime of limited, non-discriminatory control into a holistic regime of self-reinforcing control that discriminates between authorized and unauthorized repair service providers. In light of study 2 and study 3, the findings from study 4 suggest that the adoption of well-designed artifacts may be insufficient to explain a successful CE transition, if the interests and power of involved stakeholders with linear business models are ignored.

1.3 Thesis Structure

My dissertation is divided into three parts (Figure 1). Part A is the preface. It contains an introduction (Chapter 1) that motivates my work and gives an overview of the research questions guiding the four studies, and a research background (Chapter 2) that provides information about a CE as a research context and summarizes the current body of knowledge on IS and environmental sustainability.

Part B constitutes the main body of the thesis. It presents the four studies that I have conducted with colleagues over the past four years. Table 1 summarizes the publication history of the studies.

In study 1, I report on the interdisciplinary literature review that introduces the CE concept to the IS research community and forms the basis for the IS research agenda on a digital CE (Chapter 3). The following three studies then flow from the research agenda. In study 2, I present the taxonomy that categorizes CE principles based on underlying material and information flows (Chapter 4). In study 3, I report on our cross-sectional survey of 130 German waste management firms, which analyzes and identifies digitalization levels and challenges along the waste management value chain (Chapter 5). In study 4, I present our longitudinal embedded case study of Apple's iPhone repair aftermarket, from which we developed a new theory of digital product aftermarket control (Chapter 6).

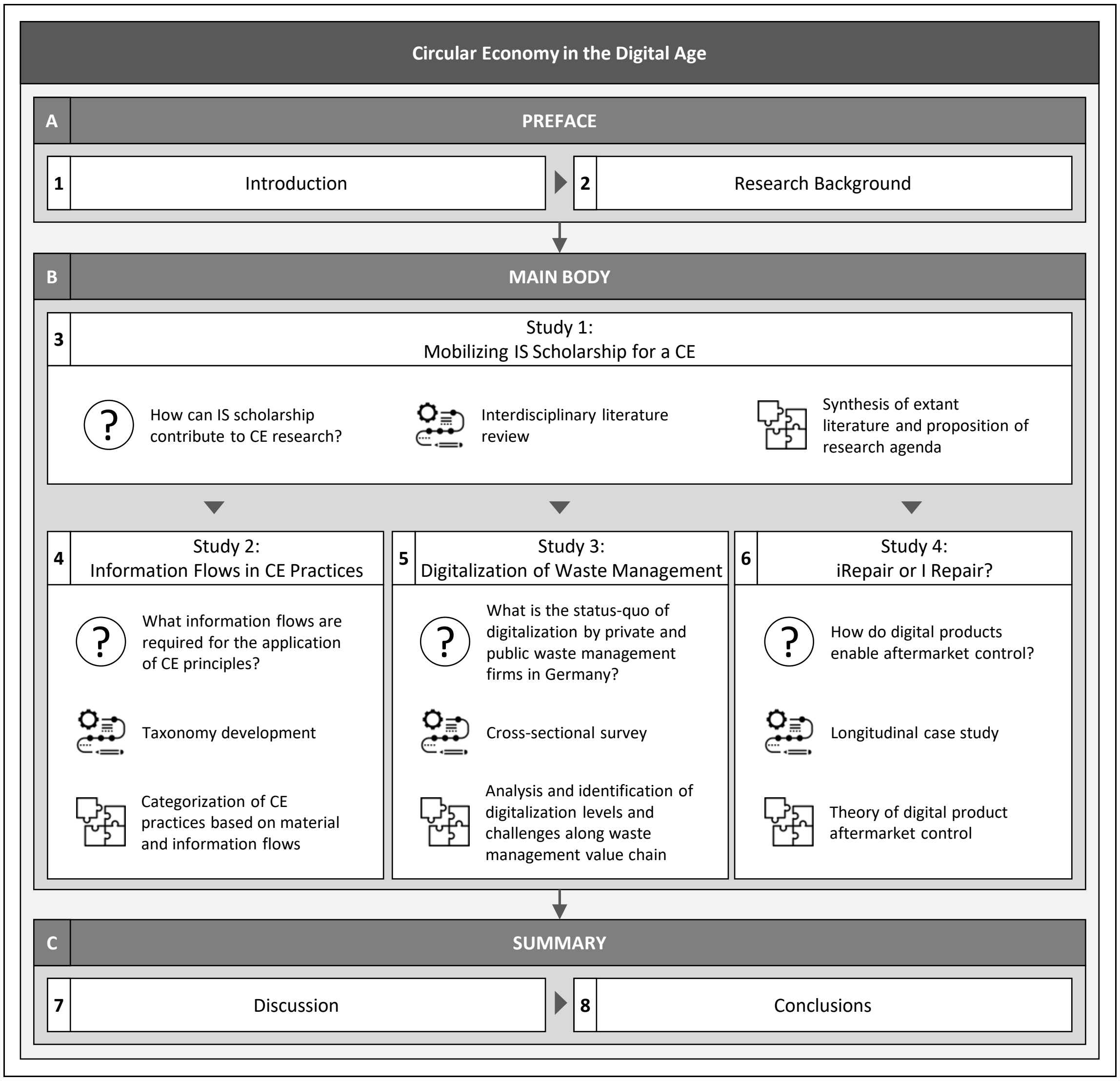
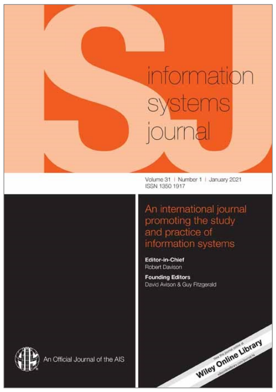


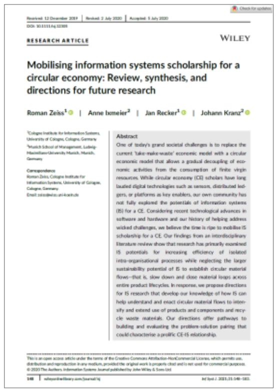
Figure 1. Dissertation structure[1]

Part C contains a summary of the dissertation. It includes a discussion that reviews the major contributions of the four studies, synthesizes implications for research and practice, and identifies general limitations and future research opportunities for studying a CE in the digital age (Chapter 7). Chapter 8 concludes this dissertation.

[1] Icons made by *mynamepong* and *eucalyp* from www.flaticon.com.

Table 1. Publication history of the four research studies within this dissertation

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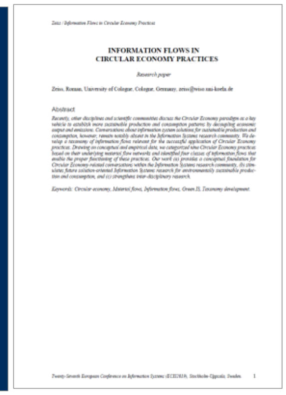
RESEARCH ARTICLE

Mobilising information systems scholarship for a circular economy: Review, synthesis, and directions for future research

Roman Zeiss | Anne Ixmeier | Jan Recker | Johann Kranz

Title: Mobilizing information systems scholarship for a circular economy: Review, synthesis, and directions for future research
Authors: Roman Zeiss, Anne Ixmeier, Jan Recker, Johann Kranz
History: International Conference on Information Systems (ICIS) 2020, Munich, SIGGreen workshop
Status: published in *Information Systems Journal*


INFORMATION FLOWS IN CIRCULAR ECONOMY PRACTICES

Research paper

Title: Information flows in circular economy practices
Authors: Roman Zeiss
History: European Conference on Information Systems (ECIS) 2019, Stockholm, track paper
Status: published in *Proceedings of the 27th European Conference on Information Systems*


WM&R

Digitalization of waste management: Insights from German private and public waste management firms

Rebecca Borchard, Roman Zeiss and Jan Recker

Title: Digitalization of waste management: Insights from German private and public waste management firms
Authors: Rebecca Borchard, Roman Zeiss, Jan Recker
History: n/a
Status: published in *Waste Management & Research*


iRepair or I Repair?

How Digital Products Enable New Forms of Aftermarket Control

Title: iRepair or I repair? How digital products enable new forms of aftermarket control
Authors: Roman Zeiss, Jan Recker, Mario Müller
History:
- 6th Innovation in Information Infrastructures (III) workshop 2019, Surrey
- International Conference on Information Systems (ICIS) 2020, Munich, track paper

Status: second round in *MIS Quarterly*

Chapter 2

Research Background

In this chapter, I provide information on the CE concept as a research context and summarize the current body of knowledge on IS and environmental sustainability. I note, IS research with a dedicated focus on resource efficiency and circular material flows (i.e., sustainable production and consumption) remains absent. I take this as a starting point for the following four studies that explore the relationship between digital technologies and CE from an IS perspective.

2.1 Circular Economy

Today's conceptualization of a CE is rooted in scientific conversations that began more than 50 years ago (Blomsma and Brennan 2017; Reike et al. 2018). At the core of these conversations, a framework of strategies and principles has been synthesized, through which economic value generation should be decoupled as much as possible from virgin resource consumption. Despite this history and the progress made over time, a transition to a CE remains slow and challenging.

2.1.1 Concepts and Definitions

The concept of a CE describes an economic model with the objective to minimize virgin resource input and waste and emission output of economic activities by pursuing three strategies: narrowing, slowing, and looping material flows (Bocken et al. 2016; Geissdoerfer et al. 2017). In this context, I define material flows as processed physical entities, including raw materials, components, and products, that move through the economic value chain from extraction of virgin resources to landfilling or incineration of waste. Simply put, the definition refers to an input-process-output model, in which materials are input resources (e.g., crude oil) required for a value-added process (e.g., plastics production) that generates outputs (e.g., plastic packaging, plastic waste, and production emissions). Then, the three CE strategies to narrow, slow, and loop material flows outline as follows (Bocken et al. 2016).

The strategy to *narrow material flows* aims to reduce the amount of input resources required and output emissions and waste caused for a unit of value produced by an economic activity (Bocken et al. 2016). It can be realized through more resource efficient production, consumption, and post-consumption practices. Resource efficient production practices include, for instance, a more precise milling machine to reduce cut-off materials or the redesign of products to reduce unnecessary filler material. Examples of resource efficient consumption practices include a better-insulated refrigerator to reduce the amount of electricity needed for cooling or anticipatory acceleration and breaking in traffic to reduce the fuel consumption per kilometer driven. A resource efficient post-consumption practice is, for instance, optimized routing of garbage trucks, which reduces fuel consumption per kilogram waste collected.

The strategy to *slow material flows* aims to intensify and extend the utilization of idle or discarded products and components (Bocken et al. 2016). This reduces the overall 'speed' with which materials move through the economy. An intensified utilization rate of a product can be achieved through collaborative consumption practices that allow for simultaneous (e.g., sharing) or sequential (e.g., leasing, renting, reselling, gifting) use of products. For example, car-sharing providers that enable the collaborative consumption of mobility services increase car utilization rates. An extended utilization period of products and components can be achieved through repair practices that restore the original functionality of broken components and through reuse practices that allow discarded but still functional products or components to be used again. For example, auto repair shops restore defective vehicles to their original functionality, and remanufacturers extract functional components from broken products to use in assembling new products.

The strategy to *loop material flows* aims to prevent waste material leakage throughout production and after consumption (Bocken et al. 2016). This can be achieved through waste recovery practices that recycle materials from post-industrial waste streams, such as transport packaging, or post-consumer waste streams, such as discarded products. First, the waste materials are collected, dismantled, and sorted. Then, mechanical or chemical recycling of the sorted waste streams generates secondary raw materials that can be incorporated into new lifecycles of components and products. A well-known German example of secondary material recycling is the reprocessing of polyethylene terephthalate (PET) bottles at the end of their life. The bottles are collected and recycled into plastic flakes that can substitute virgin PET made from petroleum.

In line with the three CE strategies, 'r-frameworks' have been developed to translate the strategies into concrete practices (Kirchherr et al. 2017; Reike et al. 2018). R-frameworks consist of 'r-principles'—a set of terms beginning with 're-' (Latin: 'again')—that are conducive to the CE strategies. The most commonly known r-framework comprises three r-principles: reduce, reuse, recycle (one r-principle per CE strategy). Over the past decades, more granular r-frameworks have emerged with up to ten r-principles specifying the original three r-principles. For example, reuse can be divided into component reuse (remanufacturing) and product reuse (resale or gifting). Table 2 depicts an r-framework that integrates Bocken et al.'s (2016) CE strategies with Potting et al.'s (2017) CE principles. In this dissertation, r-frameworks with a varying number of r-principles will be used depending on the application purpose. Despite this variance, however, the frameworks used will refer to the same three CE strategies and the overall CE objective to minimize resource input and waste and emission output.

The order of CE principles[2] depicted in Table 2 follows a 'waste hierarchy' from top to bottom (Reike et al. 2018; van Buren et al. 2016). Higher-ranking principles should be prioritized over lower-ranking ones to achieve better environmental impact. For example, not using a car—and instead using a bike—should be prioritized over reusing a second-hand car. The waste hierarchy follows the idea of dematerializing the economy and avoiding material consumption in the first place. Material resources that are never extracted from the ground cannot become waste and thus prevent any circular treatment, such as recycling, at the end of their life (Geissdoerfer et al. 2017; Kirchherr et al. 2017).

[2] Note that *r-principles*, *CE practices*, *CE principles*, *circular practices*, and *circular principles* are used interchangeably within this dissertation All refer to practices that specify and are conducive to the three CE strategies.

However, since complete dematerialization of the economy is not feasible, lower-ranking CE principles will always play an important role in a CE transition.

Table 2. r-framework based on Bocken et al. (2016) and Potting et al. (2017)

CE strategy	CE principle	Description	Example
Narrow material flows through smarter product manufacture and use	Refuse	Refuse a product's use by abandoning its function or consuming a radically different product with the same function	A consumer uses a bike instead of a car
	Reduce	Reduce material resource consumption (increase resource efficiency) during product manufacture or use	A producer uses a more precise milling machine, which generates less cut-off excess materials
Slow material flows through intensification and extension of product and component use	Rethink	Rethink a product's use to increase its utilization rate	Multiple consumers share a car
	Reuse	Reuse a discarded product, which is still in good condition, in its original function	A consumer resells a used bike to another consumer
	Repair	Repair a defective product to use it in its original function	A consumer repairs a flat tire of a bike
	Refurbish	Refurbish an old product and bring it up to date	A producer restores a worn-out bike
	Remanufacture	Remanufacture a component of a discarded product into a new product with the same function	A producer extracts a bike chain from a discarded bike to use it in another bike
Loop material flows through reprocessing of waste materials	Recycle	Recycle materials to obtain the same or lower quality	A waste manager reprocesses discarded PET bottles into recyclate that can substitute virgin PET produced from oil
	Recover	Recover heat and energy from the incineration of waste materials	A waste manager incinerates household waste to recover heat and generate electricity

CE principles span the entire economy and integrate into the linear value chain at various stages. Figure 2 illustrates how CE principles (grey boxes) transform a linear value chain (black boxes) consisting of forward material flows (solid arrows) from raw material extraction to waste disposal into a circular value network consisting of multiple loops of backward material flows (dashed arrows). The waste hierarchy is visually reflected in form of smaller and larger loops: smaller loops (e.g., repair or reuse) should be favored over larger loops (e.g., remanufacture or recycle).

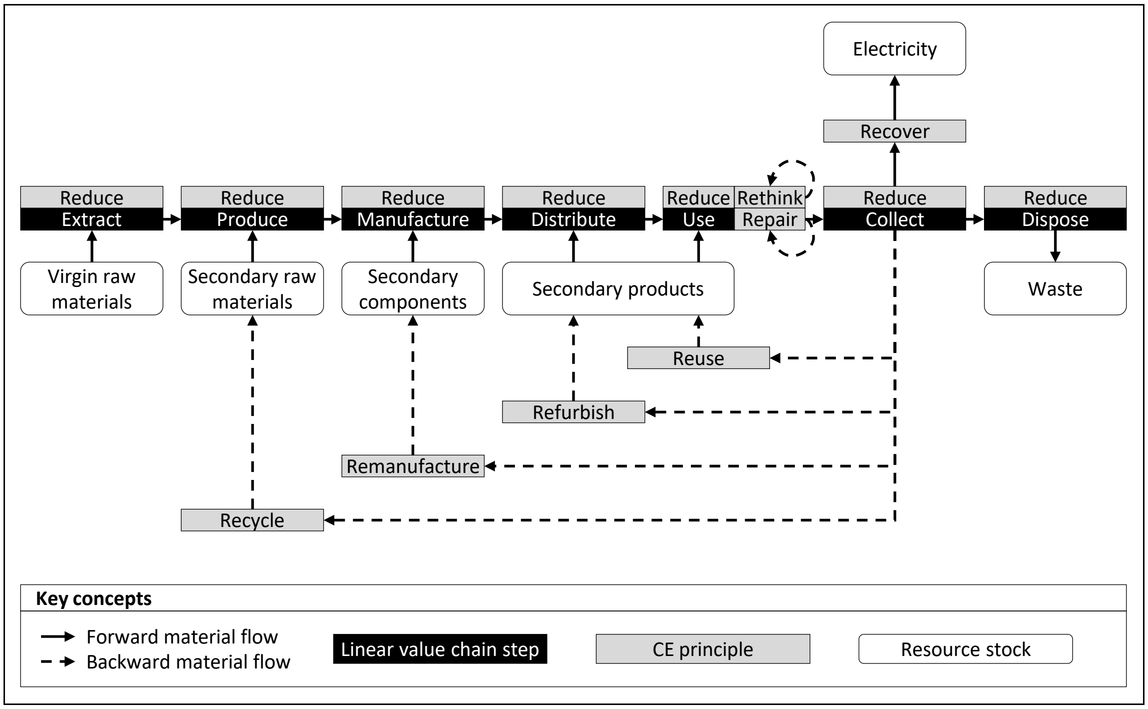


Figure 2. Conceptual model of a circular economy

Our today's understanding of a CE has its roots in conversations that started more than 50 years ago (Blomsma and Brennan 2017; Reike et al. 2018). While these conversations—and the resulting policymaking—were initially based on a problem-centered account of waste treatment through recycling (Boulding 1966; Meadows et al. 1972; Stahel and Reday-Mulvey 1981), the idea evolved into a more opportunity-centered account that aimed to preserve the economic value of products and components through CE principles, such as repair, reuse, or remanufacture (Chertow 2000; Ehrenfeld and Gertler 1997; Fiksel 1996; Sroufe et al. 2000). This development sparked research interest from other disciplines, such as Operations Research (Fleischmann et al. 1997; Govindan et al. 2015; Guide and van Wassenhove 2009; Rogers and Tibben-Lembke 2001) and Management Science (Bocken et al. 2016; Hopkinson et al. 2018; Lüdeke-Freund et al. 2019), prompting scholars to shift their research focus from a single firm to industrial parks and eventually to product lifecycles that encompass entire supply chains and ecosystems.

2.1.2 Implementation Barriers

Despite progress in scientific discourse (Ghisellini et al. 2016) and announcements in policy (European Commission 2015; United Nations Environment Programme 2015) and business (H&M 2019; IKEA 2020; Philips 2017), a transition towards a CE remains challenging and slow. In the European Union, the share of secondary materials in total processed materials increased slightly from 9.3% in 2010 to 9.6% in 2014 (Mayer et al. 2019). At the global level, it declined from 9.1% in 2018 to 8.6% in 2020 (de Wit et al. 2020). With a growing global demand for materials that has more than tripled since 1970 (United Nations Environment Programme 2020), the growth rate of virgin resource extraction is outpacing developments in material recovery.

Several scholars have identified implementation barriers that impede the transition to a CE (Araujo Galvão et al. 2018; Govindan and Hasanagic 2018; Ritzén and Sandström 2017). Kirchherr et al. (2018) structure them in four categories: First, despite increased societal sensitivity to environmental issues, scholars see *cultural barriers* as a key obstacle to a CE transition (Jesus and Mendonça 2018; Kirchherr et al. 2018). Cultural barriers refer to the lack of awareness and willingness of consumers and companies to engage with CE strategies and principles. Consumers play a similarly important role in a CE as companies and policymakers (Hazen et al. 2017). Without their willingness to engage, CE business models based on collaborative consumption practices (e.g., reuse) or product lifecycle thinking (e.g., recycle) remain risky ventures.

Second, *market barriers* inhibit a CE transition by jeopardizing the economic viability of CE initiatives and business models (Kirchherr et al. 2018). Secondary markets for reused products, components, or recycled raw materials are outpriced by their linear alternatives, as the latter usually do not account for negative environmental externalities caused during resource extraction and benefit from additional government subsidies (Ranta et al. 2018). For example, plastic recycling markets continue to struggle as fossil-fuel based plastic trades at lower costs in global markets. In addition, companies face up-front investment costs during CE transformations, rendering business cases economically infeasible and unattractive.

Third, *regulatory barriers* relate either to existing policies that impede CE transition or to a lack of policies that fail to address and remove transition barriers, such as uncompetitive recyclate markets or lack of consumer awareness (Jesus and Mendonça 2018; Kirchherr et al. 2018). Often, the implementation of CE principles clashes with long-established government regulations, such as market-efficient trade and transportation of recyclable waste materials across national borders, which is often hindered by import restrictions.

Fourth, *technological barriers* refer to the lack of technologies that would make the implementation of CE principles more efficient and effective (Kirchherr et al. 2018). In this context, the CE literature understands technology not only as a set of physical or digital artifacts, such as production machinery or production planning software, but as the practical application of knowledge in general. Technological barriers therefore include the lack of appropriate operational processes and methods, such as reverse logistics (i.e., an efficient product take-back system relevant to reuse, remanufacture, or recycle principles). Other technological barriers mentioned in the literature include a lack of technical CE know-how and skills, such as knowledge about circular product design (Jesus and Mendonça 2018), or insufficient intra-organizational collaboration mechanisms (Jaeger and Upadhyay 2020).

Most barriers to CE implementation mentioned in literature relate to an underlying information problem. For example, unawareness and unwillingness to participate in a CE appear to be addressable through informating and persuasive IS (Oinas-Kukkonen and Harjumaa 2009; Zuboff 1985). From an economic theory perspective, failing markets can be guided toward more pareto-optimal outcomes by the availability of timely and truthful information (Grossman and Stiglitz 1980; Stigler 1961).

The working thesis of my dissertation therefore assumes that the provision of the right information by digital technologies to the right actors at the right time can facilitate the implementation and entrenchment of circular principles. However, as I will show next, the details of this assumed 'information relationship' between digital technologies and a CE are as yet largely unexplored.

2.2 Information Systems and Environmental Sustainability

Scholarly inquiry into the relationship between environmental sustainability and IS has created a relevant, albeit niche, area of research within the IS discipline (Elliot and Webster 2017). Over time, two themes have synthesized that form the core of this conversation: Green IT and Green IS.

Green IT "refers to environmentally sound IT [and comprises] the study and practice of designing, manufacturing, using, and disposing of computers, servers, and associated subsystems […] efficiently and effectively with minimal or no impact on the environment" (Murugesan 2008, pp. 25-26). Green IS focuses on "IS-enabled organizational [and individual] practices and processes that improve environmental and economic performance" (Melville 2010, p. 2). The latter theme is more broadly understood to include Green IT and refers to a larger portfolio of IS-enabled initiatives that help organizations and individuals become more environmentally sustainable (Boudreau et al. 2008; Watson et al. 2010).

In the following, I sketch the historical outline and main body of knowledge of both themes within the IS discipline based on a review of the literature published in the AIS Senior Scholar's basket of journals and the four leading AIS conferences (Figure 3)[3].

[3] The literature search was carried out on 1 June 2021 using the Web of Science (for journal articles) and AISeL (for conference papers) databases. The search string '"green IS" OR "green IT" OR "sustainable IS" OR "sustainable IT"' was applied on title, abstract, and keywords and scanned literature published between 2000 and 2020. The initial literature sample was refined excluding unrelated publications and conference panel descriptions.

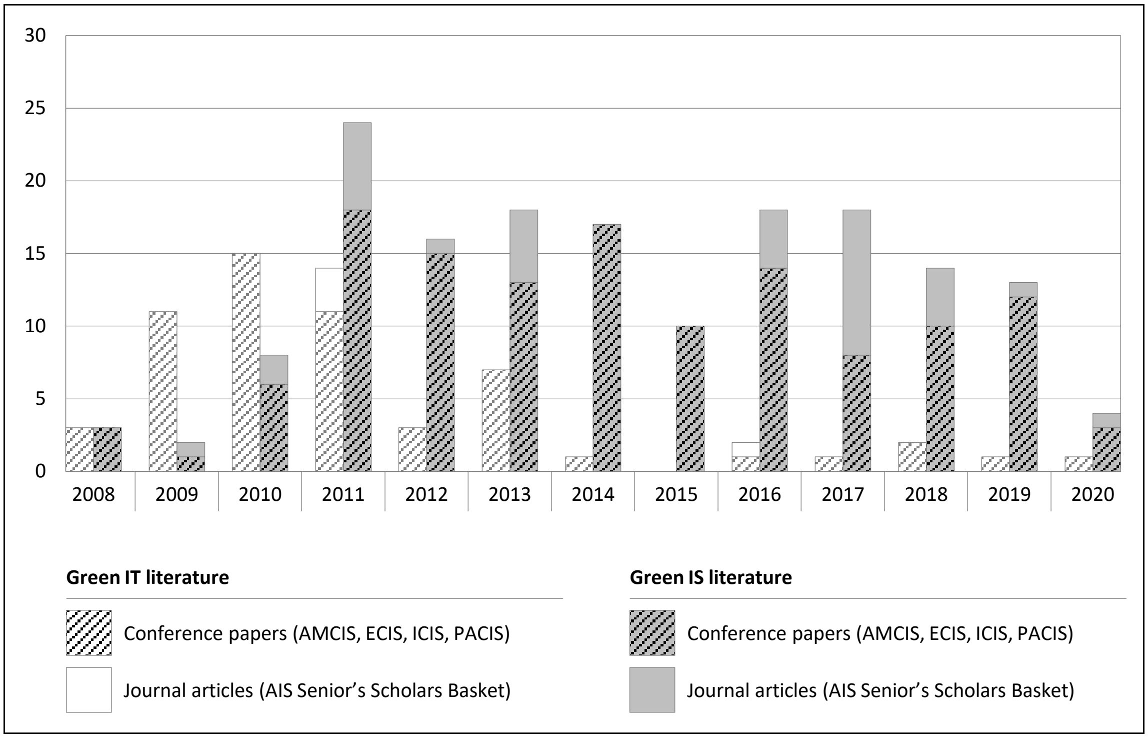


Figure 3. Number of published Green IT/IS literature over time

Green IT research emerged in 2008 following discussions in practitioner magazines and grey literature, such as Gartner's 'Hype Cycle for Emerging Technologies' (Gartner Inc. 2007, 2008). Publications revolved around conceptualizing and qualitatively exploring the relation between the production, use, and disposal of IT and the resulting environmental impacts (Butler and Daly 2009; Elliot and Binney 2008). Until its peak in 2010, Green IT research continued to dominate the publication landscape. Scholars focused on taxonomizing Green IT practices (Erek et al. 2009; McLaren et al. 2010), identifying and testing antecedents to Green IT adoption (Cooper and Molla 2010; Datta et al. 2010; Kuo 2010; Sarkar and Young 2009; Schmidt et al. 2010), and deriving organizational frameworks for Green IT readiness and implementation (Mann et al. 2009; Molla et al. 2009). After 2010, scholarly interest in Green IT waned and the focus shifted to governance of Green IT initiatives (Hedwig et al. 2011; Katchuck and Port 2011; Schmidt and Kolbe 2011), quantified economic and environmental impact of Green IT (Grimm et al. 2013; Nishant et al. 2011, 2013b; Schödwell et al. 2013), and Green IT practices outside organizational boundaries (Ixmeier and Kranz 2020; Leung et al. 2018; Samuri and Rahim, Nor Zairah Ab 2018). Overall, Green IT research within the IS discipline took place at conferences, with only four of 61 articles published in journals (Bose and Luo 2011; Desautels and Berthon 2011; Hu et al. 2016; Zhang et al. 2011). Table 3 summarizes the body of knowledge on Green IT found in the review.

Table 3. Knowledge on Green IT in reviewed literature

Topic	Knowledge	References
Green IT	*Green IT practices can render data centers more eco-efficient*	
	• Server virtualization • Server consolidation • Cooling optimization • Load balancing/ allocation	Alaraifi et al. (2011a); Alaraifi et al. (2011b); Bodenstein et al. (2011); Hedwig et al. (2009); Hedwig et al. (2010); Hedwig et al. (2011); Hedwig et al. (2012); McLaren et al. (2010); Sayeed and Gill (2009)
	Several factors affect if and how green IT practices are implemented and used	
	• Anticipated cost savings • Awareness • Acceptance • Customer requirements & attitudes • Governmental regulations • Management commitment • Normative pressures • Perceived importance • Environmental engagement • Experience • Measurement • Standards • Eco-motivations • Organizational readiness • Organizational maturity • Readiness of external IT service providers	Babin and Nicholson (2011); Bose and Luo (2011); Datta et al. (2010); Hu et al. (2016); Ixmeier and Kranz (2020); Kuo (2010); Leung et al. (2018); Loo et al. (2013); Mithas et al. (2010); Molla (2009); Molla et al. (2009); Molla and Abareshi (2011); Nash and Wakefield (2019); Nomani and Cater-Steel (2014); Abdul Rahim and Rahman (2013); Sarkar and Young (2009); Schmidt et al. (2010); Thongmak (2012); Yang et al. (2013)
	Green IT practices are planned, implemented, and governed differently	
	• Strategic green IT alignment framework • Green IT governance • Designing green IT systems • Sustaining green IT practices	Erek et al. (2011); Nanath and Pillai (2012); Schmidt and Kolbe (2011); Zhang et al. (2011)
	Green IT practices can have economic and ecologic impacts on the firm performance	
	• Carbon footprint of IT services • Metrics and indicators • Direct and indirect eco-impacts • Impact on firm market value	Grimm et al. (2013); Nishant et al. (2012); Nishant et al. (2013b); Nishant et al. (2013a); Schödwell et al. (2013)

Research on Green IS initially lagged behind Green IT research. While conceptualized since 2008 (Chen et al. 2009; Elliot and Binney 2008), Green IS research took off in 2010/2011 with a plethora of conference papers, two seminal journal articles

(Melville 2010; Watson et al. 2010), and a special issue in the *Journal of Strategic Information Systems* (Berthon and Donnellan 2011). Compared to Green IT's focus on energy efficiency of intra-organizational IT equipment (Boudreau et al. 2008), Green IS research has initiated a more heterogeneous and consistent conversation of the potentials and risks of IS for environmental sustainability.

To date, Green IS research has focused on the design, adoption, and impact of IS that help organizations, households, and individuals (a) reduce their overall energy consumption and (b) shift it to renewable energies, such as wind or solar power. A general proposition underlying the scientific conversation has been articulated by Watson et al. (2010) as "Energy + Information < Energy" (p. 24), that is, the availability of information reduces overall energy consumption and associated greenhouse gas emissions. The Green IS conversation can be summarized in three research topics: IS for sustainable business, energy, and mobility.

First, research on IS for *sustainable business* has examined IS-enabled sustainability initiatives within organizational enterprises (Table 4). Such initiatives can range from small-scale sustainable workplace improvements, such as video conferencing (Degirmenci and Recker 2018; Oppong-Tawiah et al. 2014; Sapraz and Han 2019), to large-scale sustainable business transformations (Ahmed and Sundaram 2011; Elliot 2011; Seidel et al. 2013; Seidel et al. 2018), including IS-enabled sustainable innovations (Dao et al. 2011; Hanelt et al. 2017; Loeser et al. 2017; van Osch and Avital 2010) and supply chains (Appelhanz 2013; Leyerer et al. 2018; Schrödl and Simkin 2014). Beyond initiatives in which IS support the sustainable organizational or individual behavior, researchers have investigated the role of environmental management systems in reporting organizations' environmental performance and ensuring their compliance with environmental regulations (Bengtsson and Ågerfalk 2011; Corbett 2013; Hilpert et al. 2014; Hoang et al. 2019; Ning et al. 2019; Rush and Melville 2012; Zampou et al. 2016).

Table 4. Knowledge on Green IS for sustainable business in reviewed literature

Topic	Knowledge	References
Green IS for sustainable business	*Green IS can enable sustainable innovations and business transformations*	
	• Sustainable innovations require multi-stakeholder engagement	Dao et al. (2011); Melville (2010); van Osch and Avital (2010)
	• IT capability can be an enabler of proactive environmental strategy	Benitez-Amado and Walczuch (2012)
	• Organizational power relationships can shape how Green IS practices emerge and evolve	Ijab et al. (2012)
	• IS can support organizational sustainability transformation through sensemaking and sustainable practicing affordances	Seidel et al. (2013); Seidel et al. (2018)
	• IS can encourage pro-environmental behavior in the office through persuasion, nudging, sensemaking	Degirmenci and Recker (2018); Henkel et al. (2019); Oppong-Tawiah et al. (2014)
	• Green IS initiatives can be initiated through a bottom-up process in search of management endorsement	Hedman and Henningsson (2016)
	• Green IS strategies can mediate environmental orientation and green IT/IS practices	Loeser et al. (2017)
	• Impact of eco-innovations on organizational performance can be improved by supporting IS	Hanelt et al. (2017)
	Green IS can enable more sustainable supply chains and logistics	
	• IS can support the design of sustainable supply chains	Chaabane et al. (2008); Leyerer et al. (2018)
	• IS can support sustainable procurement by integrating material parameters	Dada et al. (2011)
	• Environmental management IS can support reverse logistic processes	Stindt et al. (2014)
	Green IS can enable sustainability compliance and reporting	
	• Sustainability benchmarking can face issues of data heterogeneity and sensitivity, which encryption can mitigate	Kerschbaum et al. (2011)
	• IS can help organizations comply with reporting regulations	Butler (2011); Hilpert et al. (2014); Volkoff et al. (2011); Zampou et al. (2016)
	• IS can help improving sustainability indicators and routines	Bengtsson and Ågerfalk (2011); Petrini and Pozzebon (2009)
	• Carbon management systems can increase firms' market value, change employees' environmental behavior, and increase the carbon disclosure performance	Corbett (2013); Ning et al. (2019); Rush and Melville (2012)

Second, research on IS for *sustainable energy* has advanced our understanding of how IS can help organizations and households reduce energy demand and increase the share of renewable energies (Table 5).

Table 5. Knowledge on Green IS for sustainable energy in reviewed literature

Topic	Knowledge	References
Green IS for sustainable energy	*Green IS (here: smart meters) can spur pro-environmental energy consumption behavior*	
	• Gamification can help reduce energy consumption where social norms are strong & communities close	Yim (2011)
	• An intermediate level of information detail is most suited to guide household decision-making through smart meters	Dalén et al. (2013)
	• While benefits from load shifting exceed information costs, more information does not necessarily yield higher profits	Feuerriegel et al. (2013)
	• Nudging (e.g., intermediate level default goals) can lead to statistically significant savings by affecting goal choice	Loock et al. (2013)
	• Real-time consumption feedback can reduce energy and water consumption in the long run (i.e., no decay)	Tiefenbeck et al. (2016)
	• Setting goals can increase pro-environmental behavior (rebound possible when goal setting is removed)	Staples et al. (2017)
	Several factors affect if and how smart meters are implemented and used	
	• Technology Acceptance Model (TAM): perceived usefulness, perceived ease of use, attitude toward use • Environmental concern • Social influence (family, friends, media) • Perceived privacy risks • Perceived locus of causality	Kranz et al. (2010); Kranz and Picot (2011); Strüker and Kerschbaum (2012); Wunderlich et al. (2012); Wunderlich et al. (2013); Wunderlich et al. (2019)
	Smart grids can support the balancing of electricity markets	
	• Demand side management systems can decrease retailers' expenditures by diminishing price uncertainty	Feuerriegel et al. (2012)
	• Agent-based simulation systems can help design a sustainable electricity transformation	Ketter et al. (2016a); Ketter et al. (2016b)
	• Energy storage systems can generate profits by participating as seller in the spot and as buyer in the real-time market	Naseri et al. (2019)

The IT artifact under scrutiny is the smart meter, which adds intelligence to conventional electricity systems and turns them into 'smart grids' (Brandt et al. 2018; Corbett 2011). In this context, design-oriented research has investigated the type of consumption feedback provided by smart meters that is optimal for individual pro-environmental behavior change (Dalén et al. 2013; Feuerriegel et al. 2013; Tiefenbeck et al. 2016; Yim 2011) and how gamification and nudging mechanisms buffer or boost this change (Baeriswyl et al. 2011; Kroll et al. 2019; Loock et al. 2013; Staples et al. 2017). Adoption-oriented research examined factors that influence the acceptance and continued use of smart meters (Friedemann et al. 2011; Kranz et al. 2010; Kranz and Picot 2011; Strüker and Kerschbaum 2012; Wunderlich et al. 2019). Impact-oriented research explored the benefits of smart grids, such as the balancing of electricity markets through demand side management (Feuerriegel et al. 2012; Fridgen et al. 2014; Hylton et al. 2013; Ketter et al. 2016a; Naseri et al. 2019).

Third, research on IS for *sustainable mobility* has focused on IS that help organizations and individuals reduce transportation-related emissions (Table 6).

Table 6. Knowledge on Green IS for sustainable mobility in reviewed literature

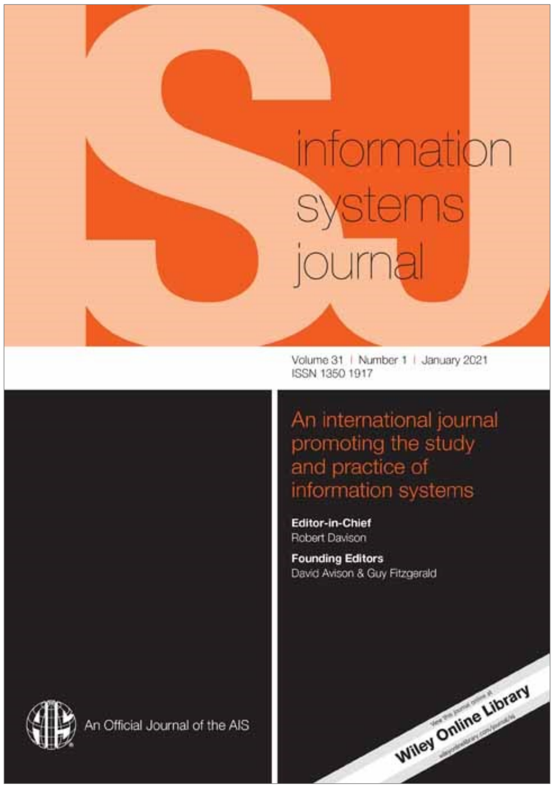
Topic	Knowledge	References
Green IS for sustainable mobility	*Green IS can spur pro-environmental travel behavior*	
	• In the long term, social normative feedback can buffer users' intrinsic motivation to use e-bikes for commuting	Flüchter et al. (2014)
	• Higher default payments can increase the level of carbon-offset payments of air travel	Székely et al. (2016)
	Green IS can enable collective mobility approaches	
	• Decision support systems can help determine the optimal size and composition of carsharing fleets	Kuehne et al. (2017)
	• Mobile apps can enable collaborative ridesharing concepts	Lembcke and Herrenkind (2020); Watson et al. (2011)
	Green IS can support the sector integration between mobility and energy	
	• Demand side management in electric vehicles can help balance electricity markets and generate significant savings	Fridgen et al. (2014); Kirpes and Becker (2018)

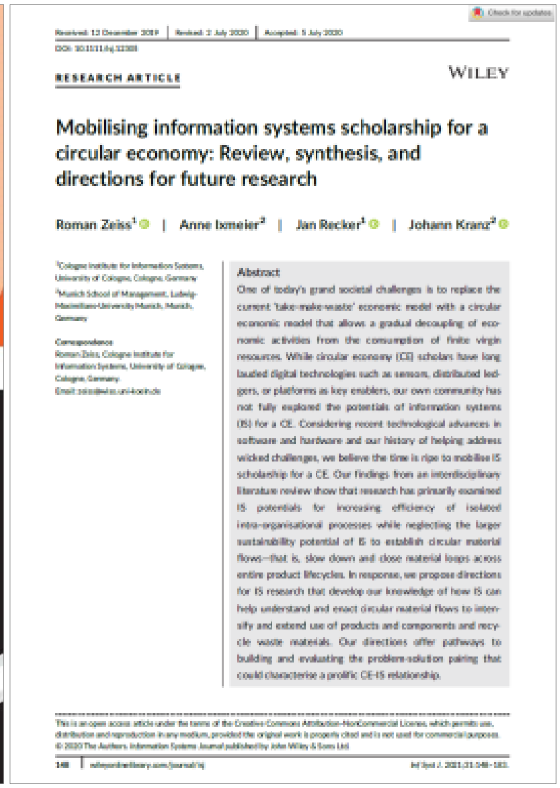
Similar to feedback from smart meters in households, scholars have explored the potential of IS to promote sustainable travel behavior (e.g., eco-driving, emission offsetting) through information feedback (Flüchter et al. 2014; Gottlieb et al. 2018), supported by various nudging mechanisms (Bui and Veit 2015; Székely et al. 2016). In addition to changing individual travel behavior, scholars have also studied the role of IS in supporting collective mobility schemes, also known as shared mobility. In this context, Green IS research has identified antecedents for participation in sharing services (Lembcke and Herrenkind 2020; Matzner et al. 2015) and developed decision support systems for the optimal sizing and composition of car-sharing fleets (Kuehne et al. 2017). Finally, scholars have transferred the idea of smart grid-based intelligence from the residential energy consumption domain to the electric mobility domain to explore the benefits of demand-side shifting of electric vehicle charging times (Fridgen et al. 2014; Kirpes and Becker 2018).

In summary, Green IT and Green IS research in leading AIS journals and conference proceedings has focused on the design, adoption, and impact of IS-enabled *energy efficiency* solutions aimed at reducing energy consumption, particularly electricity consumption in businesses, households, and mobility. The scale of such solutions can range from small-scale smartphone applications that persuade individuals to adopt pro-environmental energy consumption behavior, to medium-scale carbon emission systems in organizations, to large-scale demand side management systems in power grids. IS for *sustainable production and consumption* have been of little interest to the IS discipline. With few exceptions (Klör et al. 2018; Schweiger 2016; Stindt et al. 2014), there is a lack of research on IS-enabled *resource efficiency* and *material circularity*, which aims to reduce natural resource consumption by narrowing, slowing, and closing material loops (Bocken et al. 2017).

Solutions for resource efficiency differ from solutions for energy efficiency and therefore deserve special research attention—also from an IS research perspective. The different social and material properties of the focal systems under investigation—put simply, resources and individuals vs. energy and individuals—render the corresponding sustainability challenges different from one another. Energy efficiency deals with homogeneous commodity goods, such as electricity or gas. Resource efficiency and material circularity, instead, involve more heterogeneous goods that can combine to form even more heterogeneous higher-level goods. Moreover, compared to linear energy supply chains in which energy is produced, transported, and consumed, more actors are expected to be involved in circular resource supply chains in which materials pass through multiple industries and sectors over multiple product lifecycles. Consequently, resource processing systems tend to be more socially and materially heterogeneous than energy processing systems, making optimization of the former more challenging.

In synthesis, while we should build on existing knowledge from previous Green IT and Green IS research, the transfer of concepts and mechanisms, such as IS adoption or digital nudging, warrants closer attention given the different underlying social and material system properties. In the next chapter, I present the first study in which we derive two research trajectories and formulate corresponding research questions that deliberately draw on established knowledge from the IS discipline.

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RESEARCH ARTICLE

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Mobilising information systems scholarship for a circular economy: Review, synthesis, and directions for future research

Roman Zeiss[1] | Anne Ixmeier[2] | Jan Recker[1] | Johann Kranz[2]

Abstract
One of today's grand societal challenges is to replace the current 'take-make-waste' economic model with a circular economic model that allows a gradual decoupling of economic activities from the consumption of finite virgin resources. While circular economy (CE) scholars have long lauded digital technologies such as sensors, distributed ledgers, or platforms as key enablers, our own community has not fully explored the potentials of information systems (IS) for a CE. Considering recent technological advances in software and hardware and our history of helping address wicked challenges, we believe the time is ripe to mobilise IS scholarship for a CE. Our findings from an interdisciplinary literature review show that research has primarily examined IS potentials for increasing efficiency of isolated intra-organisational processes while neglecting the larger sustainability potential of IS to establish circular material flows—that is, slow down and close material loops across entire product lifecycles. In response, we propose directions for IS research that develop our knowledge of how IS can help understand and enact circular material flows to intensify and extend use of products and components and recycle waste materials. Our directions offer pathways to building and evaluating the problem-solution pairing that could characterise a prolific CE-IS relationship.

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Authors and contributions	Roman Zeiss	Conceptualization; Formal Analysis; Investigation; Validation; Visualization; Writing – Original Draft Preparation
	Anne Ixmeier	Conceptualization; Data Curation; Formal Analysis; Investigation; Validation; Writing – Original Draft Preparation
	Jan Recker	Conceptualization; Supervision; Writing – Original Draft Preparation; Writing – Review & Editing
	Johann Kranz	Conceptualization; Supervision; Writing – Review & Editing
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Chapter 3

Mobilizing Information Systems Scholarship for a Circular Economy: Review, Synthesis, and Directions for Future Research

Roman Zeiss
University of Cologne

Anne Ixmeier
Ludwig-Maximilians-University Munich

Jan Recker
University of Cologne

Johann Kranz
Ludwig-Maximilians-University Munich

One of today's grand societal challenges is to replace the current 'take-make-waste' economic model with a circular economic model that allows a gradual decoupling of economic activities from the consumption of finite virgin resources. While circular economy (CE) scholars have long lauded digital technologies such as sensors, distributed ledgers, or platforms as key enablers, our own community has not fully explored the potentials of information systems (IS) for a CE. Considering recent technological advances in software and hardware and our history of helping address wicked challenges, we believe the time is ripe to mobilize IS scholarship for a CE. Our findings from an interdisciplinary literature review show that research has primarily examined IS potentials for increasing efficiency of isolated intra-organizational processes while neglecting the larger sustainability potential of IS to establish circular material flows—that is, slow down and close material loops across entire product lifecycles. In response, we propose directions for IS research that develop our knowledge of how IS can help understand and enact circular material flows to intensify and extend use of products and components and

recycle waste materials. Our directions offer pathways to building and evaluating the problem-solution pairing that could characterize a prolific CE-IS relationship.

3.1 Introduction

In our current global economic model, natural resources are extracted, processed, consumed and disposed of in landfills or incineration plants. While economically viable, this 'cradle-to-grave' model inevitably leads to a scarcity of material resources and flooding waste streams while adhering to the overall dogma of economic growth (Baldé et al. 2017). In 2016, for instance, almost 45 million metric tons—equivalent to 6.1 kg per capita—of waste from electrical and electronic equipment (i.e., e-waste) were generated globally. By 2021, with a 17% growth rate, e-waste is expected to be the fastest-growing part of the world's domestic waste stream (United Nations University 2017).

The idea of a circular economy (CE) is to replace this linear 'cradle-to-grave' approach with a circular 'cradle-to-cradle' model. The primary objective of a CE is to minimize resource input and negative environmental impacts of any economic operation. To achieve this objective, research on CE provided a set of principles and mechanisms that support economic actors to systematically narrow, slow, and close material loops by optimizing production, distribution and consumption processes, extending product lifespans and reintegrating waste materials into supply chains (Geissdoerfer et al. 2017; Kirchherr et al. 2017; Potting et al. 2017).

Research on CE first emerged through scientific conversations on waste and resource management that started in the late 1960s (Boulding 1966; Meadows et al. 1972; Stahel and Reday-Mulvey 1981) in which CE served as an umbrella concept for a heterogeneous set of ideas on managing pollution and extending material resource life (Blomsma and Brennan 2017). Over the years that followed, the problem-centric narrative on waste handling and prevention shifted toward an opportunity-centric narrative that emphasized the retention of economic value and the systemic looping and cascading of materials. Since the early 2000s, the opportunity-centric narrative has gradually gained more attention in the business management context, advancing the conversation from mainly technical analysis (e.g., material flow analysis) to sociotechnical discourse (Bocken et al. 2017; Bressanelli et al. 2018; Prendeville and Bocken 2017) by taking a more inclusive view that integrates stakeholders, products, components, and material flows across all product lifecycle (PLC) stages of pre-use, in-use and post-use.

We believe the time is now ripe for information systems (IS) scholarship to join the conversation surrounding CE. CE scholars have long lauded digital technologies such as sensors, distributed ledgers, or digital platforms as key enablers (Antikainen et al. 2018; Casado-Vara et al. 2018; Reuter 2016; van Schalkwyk et al. 2018; Wilts and Berg 2017), but our own community, with its history of sociotechnical, artefact-centric research (Hirschheim and Klein 2012; Sarker et al. 2019) and its mission to explore how IS can be effectively developed and deployed in the human enterprise (Grover and Lyytinen 2015), has not yet matched that enthusiasm. Thus, our article examines how IS scholarship can contribute to the advancement of CE research.

We have two main reasons for believing it is important, timely, and relevant for the IS community to start playing a major role in CE research. First, IS has a proud history of helping solve grand, wicked problems. Examples include dynamic energy and mobility market design through competitive benchmarking (Ketter et al. 2016b), complex urban systems modelling to help develop smart city solutions (Adepetu et al. 2014), collective network of actions to help sustainable development (Braa et al. 2004), sociotechnical interventions to combat child mortality (Venkatesh et al. 2016), and IS solutions for chronic disease management under complex circumstances in rural, developing regions (Bardhan et al. 2020). Second, technological advances in software (e.g., predictive analytics, deep learning and quantum instruction sets) and hardware (e.g., microprocessors, sensors, 5G and new materials) make infusing traditional economic products and services with digital functionality increasingly possible (Yoo et al. 2010). Today, over 20 billion economic goods are connected through more than 50 billion sensors that track, monitor, or feed data to those objects (Zhang 2016). These developments provide an unprecedented opportunity to enrich and couple material flows with information flows along value chains, yielding great transformative potential if leveraged appropriately in a CE (French and Shim 2016).

To mobilize IS research on CE, we perform a structured, interdisciplinary review of literature on the relationship between IS and CE by building on a conceptual framework that comprises all PLC stages (i.e., pre-use, in-use, post-use) and CE principles (i.e., reduce, reuse, recycle)—operationalizable principles conducive to the CE objective. We find that research has primarily examined IS uses for increasing efficiency of isolated intra-organizational processes in the pre-use stage (CE principle: reduce), neglecting the larger potentials of IS to slow down (CE principle: reuse) and close (CE principle: recycle) material loops across all PLC stages.

Drawing on our synthesis and interpretation of the literature, we develop directions for IS research that emphasize a shift from the optimization of current linear processes for efficiency (CE principle: reduce) to circular processes (CE principles: reuse and recycle) that enable the extension of material life spans through circular material flows. In this direction, our agenda offers clear pathways to build and evaluate the problem-solution pairing that could characterize a prolific CE-IS relationship. The agenda aims to achieve two research objectives. First, we should expand knowledge on how IS can help actors *understand* circular material flows. Our literature review shows that applications of the *reuse* and *recycle* principles differ in social and material complexities from applications of the *reduce* principle. We suggest that recent advances in digital technologies can help capture and accommodate such complexities. Second, we should better understand how IS can help actors *enact* circular material flows. This research objective addresses how IS can enable practices that implement the *reuse* and *recycle* principles. The aim is to develop knowledge on how IS can help actors transform their linear economic activities into circular activities.

We proceed as follows. First, we briefly introduce the CE paradigm and two of its central concepts, PLC stages and CE principles. In the next sections, we combine both concepts in a conceptual framework to conduct a structured, interdisciplinary review of literature on the relationship between IS and CE. Subsequently, through a careful analysis and synthesis, we identify and present shortcomings of current literature. In response to these shortcomings, we develop actionable IS research directions comprising two research objectives and six research topics. We conclude with a call for effective theoretically abstract and experientially actionable IS research on CE.

3.2 Background

3.2.1 Circular Economy

By many, the CE model is considered a promising strategy to address global sustainability challenges to the persistence of the bounded ecosystem by reconciling the economy and the environment (Haas et al. 2015; van Schalkwyk et al. 2018).

The CE is an economic model with the goal of minimizing resource input as well as waste and emission leakage by narrowing, slowing, and closing material loops (Geissdoerfer et al. 2017; Kirchherr et al. 2017). This minimization can be realized through the avoidance of unnecessary resource inputs throughout the entire PLC (CE principle: reduce), an intensified and extended use of products and their components in the in-use stage (CE principle: reuse), and the reprocessing of materials in the post-use stage (CE principle: recycle) (Millar et al. 2019). CE principles help transform linear material flows, from sourcing to disposal, into circular material flows, from sourcing to *reuse* or *recycle*.

The CE's main potential is to improve the sustainability of consumption and production through reduced resource use, degradation, and pollution along the entire PLC. It is gaining increased attention from policymakers and business practitioners alike as a facilitator of eco-industrial development and increased well-being (Ghisellini et al. 2016). It features as Sustainable Development Goal No. 12 of the United Nations (2015) and is a core pillar of the European Union's Green New Deal (European Commission 2019). On a national level, Sweden was the first country to formulate an extended producer responsibility strategy in 1990 to achieve environmental objectives and increase producers' responsibility for end-of-life products (Lindhqvist and Lidgren 1990). In 1996, Germany integrated incentives for recycling into national law with the enactment of the Closed Substance Cycle and Waste Management Act. In 2009, China passed the Circular Economy Promotion Law and is now pioneering CE beyond industrial systems by acknowledging CE as a national development goal by law (Mathews and Tan 2011). In business, organizations such as H&M (2019), IKEA (2020), or Philips (2017) have started to invest into large transformation projects to make their operating model more circular.

In terms of information technology, waste management systems, such as those based on SAP or Microsoft solutions (Burger et al. 2018; Microsoft 2019; SAP 2019), track and process information, such as real-time locations and routes of collection vehicles, records of user payments, and the history of waste collection on a grand scale (Kaza et al. 2018). Further, digitalization has facilitated business model innovations in the sharing economy that have increased product use in the in-use stage (e.g., bike sharing) and that prevent waste by extending PLCs (e.g., digital platforms offering refurbished technical devices) (Botsman and Rogers 2011).

These examples show that organizations and regulators have already begun to implement CE principles. Now, however, rapid advancements in digital technologies and ongoing digitalization enable new forms of value co-creation between customers, firms, ecosystems, public institutions, and NGOs that can incorporate CE logic, for instance by taking into account externalities, transaction costs, and information asymmetries when exchanging resources and forming symbiotic partnerships (Geissdoerfer et al. 2017; Homrich et al. 2018; Merli et al. 2018). Therefore, implementing a CE is primarily a challenge of effective information provision and use, since improved resource use (material domain) requires linking material flows with information flows (informational domain) to enable coordination between heterogeneous actor networks (social domain) (Wilts and Berg 2017). Beyond a traditional supply chain, a wide range of other actors such as repairers, municipalities, waste managers and recyclers need to coordinate flows of materials across and between PLC stages. This activity is essentially a sociotechnical informational challenge that involves questions such as ‘what is the state of a product?’, ‘what are the qualities of its materials?’, ‘can we obtain current and future information about these qualities?’ and ‘who owns such data?’

The IS discipline has a history of demonstrating how material, social and informational domains can be bridged with ‘technology artifacts for capturing, processing, transmitting, and representing information’ (Gholami et al. 2016; Grover and Lyytinen

2015, p. 272). While much of this research explores economic impacts of IS, IS scholars have also established a stream of research that explores the potentials of digital technologies to contribute to sustainable development (Malhotra et al. 2013; Seidel et al. 2017) in contexts, such as energy (Ketter et al. 2016b; Watson et al. 2010; Wunderlich et al. 2019), mobility (Marett et al. 2013; Valogianni et al. 2020), work (Corbett 2013; Loeser et al. 2017; Seidel et al. 2013), or urban management (Corbett and Mellouli 2017). Reviews of this literature attest that this work has advanced our understanding of the complex global issue that is environmental sustainability (Sedera et al. 2017). However, knowledge on the potential use of technology artefacts to link material, social and informational domains in a CE context remains fragmented and scattered across disciplines and has not yet been examined in a structured way. Thus, a broad literature review helps to synthesize current knowledge and identify untapped potential for IS research to facilitate resource optimization, remanufacturing and regeneration of resources and novel ways of value co-creation (Ghisellini et al. 2016; Jesus and Mendonça 2018; Türkeli et al. 2018).

3.2.2 Product Lifecycle and Circular Economy Principles

We use two central CE concepts to guide our literature analysis: PLC stages (Fischer and Pascucci 2017; Herrmann et al. 2014) and CE principles (Kirchherr et al. 2017; Zhijun and Nailing 2007).

A PLC includes three key stages. The *pre-use stage* covers the product's life from the initial idea to the delivery of the final product. The *in-use stage* comprises the period of the product's use by the consumer. Finally, the *post-use stage* starts with the end of the product's functional life (Fischer and Pascucci 2017). The concept of PLC stages is widely used in lifecycle assessment methodology (Alting and Jøgensen 1993) and provides a useful structure for the allocation of material flows (Herrmann et al. 2014).

While PLC stages temporally structure material flow allocation, they do not prescribe how to improve the sustainability of resource management. To that end, literature draws on so-called ‘R frameworks’ (Kirchherr et al. 2017). These frameworks offer concrete principles conducive to the CE objective of minimizing resource input and emission output. Over the past decades, a multitude of frameworks in varying levels of granularity—ranging from three principles (Zhijun and Nailing 2007) to nine (Potting et al. 2017)—have been proposed. We draw on the 3R framework consisting of the principles *reduce*, *reuse* and *recycle* as it is the most prominent, integrative and simplest of the frameworks (Ghisellini et al. 2016; Zhijun and Nailing 2007). *Reduce* relates to minimizing the energy and material resource input during production, consumption, and waste management. *Reuse* relates to the recurring application of products or components for the same purpose as long as they work, through activities that increase use (e.g., sharing) and extend use (e.g., repairing, upgrading, redistributing, remanufacturing). *Recycle* refers to reprocessing of waste materials that cannot be reused as input for future production.

Combining PLC stages with CE principles provides a comprehensive framework that allows mapping when (i.e., PLC stages) certain activities (i.e., CE principles) are supportive for achieving a CE (Table 7). We use this framework as the foundation for our literature review.

Table 7. Operationalization of CE principles along PLC stages

PLC stage **CE principle**	**Pre-use stage** *(from idea to delivery)*	**In-use stage** *(from delivery to end-of-life)*	**Post-use stage** *(from end-of-life to next life)*
Reduce *energy and material resource input*	Optimize sourcing, manufacturing, and distribution processes Plan and design offerings with minimal inputs and outputs	Optimize consumption processes (i.e., use of the offering)	Optimize collection, disassembly, recycling, and redistribution processes
Reuse *products and components*	Plan and design offerings for reparability and upgradeability	Intensify product use through sharing Extend product and component use through repairing, upgrading, redistribution, and remanufacturing	*Not applicable*[4]
Recycle *waste into secondary raw materials*	Plan and design offerings for recyclability and with secondary materials	Optimize product return	Reprocess waste materials into secondary materials for the manufacturing of new offerings

[4] By definition, the *reuse* principle is only applicable in the pre-use and in-use stages. Once a product enters the post-use stage, it has reached its end-of-life. The only CE principles applicable at the end-of-life are *reduce* and *recycle*.

3.3 Method

First, we identified the fields of research, determined appropriate sources, decided on the specific search terms, and defined the criteria for inclusion and exclusion. Second, we searched for relevant articles. Third, we refined the sample by screening articles for inclusion or exclusion. Figure 4 depicts how we selected and refined the literature and specifies keywords, databases, refinements, and number of results. The search period was not restricted and the search was conducted in August 2018.

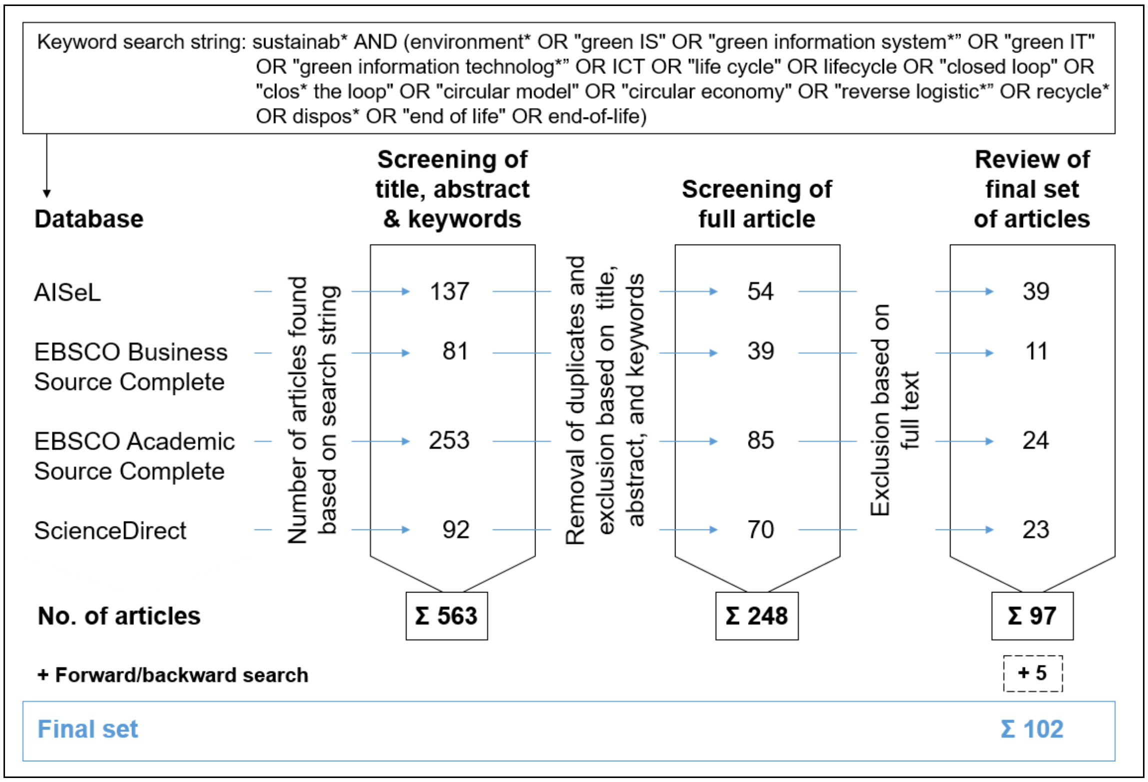


Figure 4. Literature selection process

3.3.1 Literature Selection

As sustainability research spans a wide array of outlets, we covered a broad range of top-tier journals from various disciplines. We used the broad ranking of the German Academic Association for Business Research[5] as a guiding frame of reference and

[5] https://vhbonline.org/en/vhb4you/vhb-jourqual/vhb-jourqual-3/complete-list

considered 53 A+ and A publications from the following disciplines: general business studies, service management, international management, logistics, marketing, sustainability management, operations research, production management, strategic management, technology, innovation and entrepreneurship, and business information systems. Since our focus is on the relationship between IS and CE, we broadened our literature search to include additional articles from sustainability management and IS outlets (n = 86) ranked B-D. To ensure that our selection process entailed the top IS, sustainability, and business journals beyond this list, we cross-checked our journal list on the basis of impact factors and widely used rankings such as FT50 or Harzing (2020).

We searched broadly across data sources and types of papers to include all important aspects associated with the topic of interest (Templier and Paré 2015). We included empirical and conceptual peer-reviewed articles, excluding only review articles and panel reports. We performed our search using the databases AIS electronic Library (AISeL), EBSCO Academic Search Complete, EBSCO Business Source Complete, and ScienceDirect. We used search terms that mapped the two areas of interest, CE and IS, plus more specific keywords relating to PLC, logistics, or sustainability (see keyword search string in Figure 3).

Keyword search was conducted in titles, keywords, and abstracts of publications with the meta-search tool LitSonar (Sturm and Sunyaev 2019). Our initial selection process yielded a total of 563 articles. After we removed duplicates and excluded studies that did not relate to sustainability from either an IS or circularity perspective, 248 articles remained. In this step, our selection criterion was that studies addressed at least one of the CE principles in relation to IS involvement (Geissdoerfer et al. 2017; Ghisellini et al. 2016). To be included, studies had to deal with IS to systematically narrow, slow, and close material loops by optimizing production, distribution and consumption processes, extending product lifespans, and reintegrating waste materials into supply chains. Following careful considerations for journal exclusion (Dubé and Paré 2003; Elliot 2011; Karlin et al. 2015), we read the full text of the 248 articles and excluded 151 articles that did not meet our selection criteria because they were focused exclusively on topics such as economic sustainability, urban metabolism, nanotechnology, lifecycle assessment methods or physical and biological technologies, especially in the construction and food sector. Finally, we added five articles on pro-environmental behavior and e-waste that emerged from a backward and forward search (Webster and Watson 2002). Our final sample consisted of 102 articles with a nearly equal split between articles published in outlets for IS (55 articles) and other disciplines (47 articles). Appendix A.1 summarizes outlets and disciplines included in our final sample.

3.3.2 Literature Coding

Using Microsoft Excel, we coded the 102 articles in line with the coding scheme provided in Appendix A.2. The coding scheme categorizes articles according to their *focus* and *unit of analysis* (Dubé and Paré 2003). To assess the articles' contribution to sustainability, we used as coding categories *PLC stages* (Alting and Jøgensen 1993; Schrödl and Simkin 2014) and *CE principles* (Zhijun and Nailing 2007). Appendix B provides the concept matrix, that is the outcome of our categorization.

Next, we inductively examined how the studies addressed CE principles and how CE principles were implemented through IS solutions (Schryen 2015; Wiesche et al. 2017; Wolfswinkel et al. 2011). Informed by the initial categorization based on PLC stages and CE principles, we identified prominent first-order descriptive concepts from the analyzed articles (e.g., ease of disassembly, design for minimum energy-use, toxicity and emissions). In the next step, we synthesized the first-order concepts in higher-order concepts to develop insights about how the identified first-order concepts relate to each other (Gioia et al. 2012). For example, we assigned the first-level concepts *ease of disassembly* and *design for minimum energy-use, toxicity, and emissions* to the higher-level concept of *design for environment* as both relate to reducing the overall environmental impact of products. Finally, we assigned the higher-order concepts to core categories of the analyzed studies. For example, the higher-order concept of *design for environment* relates to the core category *product design for efficiency*.

The entire coding process involved multiple iterations, throughout which we constantly compared our coding to the concepts from the literature we used to either confirm our findings or unearth possible conflicts (Corbin and Strauss 1990; Wolfswinkel et al. 2011). Coding was performed independently by two authors (Cooper 1988). Disagreements (e.g., whether *industrial recycling networks* refer to *return process optimization* or *supply chain collaboration*) were resolved through discussion, clarification, and—where necessary—modification of the coding scheme and process.

3.4 Findings

To present the findings from our coding (Rowe 2014; Templier and Paré 2015), we start by indicating the distribution of articles across the categories of PLC stages and CE principles (Table 8). The result is a skewed distribution. While reduce issues received ample research attention (85 articles), especially in the pre-use stage, very few articles have addressed the in-use and post-use stages. Also, research on the reuse (11 articles) and recycle (6 articles) principles is scarce. Regarding research disciplines (IS vs other disciplines), we found that studies published in IS outlets account for only 6% of the analyzed articles on the reuse and recycle principles, but for 64% of the research on reduce issues. We also observed a skewed distribution of articles across disciplines and PLC stages. While the IS discipline predominantly focused on the pre-use stage (64%), only 30% of articles addressed the in-use stage and none considered the post-use stage.

Across PLC stages, we observed that articles mostly focused on the *pre-use stage* (76 articles). In this stage, the articles mainly looked into process optimization (63 articles), investigating how material and energy consumption of isolated business processes can be reduced (CE principle: reduce). Studies on procedural supply chain optimization to establish inter-firm collaboration beyond organizational boundaries were much less frequent. Few articles focused on product design for efficiency (eight articles) and reparability (five articles), and these articles centered on product design for environment and durability aiming at reducing material resource input (CE principles: reduce, reuse).

Table 8. Quantitative matching along PLC stages and CE principles

PLC stage / **CE principle**	**Pre-use stage** *(from idea to delivery)*		**In-use stage** *(from delivery to end-of-life)*		**Post-use stage** *(from end-of-life to next life)*		**Sum**
Reduce *energy and material resource input*	Optimize sourcing, manufacturing, and distribution processes	63	Optimize consumption processes (i.e., use of the offering)	9	Optimize collection, disassembly, recycling, and redistribution processes	5	85
	Plan and design offerings with minimal inputs and outputs	8					
Reuse *products and components*	Plan and design offerings for reparability and upgradeability	5	Intensify product use through sharing	5	*Not applicable*	0	11
			Extend product and component use through repairing, upgrading, redistribution, and remanufacturing	1			
Recycle *waste into secondary raw materials*	Plan and design offerings for recyclability and with secondary materials	0	Optimize product return	5	Reprocess waste materials into secondary materials for the manufacturing of new offerings	1	6
Sum		76		20		6	102

Research on the *in-use stage* was limited in our sample (20 articles). We found nine articles concerned with motivating sustainable consumption behaviors to curb operational inefficiency of products (CE principle: reduce). Five articles examined the potential of digital platforms to intensify product use (CE principle: reuse) and one article developed an assessment approach for the remaining useful life of components for remanufacturing (CE principle: reuse). We identified five articles concerned with motivating individual and organizational recycling activities (CE principle: recycle).

The *post-use stage* is the least studied PLC stage in the literature (six articles). Research primarily addressed the implementation of return logistics to improve the return ratio and dissemination of returned products (CE principle: reduce) (five articles). One article focused on the reprocessing of materials for the manufacturing of new products (CE principle: recycle).

In the following, we present our qualitative findings in more depth. We analyze how the CE principles are implemented in the PLC stages. Rich and detailed accounts of the analyzed studies' findings are provided in Appendix C.

3.4.1 Pre-use Stage

In the pre-use stage, a key focus of the reviewed articles is the reduction of material and energy consumption within organizational boundaries. We found that in the pre-use stage the literature mainly emphasized increasing *eco-efficiency of business processes* (i.e., reducing energy and material resource inputs). The information and transparency capabilities of IS pave the way for sustainability-enhancing concepts such as dematerialization (e.g., Bose and Luo (2011)), knowledge dissemination (e.g., El-Gayar and Fritz (2006)), workload prediction (e.g., Hedwig et al. (2009)) or resource allocation (e.g., Sedera et al. (2017)). However, these are predominantly examined from a single producer's perspective in the field of manufacturing and distribution. Research is very limited regarding the CE principle *reuse* in up- and downstream activities of other PLC stages (e.g., sourcing, collection, redistribution) (Table 9).

Our literature review found no studies on the CE principle recycle even though product design for recyclability represents a promising lever to minimize the input of virgin physical components in future production. The one-sided focus of prior research has resulted in isolated manufacturer-centric solutions that consider material, energy and information flows only to the next supply chain tier (Bose and Luo 2011; Corbett 2013). Thus, circular solutions are often neglected. CE logic requires products to be reintroduced into further lifecycles at their end-of-life to maximize the utility and value of components and materials (Fischer and Pascucci 2017; Haas et al. 2015). Forward supply chain activities relate to extraction, design, and retail. Closed-loop supply chains additionally consider reverse supply chain activities to create a cycle of resource flows through collection, disassembly, recycle and reintroduction of components and materials (Chaabane et al. 2008; Meinrenken et al. 2014).

Table 9. Core categories from coding of articles focusing on the pre-use stage

CE principle	Core category	Higher-order concept	Selected first-order concept (in italics) and illustrative example
Reduce	**Core category 1: Process optimization**		
	Research in this category chiefly focuses on isolated, efficiency-maximizing optimization of manufacturing and distribution processes—sourcing processes are not addressed.	Information and transparency capability	Carbon management systems help to promote ecologically responsible behaviors to *improve energy efficiency and material efficiency* of organizations (Corbett 2013).
		Supply chain extension and collaboration	ICT can assist the promotion of explicit and tacit knowledge transfer through the creation of community, social capital, and trust, and, thus, minimizes *information asymmetries between collaborating firms* (Grant et al. 2010).
		Real cost pricing	IS can improve the information flow on true costs, e.g., including the environmental cost of extracting rare earth elements, between stakeholders to ensure that products are ultimately *distributed at real costs* (Desautels and Berthon 2011).
		Product–service system	IS solutions diminish uncertainties in quantity, quality, and timing of physical products that are offered as service and allow firms to improve *decision making for the optimal maintenance, repair, and general assistance* (Heyes et al. 2018).
	Core category 2: Product design for efficiency		
	Research focuses on the up-front reduction of material resources—lifecycle concerns and durability of products are largely disregarded.	Design for environment	Computer-aided design tools assist designers in evaluating products' aggregated sustainability performance and compare alternative product designs according to several dimensions, such as *minimum energy use, toxicity, and emissions* (Laurenti et al. 2015).
Reuse	**Core category 3: Product design for reuse**		
	Research addresses product design for reparability and upgradeability.	Design for environment	Digital processes and platform flexibility support the design, analysis, and collaboration on offerings aiming at *ease of disassembly* and reuse (Eppinger 2011).

3.4.2 In-use Stage

Our literature review revealed few studies about the in-use stage (20 articles). These studies broadly concentrated on *sustainable consumption*, *intensified and extended use*, and *return behavior change* (Table 10).

Table 10. Core categories from coding of articles focusing on the in-use stage

CE principle	Core category	Higher-order concept	Selected first-order concept (in italics) and illustrative example
Reduce	**Core category 4: Sustainable consumption**		
	Research chiefly focuses on efficiency-maximizing optimization of use processes via monitoring and reporting—sufficiency aspects are not addressed.	Monitoring and reporting capability	Smart meter interfaces with user-centered feedback design monitor and report energy-use of households to induce behavior change towards *efficient energy-use choices* (Dalén and Krämer 2017).
		IS capability	Individual technology readiness plays an important role for individuals to actually *apply and make use of supporting technologies* (Krishnan and Teo 2011).
Reuse	**Core category 5: Intensified use**		
	Research acknowledges that digital platforms facilitate intensified use—motivation and product offering-related aspects are not addressed.	Collective use and sharing	Digital platforms provide an opportunity for collective use and sharing activities and the *exploitation of under-utilized or unused resources* (Cohen and Muñoz 2016).
	Core category 6: Extended use		
	Product design for extended life spans is not addressed and component reuse for remanufacturing is largely disregarded.	Extended product and component use	IS can support product optimization, e.g., by *detecting the optimal life span of components*, or by trustfully exchanging reliable, fine-grained information that decision makers need to assess products' eco-impact (Mazhar et al. 2007).
Recycle	**Core category 7: Return behavior change**		
	Research acknowledges the encouragement of individual disposal, collection, and recycling behavior to activate extended producer responsibility.	Extended consumer responsibility	IS can assist the activation of extended consumer responsibility by downward informating on *efficient disposal, collection, and recycling behavior* (Tong et al. 2018).

A large share of the reviewed literature focused on increasing the eco-efficiency of product use through monitoring and reporting (Krishnan and Teo 2011; Malmodin et al. 2014) and design for environment (Laurenti et al. 2015; Rossi et al. 2006) (i.e., on minimizing the material resource input according to the *reduce* principle). The reduction of material resource input is a major goal in designing products for the environment and durability, but above all, design for environment includes effective *reuse* and *recycling* facilities in the use and post-use stages. The systemic approach not only allows for enhanced resource efficiency during pre-use stage but also for lifespan extensions and disposal efficiency during the in-use stage through built-in reparability and disassembly options enabling products to become useful inputs for other products instead of creating waste. Despite its salience, the integration of further CE principles during the in-use stage has received little attention in our literature sample. We found few studies on intensified use (5) (Achachlouei et al. 2015; Cohen and Muñoz 2016) and only one study on the remanufacturing of components to extend use (Mazhar et al. 2007). Another small stream of research was concerned with motivating individual and organizational recycling activities to optimize collection and recycling (Chen et al. 2012).

3.4.3 Post-use Stage

We found six studies focusing on the post-use stage. These investigations dealt primarily with the implementation of *efficient return processes* (Table 11).

Table 11. Core categories from coding of articles focusing on the post-use stage

CE principle	Core category	Higher-order concept	Selected first-order concept (in italics) and illustrative example
Reduce	**Core category 8: Return process optimization**		
	Research addresses efficiency-maximizing optimization of collection processes.	Extended producer responsibility	IS can improve the information flow and assess the impact of *waste management models,* such as an extended producer responsibility system (Rodrigues et al. 2016).
Recycle	**Core category 9: Material reprocessing**		
	Reprocessing materials for the manufacturing of new products is largely disregarded—accountability for the reinsertion of information is not addressed.	Circularity of global material flows	IS solutions can support material flow accounting, i.e., the assessment of the circularity of global material flows traced from extraction to disposal, to identify *options for using recycled materials,* such as metal in construction projects (Haas et al. 2015).

The studies concentrate mainly on the implementation and optimization of return logistics to improve the return ratio and dissemination of returned products, thereby minimizing the virgin material input according to the *reduce* principle (Manhart 2011). Extended producer responsibility represents an important policy-induced strategy to lead organizations to internalize disposal costs (Rodrigues et al. 2016; Tong and Yan 2013) and redesign products that facilitate the reuse of components (Webster and Mitra 2007). Our review of the literature identified only one article (Haas et al. 2015) focusing on the reprocessing of materials (i.e., on the *recycling* of waste into secondary materials that can be used in the manufacturing of new products).

The reviewed studies tackle efficient collection behavior but largely neglect recycling, reprocessing and redistribution of materials. Although the CE logic requires products at their end-of-life to be reintroduced in other lifecycles to maximize the utility and value of components and materials (Fischer and Pascucci 2017; Haas et al. 2015), the circularity of global material flows is often neglected and remains a challenge.

3.4.4 Synthesis

The literature we reviewed has focused mostly on maximizing efficiency of intra-organizational processes during the pre-use stage (i.e., sourcing, manufacturing, distribution). In addition, manufacturing organizations have been the predominant unit of analysis.

This narrow research scope on organizational *reduce* issues disregards the full spectrum of a CE to slow down (CE principle: reuse) and loop (CE principle: recycle) material flows across multiple PLCs. The lack of consideration of CE actors such as consumers, end-of-life agents or regulatory authorities neglects opportunities to direct information and knowledge from the in-use to post- and pre-use stages to raise transparency and accountability (El Idrissi and Corbett 2016; Krishnan and Teo 2011; Wirtz 2019) and enable consumer awareness, empowerment and responsibility. In short, research has so far fallen short in investigating IS support for the entire sustainability potential of a 'true' CE. In the words of the Ellen MacArthur Foundation (2016b, p. 18):

> *"Working towards efficiency—reducing the resources and fossil energy consumed per unit of economic output—will not alter the finite nature of their*

stocks but can only delay the inevitable. A more fundamental change of the operating system is necessary.”

This ‘fundamental change’ can be achieved only when *reuse* and *recycle* play a greater role, as these principles are decisive in realizing an intensified and extended use of products and components and close raw material loops at the end of a PLC (Reike et al. 2018).

However, we found that the literature on *reuse* and *recycle* is not only smaller in volume than the literature on *reduce* issues but also qualitatively different, in two main aspects. First, the available *reuse* and *recycle* studies analyze the physical materiality of products in more detail when investigating circular practices, such as the product design for recyclability (Rossi et al. 2006; van Schalkwyk et al. 2018), the remanufacturing of used components (Cong et al. 2017; Mazhar et al. 2007), or the recycling of valuable resources (Pil and Cohen 2006; Rocchetti et al. 2018). For example, Rossi et al. (2006) zoom in on the component and raw material levels to design an office chair that can be easily disassembled and recycled in later stages of its lifecycle. Second, the studies consider wider and more heterogeneous sets of actors and relationships in their research, which reach beyond the organizational boundaries of a focal manufacturer to include actors that cross supply chains and industry sectors, such as waste managers (Richter and Koppejan 2016; Tong et al. 2018) or recycling facilities (Chen et al. 2012). For example, Posch (2010) analyses an entire by-product recycling network covering 27 companies from diverse industries.

These observations suggest that the *reuse* and *recycle* principles differ from reduce in social and material complexity. The empirical settings of *reduce* studies, which investigate local optimizations of processes for resource efficiency, primarily concern the enhancement of existing, controllable systems that—clearly demarcated in time and space—contain a manageable number of predictable social and material entities. Instead, the *reuse* and *recycle* principles—which aim at the creation of circular material flows—extend beyond the structural boundaries of traditional supply chains and require an inter-organizational perspective on circular material flows. This transition from unidirectional and bilateral supply chains to multi-directional and multi-lateral value networks generates convoluted systems of heterogeneous and previously unrelated actors across multiple supply chains and industries with potentially conflicting interests. These circular value networks thus constitute *complex social systems* (Anderson 1999; Daft and Lewin 1990; Dobusch et al. 2017).

Studies on the implementation of the *reuse* and *recycle* principles further focus on practices that perform on product, component, and raw material levels across multiple stages of PLCs (e.g., material collection, decomposition, sorting and reprocessing). This focus marks a central shift from an indivisibly assembled product-centric perspective to a decomposable and recombinable material-centric perspective. The studies consider products as modular, layered and temporally stratified assemblages of components and raw materials. The shift from static to dynamic material compositions increases the level of complexity with which one perceives and investigates the materiality of products. Therefore, investigations of *reuse* and *recycle*-related phenomena deal not only with complex social systems but also *complex product systems* (Novak and Eppinger 2001; Simon 1962).

The transformation from a linear economic model to a 'true' CE, which implements circular material flows (Ellen MacArthur Foundation 2016b), is thus a complex sociotechnical challenge involving entangled, complex social and material systems where 'numerous social, economic, political, and technical factors interact' (Ketter et al. 2016b, p. 1057) in an emergent manner (Holland 1995; Simon 1962). To better understand circular material flows, including their involved complex social and product systems, IS-related CE research must therefore embrace sociotechnical complexity (Benbya et al. 2020; Jacucci et al. 2006; Merali et al. 2012).

3.5 Mobilizing Information Systems Scholarship for a Circular Economy

While complexity in circular material flows presents a substantial challenge, we believe it also offers an opportunity for impactful, solution-oriented sociotechnical research on IS for a CE (Gholami et al. 2016; Malhotra et al. 2013). IS have repeatedly been proven to play a key role in managing complex systems (Adepetu et al. 2014; Braa et al. 2004; Ketter et al. 2016b; Venkatesh et al. 2016), and sociotechnical thinking is deeply engrained in our field (Sarker et al. 2019).

Advances in IS-enabled by new types of digital technology that have underpinned productivity improvements for the last half century (Stiroh 2002) also underpin solutions to the complex challenges of today and tomorrow (Ketter et al. 2016b). Joint technological and managerial innovations can make complex problems tractable (Churchman 1967; Rittel and Webber 1973). Information-intensive problems are amenable to faster chips and new algorithms. Deep learning, for instance, has demonstrated that software can master the intricacies of Go (Gibney 2016), once deemed impossible. Likewise, digitally enabled new organizational structures for economic activity, such as multi-divisional enterprises (Chandler 1962) and digital ecosystems (Moore 2006), have expanded the capacity for addressing large-scale problems.

With this track record, we believe IS scholarship, if mobilized, can enable the management of circular material flows by assisting parties involved in implementing the *reuse* and *recycle* principles in two main ways: (a) understanding circular material flows as entangled complex social and product systems, and (b) enacting them (Kurtz and Snowden 2003).

In what follows we expand on this basic proposition. We specify a research agenda along two research objectives: understanding circular material flows with IS and enacting circular material flows with IS. The first objective builds on the key insight from our literature review that implementations of the *reuse* and *recycle* principles (i.e., circular material flows) differ from implementations of the *reduce* principle in terms of social and material complexity. Its primary research aim is therefore to generate knowledge on how IS can help actors comprehend and accommodate the social and material complexities that unfold around implementations of the *reuse* and *recycle* principles. The second objective discusses how IS can enable practices that facilitate implementations of the *reuse* and *recycle* principles across and between entire PLCs. This research aims at generating knowledge about how IS can help actors transform their linear economic activities into circular loops.

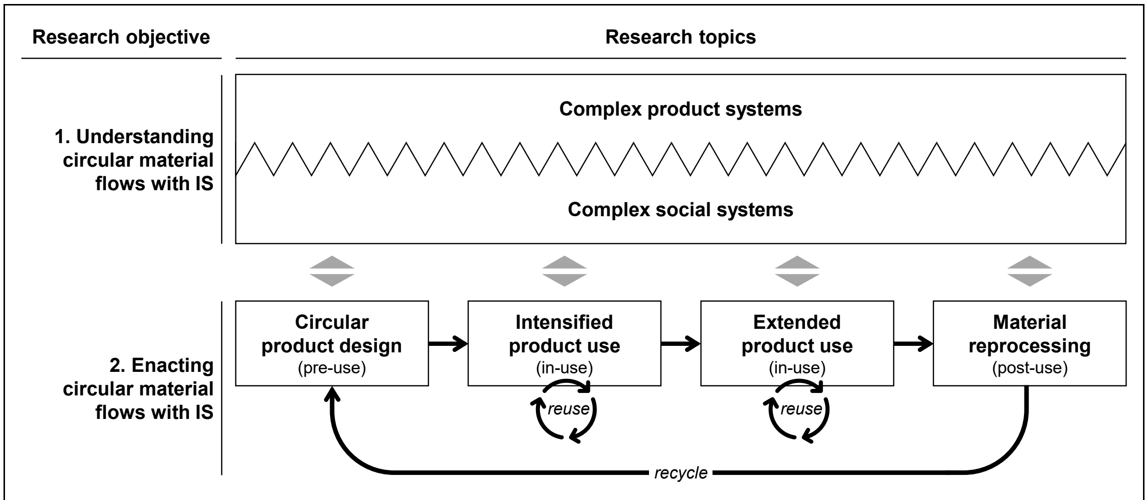
Figure 5 depicts our proposed research agenda and defines its key concepts. It shows two *research objectives* on the left-hand side and six corresponding *research topics* on the right-hand side. In accordance with our understanding of a CE as a complex sociotechnical system, the two research topics of the first research objective, complex social systems and complex product systems, are portrayed through two entangled boxes. The four research topics of the second research objective, enacting circular material flows with IS, directly derive from the core categories 3, 5, 6, 7 and 9 from our literature review.[6] All four topics concern practices to slow down (CE principle: reuse) or loop (CE principle: recycle) material flows. To depict this emphasis, we have added a schematic material flow in the form of bold arrows that connect the four topics across and between the PLC stages of pre-use, in-use and post-use, in a logical order.

Figure 5 further shows that both research objectives are interrelated (depicted through the bidirectional light grey arrows between the topics of objectives 1 and 2). This portrayal highlights that understanding and enacting circular material flows is an ongoing iterative sequence actors engage in when implementing circular principles (Kurtz and Snowden 2003).

In what follows, we expand on selected research opportunities we see within the six topics across the two research objectives. We do so by discussing illustrative research questions for each topic within each objective. To mobilize research to answer these questions, we highlight selected research streams[7] available in IS literature that in our view provide helpful knowledge traditions for launching into these inquiries. Table 12 summarizes research objectives, topics, illustrative research questions and selected IS research programs.

[6] Core categories 1, 2, 4, and 8 relate to the *reduce* principle (see Tables 4-6).

[7] Our understanding of research streams encompasses research programs driven by theory (e.g., representation theory), phenomenology (e.g., open data), and technology (e.g., distributed ledgers).



Concept	Definition
Understanding circular material flows with IS	Investigating how IS can help actors comprehend and accommodate social and material complexities that unfold around implementations of the reuse and recycle principles.
Complex product systems	Modular, layered, and temporally stratified assemblages of components and raw materials that can be decomposed and recombined into new assemblages (Novak and Eppinger 2001).
Complex social systems	Multi-directional and multi-lateral networks of heterogeneous actors across multiple supply chains and industries (Konietzko et al. 2020).
Enacting circular material flows with IS	Investigating how IS can help actors transform their linear economic activities into more circular activities by enabling practices that implement the reuse and recycle principles.
Circular product design	The practices of developing a new product that contains recycled low-impact materials, ensures a long use period, and allows lifetime extension and material reprocessing (Rossi et al. 2006).
Intensified product use	The practices of lending, renting, or leasing a product to increase its use rate by enabling its sequential, ownership-less consumption through multiple users (Cohen and Muñoz 2016).
Extended product use	The practices of repairing, upgrading, redistributing, or remanufacturing a product to extend its lifetime or the lifetime of its components (Tunn et al. 2019).
Material reprocessing	The practices of collecting, dismantling, sorting, and reprocessing materials to reintegrate them as secondary material resources in the manufacturing of new products (Rodrigues et al. 2016).

Figure 5. Definition of research objectives and topics for IS scholarship for a CE

Table 12. Opportunities for IS research to contribute to a CE

Research topic	Illustrative research questions	Suitable IS research stream
Research objective: Understanding circular material flows with IS		
Complex product systems	How can IS faithfully represent and track complex product systems?	Representation theory
	How can public material databases improve representational faithfulness of complex product systems?	Open data
Complex social systems	How can data governance improve data availability and quality in complex social systems?	Data governance
	How can IS support the implementation of data governance in complex social systems?	Distributed ledger technology
Research objective: Enacting circular material flows with IS		
Circular product design	How can IS enable the design of more durable, repairable, upgradeable, dismantlable, and recyclable products?	Generative design
	How can digital product offerings be designed to mitigate their negative environmental impact?	Green IT
Intensified product use	How can IS enable collaborative consumption models in an online and offline context?	Sharing platforms
	How can IS be designed to prevent unintended user behavior in collaborative consumption models?	Digital nudging
Extended product use	How can IS enable the repair, remanufacture, and redistribution of consumer products?	Recommendation agents
	How can IS leverage the modular-layered architecture of digital products to extend their replacement cycles?	Digital product innovation
Material reprocessing	How can IS inform the raw material recycling of waste materials?	Technology standard making
	How can IS help increase the use of secondary materials in new product offerings?	Online-to-offline platforms

3.5.1 Understanding Circular Material Flows with Information Systems

Our first research objective aims at generating knowledge on how IS can help actors comprehend and accommodate the social and material complexities that unfold around implementations of the *reuse* and *recycle* principles. We focus on two research topics to illuminate corresponding research opportunities. First, in consideration of recent advances in tracking technologies, we invite discussions on the issue of representational faithfulness of complex product systems in circular material flows. Second, in acknowledgement of the dynamic and often unpredictable nature of circular material flows, we invite discussions on issues of data sharing in large and complex social systems.

3.5.1.1 Complex Product Systems

Material complexities in circular material flows emerge from the dynamic and unpredictable behavior of product assemblages throughout their lifecycle. For example, once released in the market, the assemblages of components and raw materials can change either passively, for instance through wear and tear, or actively, such as through after-sales repairers exchanging deficient components (Zeiss et al. 2019). At their end-of-life, product assemblages are decomposed into their constituent parts to find their way into new product assemblages as either functional components or recycled raw materials.

Recent advances in digital tracking and tracing technologies, such as digital identifiers, physical markers, or sensors, provide opportunities to capture these after-sales dynamics of complex product systems across product, component, and raw material levels. But the advances also bring forward challenges of *representation*. How can the dynamic whereabouts and conditions of complex product systems across compositional levels and PLCs be appropriately modelled within an IS?

IS research is well positioned to take on challenges of representation (Burton-Jones et al. 2017; Weber 1997). The research program on IS as representational vehicles (Burton-Jones et al. 2017; Recker et al. 2019) has spent decades evaluating how IS can 'faithfully'—that is, completely and clearly—represent real-world domains in terms of relevant things and properties in that domain, the systems composed by these things and their couplings, and the events that occur and enable transitions in the state of these things (Weber 1997).

However, circular material flows not only require mere *representation* of complex, modular products and their components. Material flows also entail the ability to *track* over time the changes in states of product assemblages (e.g., new, used, broken, repaired, unusable) evoked through events alongside the PLC (e.g., a purchase, a transfer, a defect, a decommission). Wand and Weber's (1995) state-tracking model offers a method to faithfully track such events and changes over time. It stipulates four criteria (Recker et al. 2019, pp. 769-770) that an IS representation of a phenomenon (e.g., a circulating product or material) must meet to ensure the model of the material object maintains an accurate and complete representation as the object changes or external events occur that alter the state of the object.

Research could now be conducted in terms of design and evaluation of IS for representing and tracking material flows in a CE. On the one hand, Wand and Weber's (1995) representation and state-tracking models provide a solid conceptual basis that offers a suitable lens for designing IS that represent and track complex product systems. The evidence to date (Recker et al. 2019) suggests this lens will provide effective guidelines for the design of faithful and hence effective IS (Burton-Jones et al. 2017). On the other hand, the relative merits of the state-tracking model are at this point uncertain, as 'uptake has been too limited to evaluate [the state-tracking model's] premises' (Recker et al. 2019, p. 753). The opportunity is thus to develop representational systems that can faithfully model and track a complex product system over time when future compositional states and events in which it interacts with its environment (e.g., other product systems or social actors) are not entirely predictable at the time of design. Systematic evaluation of the effective use of such a system could then support CE practices as well as inform the future theoretical development of representation theory by refuting, accepting, or modifying the theorized criteria for faithful state-tracking.

The issue of representation of complex product systems is not restricted to the deep structure of IS—the conceptual representation that manifests its meaning (Recker et al. 2019). Representation also concerns physical structure elements—the hardware/software platform used to implement the IS. Technology-driven research on current and future digital tracking systems can improve the representational fidelity of complex product systems in circular material flows. For example, digital sensors allow the capture of more, and more granular, states of physical objects, such as location and storage capacities of batteries in electric vehicles. But still unclear is on which level of granularity—in terms of both the physical and temporal levels—data need to be captured to achieve appropriate and feasible product information quality for applications of CE principles.

IS research on digital object tracking systems (Bardaki et al. 2011; Thiesse et al. 2009; Wamba and Chatfield 2009) could be combined with the principles stipulated by representation theory to evaluate this question. For instance, an information completeness assessment metric (Bardaki et al. 2011) might be a practicable tool to evaluate the representational faithfulness of circular material flows and optimize the capture points and labelling levels of tracking sensors such that the *tracking condition* and the *sequencing condition* of the state-tracking model (Recker et al. 2019) can be met.

The IS research opportunity here extends beyond theory and design, as it is also empirical. In practice, first attempts of representations beyond the point of sale are emerging. For instance, the Swedish-Finnish steel company *SSAB* has developed a digital twin (Grieves and Vickers 2017) for its steel plates. Digital twins are 'an asset's virtual counterpart that enables enterprises to digitally mirror and manage an asset along its lifecycle' (Dietz and Pernul 2020, p. 179). Data linked to this twin allow actors further down the supply chain to identify the product, query its material properties, and check relevant material certificates (SSAB 2017). While the first version was built for a limited number of linear economy use cases and does not leverage data captured by sensors, *SSAB* is planning to expand its solution to other actors from recycling and remanufacturing industries.

Finally, not all data on complex product systems must be generated from scratch through manual or automatic sensor-driven data entry. Scholars in material sciences and engineering (Jose and Ramakrishna 2018; Ramakrishna et al. 2019) have published open engineering material databases, such as *ChemSpider* or *MatWeb*, that provide large datasets on physical and other material characteristics, such as chemical, mechanical and thermal properties, relevant for mechanical and environmental engineers in the composition (i.e., production) and decomposition (e.g., recycling) of product systems. These data sources can extend the transparency of complex product systems from the product and component level to raw material levels and potentially support circular practices like the reprocessing of secondary materials. However, still unclear is whether any benefit will arise in a CE from an integration of publicly available material property data with product trace data, and if so, who will gain and how.

3.5.1.2 Complex Social Systems

Travelling through circular value networks, complex product systems pass multiple actors that either use or transform them. Beyond well-known actors such as producers, retailers and consumers, product systems might also involve less obvious actors, such as repairers, refurbishers, remanufacturers, waste collectors or recyclers, that either intensify and extend the lifetime of the product system and its components or loop its raw materials into subsequent PLCs.

To effectively carry out CE practices, actors require sufficient and relevant product data, such as the provenance and composition of product systems, their condition, or instructions on how to disassemble them (Cong et al. 2017; Moreno et al. 2011). This information dynamically changes over PLC stages, and its availability to the different involved actors varies, which renders circular practices unfeasible and unprofitable. Decentrally capturing data across product, component, and raw material levels could lead to greater transparency in circular material flows if the data can travel virtually with the product systems across one PLC or between multiple PLCs and become available to actors that require the data. Otherwise, isolated windows of data availability only lead to local optimization of process efficiency for individual actors but fail at realizing CE's full potential.

As our review showed, social complexities, such as conflicting business interests or low trust levels between actors, presently impede greater data availability among participants involved in circular material flows (Fischer and Pascucci 2017; Grant et al. 2010; Wilhelm et al. 2016). Product system data shared across circular value networks can contain sensitive business information and valuable trade secrets (Fraccascia and Yazan 2018), and to establish a CE, data providers would be asked to share these data with an unknown set of potentially competing actors.

One research opportunity to help advance establishment of a functioning CE via data sharing is to leverage and extend IS research on data governance (Khatri and Brown 2010; Otto 2011; Tallon 2013). While IS literature has developed a thorough understanding of intra-organizational data governance, less is known about governing collaboration and data sharing in an inter-organizational setting (Abraham et al. 2019).

Existing frameworks may help identify features to consider when designing data governance for circular value networks, but their direct applicability in a CE context is debatable and should be evaluated first (Rasouli et al. 2016).

Consider, for instance, Khatri and Brown's (2010) five decision domains for data governance: data principles, data quality, metadata, data access, and data lifecycle. Developed for an intra-organizational application context, these domains assume clear and static boundaries of the scope of governance. A circular value network, however, is dynamic and emergent, in turn rendering the elaboration of the domains a challenging exercise. Definitions of *data principles* to 'set the boundary requirements for the intended uses of data' (Khatri and Brown 2010, p. 149) or *data access* to specify access requirements of data become moving targets, as data use cases and corresponding access requirements might change depending on the condition and current lifecycle stage of the product system represented by the data. For example, a repairer has different data use cases than a recycler. In addition, *metadata*, *data quality* and *data lifecycle* policies become more important in the context of dynamic circular value networks (Abraham et al. 2019; Rasouli et al. 2016). For instance, if not governed centrally by *metadata* and *data quality* policies, heterogeneous actors in circular material flows follow local rules or language when providing data to the circular value network, and thereby risk the syntactic and semantic interoperability of decentralized data sources. Appropriate *data lifecycle* procedures ensure a lasting effect of agreed upon metadata and data quality policies by providing for the traceability of data provenance.

A second research opportunity is to examine how recent advances in distributed ledger technology (Beck et al. 2018) can support the design and implementation of CE data governance solutions. The Dutch start-up *Circularise* (2019), for instance, developed a blockchain-based decentralized communication protocol to enhance data availability and quality in circular value network without disclosing datasets or actor identities. This solution addresses several social complexities such as (a) fragmented product system data, (b) opaque circular value network structures, (c) non-willingness to share confidential product system data, and (d) unpredictable future data requirements. Through a so-called 'smart questioning' protocol, actors in need of product system data can pose questions to the entire distributed network (e.g., ‘Does the to-be-recycled product contain lead?’) and receive a confidence-weighted yes or no answer from the network. The data necessary for this response have been pre-recorded by data providers and verified in advance by trusted third parties. Thus, affordances of distributed ledger technology may help overcome both social and technical challenges involved in inter-organizational data governance.

3.5.2 Enacting Circular Material Flows with Information Systems

Our second research objective aims at generating knowledge on how IS can help actors transform their linear economic activities into circular activities by using IS solutions that enable practices that implement the principles of *reuse* and *recycle* across and between entire PLCs. We suggest four research topics that flow from our analysis of the reviewed literature: IS-enabled solutions for circular product design (core category 3), intensified product use (core category 5), extended product use (core category 6) and material reprocessing (core categories 7 and 9).

3.5.2.1 Circular Product Design

Circular product design aims at developing new products based on recycled low-impact materials that ensure a long use period and allow lifetime extension and material reprocessing (Chang and Lu 2014; Rossi et al. 2006). Regulatory institutions (European Commission, 2018) increasingly demand that products embrace eco-design standards and follow guidelines like design for environment (International Organization for Standardization 2020), which are assessed by criteria such as product durability, dismantlability or recyclability.

Research on eco-design standards has already studied the environmental and economic benefits of design for environment (Eppinger 2011; Sihvonen and Partanen 2017) and suggested a number of technical improvements for lifecycle assessment methods that quantify the environmental impact of designed products (Cong et al. 2017; Frey et al. 2006; Huang 2008; Laurenti et al. 2015; Mazhar et al. 2007; Pil and Cohen 2006; Shuaib et al. 2014). However, only limited research has approached these concepts from a sociotechnical perspective to investigate how product designers and engineers leverage digital work environments of data and software to balance paradoxical demands regarding products' physical properties, ecological impacts, and economic returns (Chang and Lu 2014; Rossi et al. 2006; van Schalkwyk et al. 2018). The opportunity arises because product system data across material levels and PLC stages increasingly become available in near-real-time and advanced data analytical processing and presentation techniques are being integrated in traditional computer-aided design software.

For individuals engaged in a creative design process relying on advanced data-driven decision support to balance conflicting heterogeneous goals, the sociotechnical setting renders the phenomenon of computer-aided circular product design relevant and interesting from an IS research perspective. The research focus should be on the design and use of IS that offer both generative and constraining support for product design problems. To illustrate the need for generative and constraining support of IS, Rossi et al. (2006) report on a design for environment product assessment tool used in the design of an office chair. The team of designers had to actively balance competing economic, social, and environmental requirements multiple times. For instance, eliminating the use of polyvinyl chloride in the armrests' foam padding by replacing it with a suitable alternative was a significant challenge because many candidate materials failed to comply with physical performance requirements, such as abrasion resistance or comfort, or were more costly. In the end, the slightly higher costs of the alternative—thermoplastic urethane—were offset by other design choices. While in 2006 the assessment tool involved considerable manual work (e.g., collating reliable data on the material properties of the candidate materials) and social collaboration between designers and engineers, Chang and Lu (2014) were able to present the more automated and interactive *EcoCAD* add-on for the *SOLIDWORKS* software. The add-on enables designers to monitor toxic indicators in real time during the design process and suggests design choices for reducing toxicity and improving the product's ease of disassembly.

This tension between generativity and constraint is also known in the digital innovation literature (Avital and Te'eni 2009; Yoo et al. 2010). Generative capacity is open-ended, creative, and innovative but also ambiguous, divergent and unknown (Avital and Te'eni 2009). To make a CE work, in some settings generativity is counterproductive and must be considered under other constraints, such as economic efficiency (Rossi et al. 2006). To explore this dialectic in circular product design, digital-first representations could be as used as probes (Jarvenpaa and Standaert 2018) before committing to material object production to generate views that 'unravel and challenge' (Jarvenpaa and Standaert 2018, p. 983) prevailing linear practices as a consequence of product design choices.

IS not only enable designers and engineers to make sense of complex decision problems and their consequences during product design. They can also be part of new digital product offerings (Porter and Heppelmann 2014). The IS conversation on the digital augmentation of product offerings has focused on how economic value-in-use can be increased (Kohli and Melville 2018; Lusch and Nambisan 2015; Yoo et al. 2010). This focus needs to be complemented with a more differentiated view of the positive and negative impacts on sustainability when infusing digital technology into products. While positive effects such as dematerialization have received some scholarly attention (Ryen et al. 2014), negative impacts such as faster obsolescence of interdependent software and hardware (Ixmeier and Kranz 2020; Jenab et al. 2014; Sandborn 2007) are under-researched. Future research could (a) highlight and discuss both positive and negative sustainability effects of digital technologies in the design of new product offerings, (b) provide practical guidelines for how to mitigate negative effects, and (c) study how to design digital products that use digital technologies to dematerialize the product offering.

This research could draw on the Green IT literature (Murugesan 2008) that examines the environmental effects of digital technology. So far, this literature stream has primarily focused on improving energy and resource efficiency of intra-organizational enterprise IT (Murugesan 2008; Sedera et al. 2017) through practices such as optimizing algorithmic energy efficiency (Mukherjee and Sahoo 2010), power management (Jenkin et al. 2011), or server virtualization (Bose and Luo 2011). These concepts and recommendations could be explored further. For example, goal-oriented requirements modelling language for environmentally concerned organizational systems design (Zhang et al. 2011) could also be leveraged to conceptualize the PLC of digital objects (e.g., smartphones) and aid product designers in estimating the environmental impacts of design alternatives.

3.5.2.2 Intensified Product Use

Resource efficiency during the in-use stage can be increased through intensified use of product systems. This increase can be achieved through the product's sequential, ownership-less consumption through multiple users, so-called collaborative consumption (Cohen and Muñoz 2016). Thereby, the service value (e.g., mobility) generated by-product systems (e.g., a car) is maximized and the overall consumption of natural resources can be lowered (Bardhi and Eckhardt 2012).

The idea of intensified product use has been implemented in numerous sharing, lending, renting, or leasing business models (Tunn et al. 2019), which often build on platforms as an enabling digital technology (Tiwana et al. 2010). However, our review showed that platform research on intensified product use beyond a purely economic motive is scarce (Achachlouei et al. 2015; Achachlouei and Moberg 2015; Cohen and Muñoz 2016; King et al. 2006; Vykoukal et al. 2009). Most IS research on collaborative consumption and the sharing economy refers to sustainability only indirectly or spuriously, if at all (Greenwood and Wattal 2017; Guo et al. 2019; Mittendorf et al. 2019; Teubner and Flath 2019; Weber 2014, 2016, 2017; Zimmermann et al. 2018). Future research could leverage current knowledge on platforms to better understand how digital platforms enable intensified product use to improve both economic and environmental sustainability.

Therefore, we suggest a key extension: Platform research must advance beyond the idea that IS primarily facilitate collaborative consumption through online matchmaking functionality. While existing IS research explains how two-sided intermediary platforms a priori facilitate transactions between supply and demand (Mittendorf et al. 2019; Teubner and Flath 2019; Zimmermann et al. 2018), we need to understand how digital platforms help manage material and social complexities of shared products in collaborative consumption networks a posteriori after the transactions agreed upon online are fulfilled offline.

This key extension involves two key challenges. First, offline collaborative consumption networks are more socially complex than currently reflected in existing online-only research. Typically, research on online market platforms and platform economics restrict the scope of involved actors to supply, demand, and an intermediary (Constantiou et al. 2017) to investigate how factors like price (Zimmermann et al. 2018) or trust (Mittendorf et al. 2019) affect collaborative consumption behavior. However, collaborative consumption networks involve additional actors that provide essential complementary services to the platform model. Mobility platforms, for instance, rely on value-adding actors that take care of the relocation and maintenance of the fleet (e.g., the bike-sharing provider *Donkey Republic* (2019)), while fashion platforms rely on logistics and laundry service providers that ship and clean the apparels (e.g., the designer dress rental service *Rent the Runway* (2019)).

Second, the focus on matchmaking capabilities of IS tends to neglect unintended sustainability consequences that primarily manifest in the offline world. Not all collaborative consumption initiatives are environmentally sustainable per se (Briceno et al. 2005; Hollingsworth et al. 2019; Martin 2016; Zamani et al. 2017). Unintended offline consumption behavior is a primary reason for rebound effects that reverse some of the initially prevented emissions. For instance, shared products in collaborative consumption networks show greater wear and tear owing to more careless consumption behavior, which shortens products' average lifetime and thwarts sustainability efforts (Hildebrandt et al. 2018; Hollingsworth et al. 2019).

Through an expanded research focus on the offline impacts of platform-enabled collaborative consumption, future IS research could investigate how such unintended behavior can be ‘designed out’ through deliberate interface design choices when building collaborative consumption platforms. In a first step, different forms of unintended consumption behavior must be empirically documented and underlying social and psychological mechanisms that explain this behavior must be explored. In a second step, countermeasures in the form of IS design choices should be discussed, implemented, and tested.

To inform the development of appropriate design principles, IS research on digital nudging (Weinmann et al. 2016) could be a promising starting point. While originally defined as ‘the use of user-interface design elements to guide people's behavior in digital [(online)] choice environments’ (Weinmann et al. 2016, p. 433), digital nudging might also be applied to guide real-world (offline) behavior, such as encouraging energy-efficient behavior in private households using IS feedback systems (Loock et al. 2013) or invoking change in people's health behavior (Noorbergen et al. 2019). Mitigating unintended consequences of collaborative consumption platforms with digital nudges suggests interesting real-world application scenarios, but it comes with greater complexity than pure digital choice environments: A posteriori choices in the offline world (e.g., 'Do I park the returned e-scooter where I have to get off letting it block the sidewalk or do I park it 50 meters down the road, where it does not disturb?') must be nudged a priori in the online world (e.g., via an e-scooter-sharing smartphone app). Moreover, existing studies focus on the short-term effects of digital nudges in one-off decisions (Schneider et al. 2019). Collaborative consumption, however, involves long-term, recurrent choice architectures—for instance, reporting broken shared assets like a bike to the sharing service provider to ensure continuing high-level service quality in terms of the availability of functioning bikes. To summaries, how to design digital nudges for offline choice architectures is still unclear, as is how effective they are.

3.5.2.3 Extended Product Use

In the in-use stage, not only intensity but also duration of the product system's use is an important indicator for resource efficiency. The shorter the average lifespan of a product, the more quickly it turns to waste and, eventually, ends up in incineration plants or landfills. The reuse principle suggests that non-functional product systems should be repaired by replacing deficient components. Obsolete but still functional products should either be upgraded to overcome obsolescence or redistributed to a subsequent owner via resale, donation, or trade-in. In the case of final disposal, product systems should not be entirely discarded, but remanufactured to use their functional components in other product systems.

However, many consumers dispose of broken or obsolete products via the waste bin instead of having them fixed or upgraded. Many discarded products are either kept at home (Wieser and Tröger 2018) or thrown into domestic waste streams to eventually end up in incineration plants (Manhart et al. 2016). Material value that could have been extracted from secondary use is wasted. This behavior has various reasons, ranging from lack of awareness and low trust in repair or upgrade services to lack of economic incentives (Cole et al. 2019; Wieser and Tröger 2018). Moreover, self-repair requires technical knowledge (e.g., disassembly instructions), skills (e.g., training), and resources (e.g., tools and spare parts). For most products to date, relevant information on repair is not readily available to consumers or repair professionals, if at all (Ellen MacArthur Foundation 2016a; Riisgaard et al. 2016). This lack of information and guidance leads to ecologically and economically suboptimal dispositions (Atlason et al. 2017; Sabbaghi et al. 2015).

With increasing availability of distributed IS and sensor technologies, manufacturers can store information about products' compositions and disassembly instructions and track product condition changes over PLCs (see Chapter 3.5.1) using digital formats. Companies such as *Hilti* (2019) have introduced digital twins to store product information and use it to increase the quality of their aftermarket repair services. *HP Inc.* (2020) enables users and independent aftermarket service providers to perform lifespan-extending maintenance and repair via online service instructions that can be accessed through QR codes attached to the physical products. Independent online repair movements, such as *iFixit* (2019), generate and disseminate repair information to end users, provide reliable supply channels of high-quality spare parts, and actively engage in legal action to fight for more repair rights (Zeiss et al. 2019).

Despite this growing digitalization of aftermarket services, in our review we did not find any study that investigated the relationship between IS and extended product use. We highlight two IS research opportunities to fill this void. First, research could attempt to better understand how the increasing availability of product data can be used for data-driven decision support at products' end-of-life. To date, we know little about how the information finds its way to the right actors at the right time and how it can trigger and facilitate lifespan-extending practices. While existing studies focused on industrial decision support systems that aid the selection of end-of-life products' recovery options for recycling in the post-use stage (Goggin and Browne 2000; Staikos and Rahimifard 2007; Ziout et al. 2014), we see an opportunity to provide IS-enabled decision support to individual consumers during the in-use stage to enable them to identify appropriate end-of-life scenarios at home (e.g., resale or donation). The UK-based reverse supply chain start-up *Stuffstr* (2019), for instance, partners with apparel retailers like *Adidas* (2019), to enable buy-backs of discarded clothing. Integrating its app into the online shops of its partners, *Stuffstr* encourages consumers to inventory their closets step-by-step. Each inventoried garment is evaluated, and appropriate end-of-life scenarios are suggested.

This research can draw on and extend the knowledge base on customer decision support systems (O'Keefe and McEachern 1998) and, in particular, recommendation agents (Maes et al. 1999; Wang and Benbasat 2005). So far, recommendation agents have been used and investigated primarily in e-commerce contexts, where they support consumers in overcoming information overload and provide purchase recommendations based on consumers' preferences and needs (Komiak and Benbasat 2006; Xiao and Benbasat 2007; Xu et al. 2018). However, recommendation agents could also provide consumers with decision support in end-of-life scenarios for discarded product systems. End-of-life decision problems grow in difficulty with the material complexity of the discarded product systems, and software agents can help integrate complicated decision criteria of end-of-life scenarios with unique material properties of discarded products. For example, the key decisions in a CE context are about *reusing* and *recycling*, whereas the key decision in e-commerce is about consumer *purchasing*. Reuse and recovery are complex matching problems, whereas consumer purchase is a preferential choice problem.

The second IS research opportunity concerns short replacement cycles of consumer goods. Especially in fast-paced industries (e.g., consumer electronics), many consumers discard functioning products to replace them with newer models (Welfens et al. 2016; Wieser and Tröger 2018). New models and technology innovations drive consumers' perceptions of products' obsolescence, which in turn affects consumers' preferences favoring product replacement over product repair and new products over second-hand products (Jardim 2017; Ongondo et al. 2011).

Because of their modular-layered architecture, digital products are actually well designed to extend lifespans through upgrades (Yoo et al. 2010). Modularity is an important enabler of product upgrade and repair (Bi and Zhang 2001; Erixon 1998). In practice, however, only a few consumer electronics companies tap into digital architecture's modularity potential to offer more durable and upgradable products. Examples include the smartphone manufacturers *Fairphone* (2019) and *Shiftphone* (2019). In contrast, higher processing needs of new software applications as well as expiring software support for older devices drive the technological obsolescence of digital products (Benton et al. 2015). Thus, investigation of the relationship between Yoo et al.'s (2010) layered modular architecture of digital products and product lifespan extension is warranted. Building on research on digital innovation (Lusch and Nambisan 2015; Yoo et al. 2010), the IS community is well positioned to examine forthcoming digital product innovations to understand threats and opportunities of digital technology for innovations in consumer products that have the objective of reuse, not new purchase.

3.5.2.4 Material Reprocessing

At the end of their functional life, raw materials contained in product systems and their components can be reprocessed to make them available as secondary materials for new offerings (European Parliament and European Council 2008). While waste management is one of the oldest and most established fields in the CE realm, it is overstrained with increasingly complex and harmful but valuable waste streams (Reike et al. 2018). Electronic equipment, for instance, can contain up to 60 different elements, including precious metals (e.g., gold), rare earth metals (e.g., yttrium), and hazardous metals (e.g., mercury). In 2016, the total material value present in e-waste was estimated at approximately €55 billion (Baldé et al. 2017). Globally, several countries have implemented take-back schemes for municipal solid waste, which coordinate collection, treatment, and remarketing of simple domestic waste materials like cardboard, plastic packaging, or beverage bottles. However, owing to the rising complexity of waste streams these schemes increasingly fail to achieve satisfying recovery rates (Gundupalli et al. 2017; Tam et al. 2019). Therefore, more innovative treatment and remarketing systems are required to extract and retain more value than extant waste management systems (Parajuly et al. 2019).

We suggest two key intervention points that would benefit from IS research. First, increased transparency across material levels can improve waste handling (i.e., pre-sorting, dismantling, separation, and end-processing). Today, waste managers find collected domestic waste streams that enter treatment facilities largely opaque because they are unaware of the streams' ingredients. Machines that pre-sort and separate inbound waste streams rely on mechanical and optical material detection techniques, such as magnets and near-infrared sensors, to sequentially increase the transparency of waste streams (Gundupalli et al. 2017). However, existing detection methods are not able to effectively separate increasingly complex waste streams. If products carried a digital tag containing information on embedded materials, recycling machines could separate waste with higher accuracy. For example, the project *HolyGrail* (2019) piloted digital watermarks, invisible to the human eye, on plastic packaging. The watermarks link to a database containing relevant packaging attributes that help increase sorting purity. This technological innovation can potentially revolutionize waste sorting in recycling facilities.

We call for future IS research that increases understanding of how data in recycling processes can be effectively shared and how this sharing affects sorting purity and recycling quotas. So far, research on digital watermarks has investigated the technical feasibility in smaller pilot project environments. IS research could now focus on the scalability of such solutions. For digital watermarks to reach broad adoption in a CE, they first need to become a cross-industry standard. Standard making has long been considered a challenging and complex task driven by power and politics (Besen and Farrell 1994; Farrell and Saloner 1985), and we expect to find these properties exacerbated in a CE context involving parties alongside the PLC from various sectors and industries. We believe future IS research could help avoid lock-ins on inferior standards by leveraging existing knowledge on de facto and de jure IT standardization processes. IS research could inform the standard-setting process by, for instance, evaluating the effectiveness of different IT architectural design choices (Baldwin and Woodard 2009) or investigating the effect of different standardization processes, such as management-based, technology-based, or performance-based standards (Roca et al. 2017) on standard adoption, governance, social welfare, network externalities or standardization costs (Liu et al. 2011; Lyytinen and King 2006; Zhao et al. 2011). For instance, IS research could provide dynamic perspectives on standardization relating to the interaction between complex social systems formed by heterogeneous stakeholders such as manufacturers, recyclers, customers, non-corporate players such as NGOs or academics, industry standards bodies, and national and international regulators and the affordances of technologies as they move from infancy to maturity (Roca et al. 2017).

Second, IS can help increase the use of secondary materials in new product offerings by connecting data of the recycled material with material requirements from potential secondary use scenarios (Fraccascia and Yazan 2018; van Capelleveen et al. 2018). In recycling markets, matching supply of secondary materials with demand is a significant challenge (OECD 2006) because of the geographical dispersion of unrelated, heterogeneous actors and the asynchronous and irregular occurrence of material supply and demand (Wilts and Berg 2017). Waste producers often lack information on companies in need of recycling derivatives (Aid et al. 2017; Golev et al. 2015). Further, the quality of recycled materials can vary considerably, resulting in a market characterized by low trust, information asymmetries, and high transaction costs. Even the smallest impurities in recycled materials can lead to significant changes in material properties, rendering their use infeasible for certain new product offerings (Shen and Worrell 2014).

Online platforms have been recognized as important enablers to form and coordinate markets for secondary resources (Grant et al. 2010; Konietzko et al. 2019). Previous studies have mainly focused on platforms for industrial symbiosis (Halstenberg et al. 2017; Low et al. 2018), which set out to engage 'traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products' (Chertow 2000, p. 314). Platforms like *Kalundborg Symbiosis* (2019) bring together business actors located in close geographical proximity (e.g., within industrial parks) with predictable streams of by-products (Ashton 2008; Bellantuono et al. 2017). Recently, third-party online market platforms have emerged, such as *Cirplus* (2019) or *Excess Materials Exchange* (2019), that attempt to connect actors from different industrial sectors across larger geographical distances. These platforms provide value-added services such as material certifications or innovative matchmaking opportunities to overcome material (e.g., material purity) and social (e.g., trust) complexities that increase with the size of the circular material flows.

Drawing on the extensive knowledge base on multi-sided platforms (Boudreau and Hagiu 2009; de Reuver et al. 2018; Gawer and Cusumano 2014) seems an intuitive approach to explaining platform phenomena in a CE context (Konietzko et al. 2019). But two peculiarities of circular material flows call for a careful evaluation of the applicability of seminal market platform concepts, such as network effects (Katz and Shapiro 1985) or the role of intermediaries (Evans 2003). First, looping secondary resources into new product systems comprises a combination of online (i.e., matchmaking) and offline (i.e., fulfillment) transactions. Second, supply and demand of secondary materials occur asynchronously and spatially dispersed (Wilts and Berg 2017). Therefore, investigating platforms for circular material flows from a merely online-centric perspective runs the risk of missing half of the story taking place offline.

Consequently, research on online-to-offline platforms (Brynjolfsson and Smith 2000; Forman et al. 2009) will be important to consider in future investigations on platforms for secondary materials exchange. For instance, Li et al. (2018) show how online-to-offline platforms 'differ from traditional two-sided online platforms by emphasizing the importance of local [offline] characteristics in determining the growth and scale of these platforms' (p. 1875). Online-to-offline platform studies have so far focused primarily on the business-to-consumer retailing domain. Industrial symbiosis and third-party recycling platforms could now both be considered as online-to-offline platforms in a business-to-business context. However, they deal with characteristics of the offline world differently. While industrial symbiosis platforms bring together business actors located in close geographical proximity, third-party recycling platforms do not tend to limit their services to a certain region. How such differences in local characteristics—as well as properties of traded secondary materials—affect the design, growth, and scale of supporting online platforms is unclear.

3.6 Conclusions

Many grand challenges affecting economies, societies, and the environment strongly involve IS and need attention from scholars (Davison and Tarafdar 2018). Replacing the current 'take-make-waste' economic model with a circular economic model is one of these. A CE model would enable the gradual decoupling of economic activity from the consumption of finite virgin resources and building economic, natural and social capital (Ellen MacArthur Foundation 2012).

We believe the move toward a CE presents a grand opportunity for our discipline (Rai 2017). But the IS discipline has so far not studied or realized the full sustainability potential of a CE model. We hope that our article will mobilize more IS research on CE. Toward that end, we developed research directions to carry the conversation regarding a CE into our own field and conceptual lexica. We have elaborated on two IS research objectives that would foster better comprehension of how IS help understand and enact circular material flows, thereby addressing problems of wicked material and social complexity inherent to applications of the reuse and recycle principles.

We based our research objectives on the belief that IS can play a transformative, solution-oriented role (Corbett and Mellouli 2017; Elliot and Webster 2017; Hedman and Henningsson 2016) in supporting actors to understand and implement CE systems. In this light, IS scholarship can yield impactful sociotechnical solutions and provide policy recommendations in favor of reasonable technology support. However, sustainability research spans a wide array of disciplines, and the IS discipline cannot master the sustainability challenge on its own. A joint endeavor and networked collaboration across research disciplines will ultimately be needed.

Zeiss / Information Flows in Circular Economy Practices

**INFORMATION FLOWS IN
CIRCULAR ECONOMY PRACTICES**

Research paper

Zeiss, Roman, University of Cologne, Cologne, Germany, zeiss@wiso.uni-koeln.de

Abstract

Recently, other disciplines and scientific communities discuss the Circular Economy paradigm as a key vehicle to establish more sustainable production and consumption patterns by decoupling economic output and emissions. Conversations about information system solutions for sustainable production and consumption, however, remain notably absent in the Information Systems research community. We develop a taxonomy of information flows relevant for the successful application of Circular Economy practices. Drawing on conceptual and empirical data, we categorized nine Circular Economy practices based on their underlying material flow networks and identified four classes of information flows that enable the proper functioning of these practices. Our work (a) provides a conceptual foundation for Circular Economy-related conversations within the Information Systems research community, (b) stimulates future solution-oriented Information Systems research for environmentally sustainable production and consumption, and (c) strengthens inter-disciplinary research.

Keywords: Circular economy, Material flows, Information flows, Green IS, Taxonomy development.

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Chapter 4

Information Flows in Circular Economy Practices

Roman Zeiss
University of Cologne

Recently, other disciplines and scientific communities discuss the Circular Economy paradigm as a key vehicle to establish more sustainable production and consumption patterns by decoupling economic output and emissions. Conversations about information system solutions for sustainable production and consumption, however, remain notably absent in the Information Systems research community. We develop a taxonomy of information flows relevant for the successful application of Circular Economy practices. Drawing on conceptual and empirical data, we categorized nine Circular Economy practices based on their underlying material flow networks and identified four classes of information flows that enable the proper functioning of these practices. Our work (a) provides a conceptual foundation for Circular Economy-related conversations within the Information Systems research community, (b) stimulates future solution-oriented Information Systems research for environmentally sustainable production and consumption, and (c) strengthens inter-disciplinary research.

4.1 Introduction

Our society is living beyond the regenerative capacity of the biosphere (Boyden and Dovers 1992; Lin et al. 2018; Wackernagel et al. 2002). Growing, resource-intensive, and mainly fossil-fuel-based material consumption patterns are considered as major drivers of global resource use and key contributor to increasing greenhouse gas emissions (Davis and Caldeira 2010; Fleurbaey et al. 2014). Recently, the Circular Economy (CE) paradigm is discussed as a key vehicle to establish more sustainable production and consumption practices by decoupling economic output and emissions (Ghisellini et al. 2016; Lazarevic and Valve 2017; Stål and Corvellec 2018).

With the uptake of this debate in other scientific (e.g., Environmental Sciences), business, and policymaker communities, we note comparable conversations about information systems (IS) roles for *CE practices* remain largely absent in the IS research community[8], a few notable exceptions aside (Klör et al. 2018; Seidel et al. 2018). Nonetheless, research on "Green IS" has repeatedly highlighted the IS solution potential for environmental sustainability issues by investigating the diverse IS roles for *sustainable energy* (cf., Ketter et al. (2016a), Irani et al. (2015), Wagner et al. (2013), or Watson et al. (2010)), *mobility* (cf., Brendel et al. (2017), Marett et al. (2013), or Sonneberg et al. (2015)), and *organizational work practices* (cf., Degirmenci and Recker (2016), Corbett (2013), Seidel et al. (2013)).

We take steps to extend the IS solution potential towards *sustainable production and consumption practices*. Considering alarming consequences of unsustainable consumption behavior, on the one hand side, and the scientific track record of Green IS research, on the other, we deem this so-far neglected sustainability phenomenon also relevant to the Green IS research community.

Our motivation for initiating this scholarly conversation is grounded, first, in the observation that information availability and flow play a critical role when establishing CE practices (European Commission 2014; Kirchherr et al. 2018). For instance, prolonging a product's life through repairing requires knowledge about its condition, location, and reparability. Second, recent advances in digital technology, such as sensor-based technologies to generate information, or predictive analytics that can utilize such information, provide opportunities to integrate information with material flows, which

[8] In fact, querying the AIS Seniors' Scholars Basket with the keyword "circular economy" reveals the paradigm to be completely absent in leading IS journals.

may exhibit great transformative power in CE application scenarios if leveraged appropriately (French and Shim 2016).

Our goal is to examine how IS solutions can support, enable, or enact CE practices. Considering the absence of a comprehensive discussion of the CE paradigm in the IS research community as well as its systemic complexities, we believe the most opportune first step is to develop a taxonomy of critical information flows that are at the core of CE practices. Taxonomies reduce complexity and provide scholars a conceptual and structural basis from which advanced scientific discourse, for instance in form of new theories, can emerge (Nickerson et al. 2013). Consequently, the research question guiding the development of this taxonomy is:

RQ: *What information flows are relevant for the application of CE practices?*

We pursue three major goals with this work. First, our taxonomy introduces the CE paradigm and its central practices to IS scholars, providing a conceptual foundation for CE-related conversations within and across the boundaries of the IS research community. We achieve this goal by developing a conceptual lexicon describing the constituent components of the material flow networks underlying the CE practices. Second, we identify information flows that enable the proper application of CE practices and discuss an initial set of roles that IS might play to cater for these information flows. In that way, we hope to facilitate future solution-oriented IS research for environmentally sustainable production and consumption practices. Third, through the combination of the first two goals we attempt to strengthen inter-disciplinary research spanning other scientific communities and the IS field in the long-term, as specifically requested by Seidel et al. (2017) in their 'Sustainability Imperative in IS Research'.

We proceed as follows: Next, we introduce the concept of a CE, which will inform the initial dimensions and variables of our taxonomy. Furthermore, we offer a short account of the current state of Green IS research to assess the CE paradigm in light of existing knowledge. We collate a brief introduction and history of the taxonomy development method by Nickerson et al. (2013) in Chapter 4.3 and describe how this generic method was instantiated in this paper. Drawing on conceptual work from the Environmental Sciences as well as on empirical data on CE-driven business models and initiatives available online, we present the final taxonomy of information flows relevant for CE practices in Chapter 4.4. Before concluding, we discuss various future research trajectories—in form of general IS roles in a CE—emerging from the key findings of our taxonomy development.

4.2 Background

This paper introduces the CE paradigm into the existing Green IS body of knowledge. We use the first subsection to present the key concepts of the paradigm, relying on knowledge from the Environmental Sciences research community, and relate these concepts to existing research on environmentally sustainable IS in the second subsection.

4.2.1 Circular Economy

The CE is an economic model with the goal of minimizing resource input as well as waste, emission, and energy leakage by slowing, closing, and narrowing material and energy loops (Geissdoerfer et al. 2017; Kirchherr et al. 2017; Potting et al. 2017). This is purportedly realized through the <u>useful application of materials at the end of their lifespan</u> (i.e., *recovering* and *recycling*), an <u>extended lifespan of products and their components</u> (i.e., *remanufacturing*, *refurbishing*, *repairing*, and *reusing*), and a <u>smarter product use and production</u> (i.e., *reduce*, *rethink*, and *refuse*). These <u>objectives</u> and *practices* span the entire value chain (i.e., in sourcing, production, manufacturing, distribution, and use) and can be examined on a micro (e.g., individual producer and consumer), meso (e.g., organization, group, team, joint-ventures), and/or macro level (e.g., city, country, society).

Figure 6 illustrates how the different CE practices (e.g., *recycle*) help transform the traditional linear material flow, from sourcing to disposal (i.e., cradle-to-grave), into a circulating material flow, from sourcing to reuse (i.e., cradle-to-cradle).

Throughout its development, several so-called ‘R-frameworks’ have been developed to describe the core practices of the CE (cf., van Buren et al. (2016), Sihvonen and Ritola (2015), or King et al. (2006)). These frameworks represent the holistic lifecycle view characteristic for the CE paradigm and provide a very tangible depiction of corresponding circulating material flows. We draw on Potting et al.'s 9-R-framework (2016) and the definitions by Kirchherr et al. (2017), as they represent the most nuanced and integrated conceptualizations to date (Table 13).

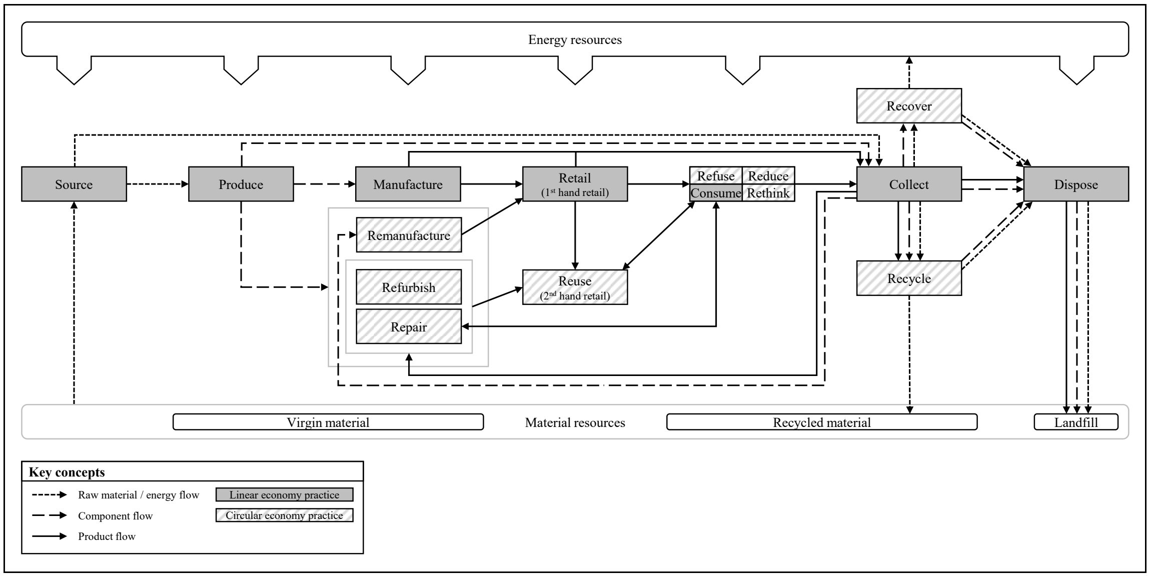

Figure 6. Conceptual model of a circular economy and its material flows

Table 13. r-framework, based on Potting et al. (2016) and Kirchherr et al. (2017)

CE Objective	CE Practice	Description
Smarter product use and production	R1 Refuse	Refuse product use by abandoning its function or consuming a radically different product with the same function
	R2 Rethink	Rethink product use to increase its utilization rate (e.g., through sharing or lending)
	R3 Reduce	Reduce energy and material resource consumption during product manufacture or use
Extended lifespan of products and their components	R4 Reuse	Reuse a discarded but still working product in good condition by another consumer
	R5 Repair	Repair a defective product to use it with its original function
	R6 Refurbish	Refurbish an old product and bring it up to date
	R7 Remanufacture	Remanufacture parts of discarded product in a new product
Useful application of materials at the end of their lifespan	R8 Recycle	Recycle materials to obtain the same or lower quality
	R9 Recover	Recover energy through incineration of materials

4.2.2 Circular Economy in Information System Research

Research on IS for environmental sustainability has just celebrated its ten-year anniversary. While the *Green IT* research field – with its focus on IT energy efficiency and equipment utilization over its technology lifecycle (Boudreau et al. 2008) – is currently attracting comparably little scholarly interest, *Green IS* research – focusing on IS-enabled sustainability phenomena (Melville 2010) – has persisted as relevant albeit niche topic in the IS research community (Elliot and Webster 2017).

Despite the diversity of investigated sustainability phenomena (Sedera et al. 2017), we believe that the absence of a discussion of CE, one of the currently most debated topics in the Environmental Sciences (Geissdoerfer et al. 2017; Kirchherr et al. 2017), denotes a key shortcoming of the Green IS literature to date: searching the *AIS Senior's Scholar Basket* for the string "circular economy" yields no results at all; extending the review to proceedings of AIS conferences returned 13 research papers of which ten do not substantively deal with the CE paradigm. The remaining three conference papers are conceptual:

- Benedict et al. (2018) provide guidelines for developing an *Industrial Symbiosis Platform Ecosystem*;
- Schoormann et al. (2018) present design requirements and principles for a *sustainable business model* development tool; and
- Schrödl and Simkin (2014) integrate the CE paradigm with the *Supply Chain Operations Reference* (SCOR) model to create a blueprint for sustainable interorganizational eco-systems.

To substantiate our claim, we broadened our search criteria to also consider articles from AIS Senior's Scholar Basket that primarily address other sustainability phenomena[9] and which, upon reading, could be interpreted as implicitly addressing CE practices. We found two such papers:

[9] search strings: "green IS", "green IT", "sustainab*"; last query date: 18 Nov 2018.

- Seidel et al. (2018) provide design principles for sensemaking support systems stimulating individuals to eventually *refuse* existing consumption behaviour (e.g., drink from plastic cups) and *replace* them with more sustainable alternatives (e.g., drinking fountains) to cut down on waste;
- Klör et al. (2018) develop a decision support system for *remanufacturing* electric vehicle batteries.

In summary, we interpret the above presented current state of knowledge as insufficient in coverage yet promising in application. In our reading, the work to date hints at a lurking solution potential of IS for action-oriented pro-environmental behavior on individual and organizational levels. However, the CE paradigm extends beyond Seidel et al. (2018) and Klör et al. (2018) with more principles to be supported.

4.3 Method

We developed a taxonomy of information flows in CE principles. The taxonomy provides two things: (a) a set of relevant conceptual components that uniquely form the nine CE practices introduced in Table 13 and (b) a set of recurrent information flows that are central for the successful application of the respective CE practices. With this work, we believe a foundation is set enabling us to theorize an initial set of roles that IS play during the deployment of CE practices in the end of this paper and invites other scholars to conduct future solution-oriented Green IS research for sustainable production and consumption.

A taxonomy is an empirically or conceptually derived set of dimensions and characteristics used to uniquely describe and classify real-world phenomena (Nickerson et al. 2013). While the first taxonomies originated in Biology to hierarchically classify living organisms (Eldredge and Cracraft 1980; Sneath 1995), the method diffused into the Social Sciences (Bailey 1994) and Management Sciences (Doty and Glick 1994). It, eventually, found its way into IS research and is, today, a well-established and accepted method for theory-building (Bapna 2004; Earl 2001; Fiedler et al. 1996; Gregor 2006; Oberländer et al. 2018; Prat et al. 2015; Sabherwal and King 1995).

We generated our taxonomy following Nickerson et al.'s (2013) method choosing the conceptual-to-empirical approach (Figure 7).

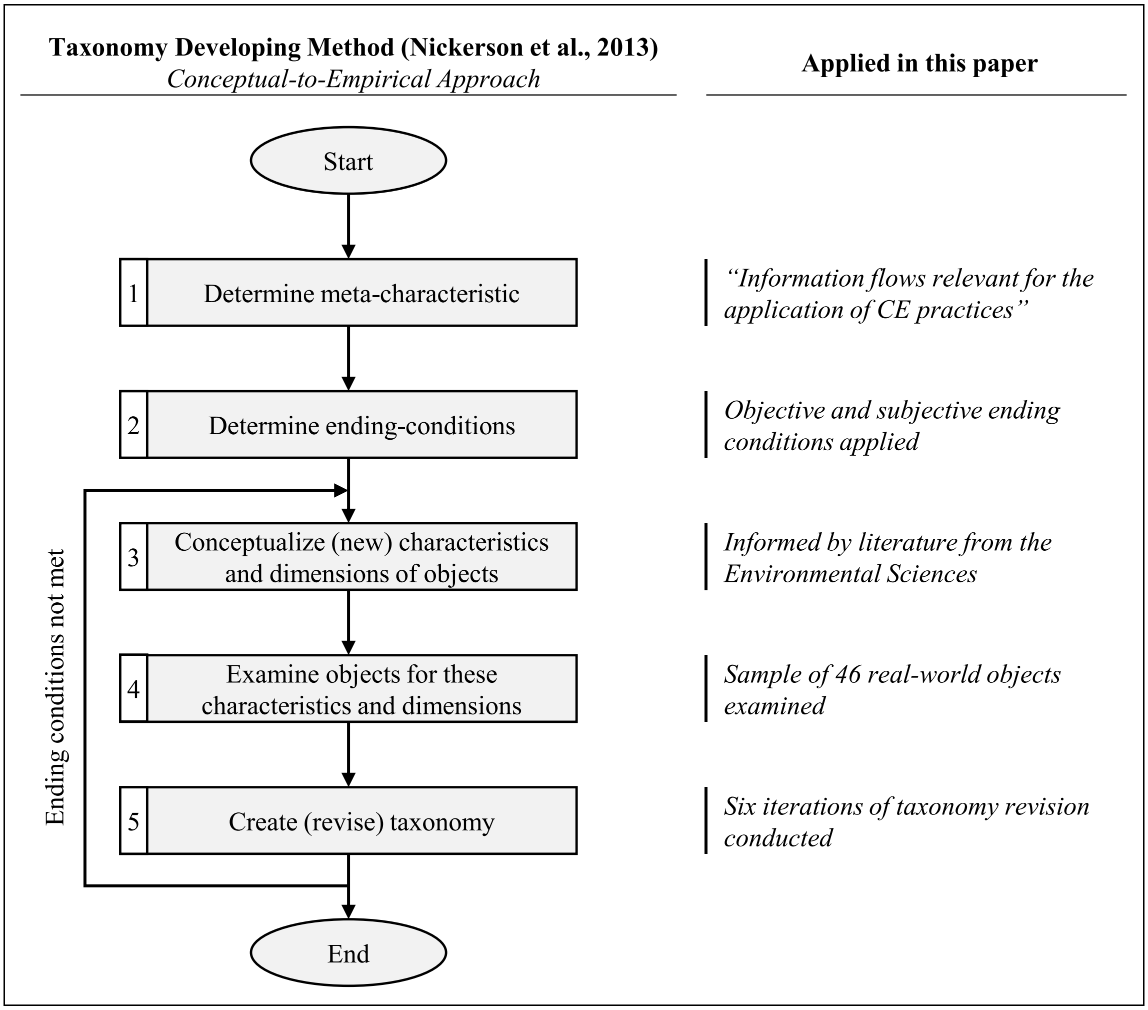

Figure 7. Taxonomy developing method applied in this paper, following Nickerson et al., 2013

With the Green IS research community as potential taxonomy user in mind, we defined the taxonomy's meta-characteristic as: *'information flows relevant for the application of CE practices'* (step 1). The iterative taxonomy development process was guided by the objective ending conditions proposed by Nickerson et al. (2013) (step 2). Regarding the subjective ending conditions (e.g., concise, robust, comprehensive, extendible, and explanatory), we actively balanced the conciseness and comprehensiveness conditions. While we initially started with four main dimensions (i.e., 'circulating good', 'involved stakeholder', 'activity', and 'information flow') and twelve subdimensions, we iteratively reduced it to three main dimensions (i.e., 'flow network', 'material objects', and 'information flow') and ten subdimensions. In the first iteration, we relied on concepts from the Environmental Sciences literature (e.g., Reike et al. (2018) or Kirchherr et al. (2017)) to derive the initial dimensions and characteristics of our taxonomy (step 3). We then classified real-world objects (Gregor, 2006) from a sample of 46 CE-driven business models and initiatives, which we identified from online public CE-databases[10], a digital sustainability platform[11], and from press releases of an annual green start-up competition[12] (step 4). The cases were included in the sample, if their business model or initiative could be clearly linked to one or more CE principles and sufficient information was available online as input for the empirical analysis part of our taxonomy development. We stopped our online research, once we reached saturation of insights (i.e., new real-world objects did not add new details to already identified real-world objects in the same CE practice). The development process was iterated six times until the taxonomy met the predefined objective and subjective ending conditions (step 5).

4.4 Information Flows in Circular Economy Practices

We now present the outcomes of our taxonomy development process in Table 14. The final taxonomy covers all nine CE practices, displayed in the table columns, and consists of three main dimensions, structured in the table rows. The first two dimensions represent constituent components of the physical world, with several sub dimensions each, which instantiate differently for each CE practice: a **flow network** and **material objects**. The third dimension categorizes the **information flows** that enable a successful application of CE practices. These information flows are grouped into four sub dimensions. In what follows, we define each dimension and present the results of our classification process.

[10] Circle Lab Knowledge Hub and Circular Economy 100

[11] Reset

[12] Green Alley Award

Table 14. Taxonomy of information flows in circular economy practices

Dimension	Subdimension	Characteristic	Refuse	Rethink		Reduce	Reuse		Repair		Refurbish	Remanufacture	Recycle	Recover
			Circular Economy Practices											
Flow network	Type	P2P		x			x		x					
		P2B			x			x		x				
		B2B								x	x	x	x	x
	Actors	Producer								a. ●	●	●		
		Manufacturer									▲ ▼	▲ ▼		
		Retailer			a. ● b. ▲			●	●					
		Repairer								a. ▲ ▼ b. ●				
		Consumer x		a. ● b. ▲	a. ▼ b. ●		●	▼	▼	a. ● b. ▼				
		Consumer y		a. ▼ b. ●			▼							
		Collector									●	●	● ● ●	● ●
		Recycler											▼ ▼ ▼	
		Incinerator												▼ ▼
	Change of ownership						x	x	x	x	x	x	x	x
Material objects	Product ●—▶|	Used		x	x		x	x		x	x		x	
		New												
	Component ● - -▶|	Used										x	x	x
		New							x	x	x	x		
	Raw material ●---▶|	Used											x	x
		New												
Information flows	Market	Supply/Demand		x	x		x	x	x	x	x	x	x	x
	Actor	Location		(x)			(x)			x				
		Availability		(x)			(x)			x				
		Behaviour		x	x					x				
	Material object	Properties	x	x	x	x	x	x	x	x	x	x	x	x
		Location		x	x		x	x	x	x	x	x	x	x
		Utilization		x	x									
		Condition		(x)	(x)	x	x	x	x	x	x	x	x	x
	Activity	Use	x	x	x	x								
		Transformation							x	x	x	x	x	x
Real-world objects (Circular Economy-driven business models or initiatives)			*- codecheck - ecoGator - Evocco - LoopedGoods - ToxFox*	*- Airbnb - Car2Go - Drivy - Nebenan.de - Neighbourly - Nextdoor - peerby - Style Lend*	*- Bundles - Gerrard Street - Grover - Readymade Furniture - Vigga*	*- GreenMeter - Nest Mobile*	*- Kleiderkreisel - LoopRocks - Nebenan.de - Neighbourly - Nextdoor - peerby - Restado - The Next Closet*	*- kaputt.de - Patagonia*	*- Fairphone - ifixit - kaputt.de - Patagonia - Shiftphone*	*- clickrepair - kaputt.de - ReplaceDirect - Twindis - veloyo*	*- Amazon Renewed - Circular Computing - MUD Jeans - refurbed - RICOH*	*- Excess Materials Exchange - Roetz Fair Factory - Van Hulley - Vege*	*- binee - Dutch Awearness - renewi - Scrap Connection - Wasted*	*- plethora of 'waste-to-energy' or 'energy-from-waste' cases*

4.4.1 Flow Network

We define a CE flow network as a heterogenous set of connected but spatially distributed actors between whom the material objects move with or without changing the ownership. If involved, the actors either represent the origin (cf., start of an arrow in Table 14) or destination (cf., end of an arrow in Table 14) of a material flow. As depicted in the conceptual CE model in Figure 6, actors in the CE processes comprise producers, manufacturers, retailers, repairers, consumers, collectors, recyclers, and incinerators.

As a result of the classification of real-world objects, we specified three types of flow networks: peer-to-peer (P2P), peer-to-business (P2B), and business-to-business (B2B). **Peer-to-peer flow networks** emerge from transactions created between peers (e.g., *Drivy*), **peer-to-business flow networks** involve transactions between consumers and organizations (e.g., *Patagonia*), and **business flow networks** characterize themselves by transactions between individuals and businesses (e.g., *Car2Go*).

Furthermore, we identified various manifestations of material flows: For instance, in peer-to-peer *reuse*-cases (e.g., *LoopRocks*) we observe **single one-way material flows** (i.e., a used product flows from one consumer to another consumer), in business-to-business *remanufacture* cases (e.g., *Vege*) we see **multiple one-way material flows** (i.e., a used component flows from a collector and a new component flows from a producer to a manufacturer), and in peer-to-business *repair* cases (e.g., *clickrepair*) we identified **multiple one-way** (i.e., a new component, the spare part, flows from a retailer to a repairer**) and return** (i.e., a used, defective product flows from a consumer to a repairer and back) **material flows**. Both peer-to-peer and peer-to-business *rethink* cases (e.g., *Style Lend* or *Vigga*), where products are shared and lend among several users, are special cases of **continuous material flows**. We also observe CE practices with **no material flow** at all. These include situations, where an actor refuses to consume or alters the handling or use of a previously acquired (i.e., already flowed) material object.

Finally, dynamic ownership structures create an additional layer of complexity. While *refuse*, *rethink*, and *reduce* practices do not involve any **change of ownership**, the remaining practices all come with a proprietary ownership change.

4.4.2 Material Objects

We define a material object in a CE as a *physical artefact, whose life and use are extended and intensified, respectively, through the application of CE practices*. Material objects are purposefully created from virgin or recycled material resources and, over their lifetime, circulated between and owned by one or more actors. Every material object, therefore, (a) requires input of material resources in the beginning of its life, (b) requires energy input for material transformation, transportation, and utilization during its life, and (c) causes waste emissions at the end of its life.

In our taxonomy, we classify material objects according to their level in the **product hierarchy** and **utilization history**. Based on the analysis of real-world objects (i.e., CE-driven business models or initiatives), we specified the product hierarchy into **products**, **components**, and **raw materials** and the utilization history into **used** and **new**. A product decomposes into two or more components and a component consists of one or more processed raw materials. Please note that we consider repair tools as products and spare parts as components. We call (a) a raw material “new”, if it is sourced from virgin material resources, (b) a component “new”, if it is freshly produced from raw material, and (c) a product “new”, if it only consists of new components and was never used by an actor before. Contrasting, our understanding of “used” material objects logically establishes as negated definitions of “new” material objects.

We observe that most of the CE practices involve the **movement of used products**, for instance, in peer-to-peer or business *reuse* (i.e., second hand retailing) and *rethink* (i.e., sharing and lending) cases (e.g., *The Next Closet* and *Bundles*, respectively). In addition, the CE practices *repair* (e.g., *kaputt.de*), *refurbish* (e.g., *Circular Computing*), and *remanufacture* (e.g., *Roetz Fair Factory*) characterise themselves by the **movement and combination of used and new material objects**, including both products and components. The case for moving material objects on all hierarchy levels, including raw materials, can be found in *recycle* (e.g., *binee*) and *recovery* (i.e., *waste-to-energy*) practices, which form the “last resort” in a material object’s lifecycle.

4.4.3 Information Flows

So far, the developed taxonomy classifies main components of the underlying material flow networks that uniquely constitute a CE practice. Recalling the target users and the meta-characteristics of the taxonomy, we extended it in a second step to include recurrent information flows that are critical enablers of these practices. Building on literature on data and information quality (cf., Boritz (2004), Bovee (2004), Lee et al. (2002), or Wang and Strong (1996)) we define **information** as *structured data, which is accurate, relevant, timeliness, complete, and accessible to actors*. We talk of an **information deficit** in *situations where structured data is either unavailable or available in poor quality* (e.g., lack of accuracy, relevance, timeliness, completeness, accessibility).

In our sample of real-world objects, we identified four classes of information flows that are critical for the successful application of CE practices: **market**, **actor**, **material object**, and **activity-related information flows**. In the following subsections, we introduce these classes, describe their specifying characteristics, and explain why they are critical for the application of CE practices.

4.4.3.1 Market-related Information Flows

Market-related information flows concern the availability of structured data about **supply and demand of material objects**. They represent a prevalent information flow class among the investigated CE practices in our sample. Except for *refuse* and *reduce*, all other practices critically rely on market-related information.

The market-related information flows are critical as their absence increases **ex-ante transaction costs** (UNEP, 2016; World Economic Forum, 2016). In particular, these costs add up from **initiation costs** (e.g., search for available quantities of specific circulating material objects, for instance, spare parts or used components) and **agreement costs** (i.e., short-term individual ad-hoc contracting dominates long-term general agreement contracting). Initiating and agreeing on a transaction is particularly cumbersome in secondary or shared markets (i.e., flow networks with used or shared material objects), where supply and demand are spatially scattered and temporally asynchronous and irregular (Wilts and Berg 2017).

Deficient market-related information, eventually, lead to two outcomes in CE practices: First, the absence of information about supply and demand of circulating material objects entirely prohibits markets to find the optimal allocation of secondary resources (i.e., no transaction takes place). Second, available poor-quality information prohibits secondary resource markets in the long-term, as their inefficient cost structures are not competitive with the cost structures of alternative primary resource markets.

4.4.3.2 Actor-related Information Flows

Actor-related information flows concern structured data about **location**, **availability**, and **behavior of an actor** involved in a flow network. This class of information is especially relevant for CE practices that rely on an actor's physical participation, either in transportation, transformation, or utilization of material objects.

We observed the importance of the information in our sample for *rethink* and *reuse* practices in peer-to-peer flow networks as well as in *repair* practices in peer-to-business flow networks. For instance, *Style Lend*, a peer-to-peer sharing platform for female designer fashion, requires the lending actor (or an organized deputy) to be physically available for pick-up of the shared material object (i.e., clothing) by the borrowing actor. Another example is *kaputt.de*, a mobile phone repair platform, that relays repair services of repair professionals to end consumers with defective mobile phones. These CE practices would fail because no agreement on the spatial and temporal terms of the physical settlement would be achieved in the absence of location (i.e., spatial), availability (i.e., temporal), and behavior (i.e., service quality) information on involved actors.

The above-mentioned examples represent a recurrent pattern implying that deficient actor-related information increase **ex-post transaction costs**. The uncertainties resulting from actors' physical participation in the flow network drive **handling costs** (e.g., transportation), **adjustments costs** (e.g., changing temporal availability of involved actors), and **control costs** (e.g., quality assurance) (Kirchherr et al. 2018). Especially in the observed peer-to-peer (e.g., *Airbnb*) or peer-to-business (e.g., *kaputt.de*) flow networks, where the utilization (e.g., housing) or transformation (e.g., repairing) of material objects (e.g., flats or mobile phones) requires the active involvement of actors (e.g., house lenders or repairers), the presence of actor-related information is critical for the entire CE practice.

4.4.3.3 Material Object-related Information Flows

Material object-related information flows concern structured data about **properties**, **utilization**, **location** or **condition of material objects**. Like market-related information flows, this class is prevalent among various CE practices. However, during the empirical analysis of our real-world sample, we identify a more heterogenous set of enablement patterns of object-related information in CE practices.

First, the critical information about **properties of material objects** affects all CE practices. To name a few, information on dimensional properties (e.g., size) enable CE practices relying on transportation of material objects (e.g., *reuse*). Furthermore, information on material properties (e.g., ingredients) is crucial in (a) *refuse* and *reduce* practices educating private actors (i.e., consumers) to achieve pro-environmental consumption behavior change (e.g., *Evocco*) and (b) *remanufacturing* and *refurbishing* practices guiding institutional actors (i.e., business) to transform material objects and extend their lifespan.

Second, information about the **utilization of material objects** support *rethink* practices where the core principle of shared resource utilization, essentially, relies on information-based and real-time coordination. For instance, *Car2Go* coordinates the shared utilization of its material objects (i.e., cars) based on information about future (i.e., reservation), current (i.e., rental), and past (i.e., rental history) utilization by actors.

Third, information about the **location of material objects** is especially important for the application of any CE practices that involve the movement of material objects. These practices comprise *rethink* (i.e., sharing) scenarios relying on spatial information for utilization of products (e.g., *Readymade Furniture*) and *reuse*, *repair*, *refurbish*, *remanufacture*, *recycle*, and *recover* scenarios relying on spatial information for transportation of products (e.g., *Patagonia*), components (e.g., *Twindis*), or raw materials (e.g., *Scrap Connection*).

Fourth, information about the **condition of material objects** is enabling CE practices that include a change of ownership of a material object or a dependence of an actor on the proper utilization of a material object's functionality. A change of ownership increases the financial risk involved in the transaction and incurs opportunity costs due to forgoing primary market alternatives. Among our set of CE practices, *reuse*, *repair*, *refurbish*, *remanufacture*, *recycle*, and *recover* represent scenarios with ownership changes, either on product (e.g., *Loop Rocks*), component (e.g., *RICOH*), or raw material (e.g., waste-to-energy cases) level. If a CE practice (e.g., *Drivy*) involves the utilization of a material object (e.g., driving), the utilizing actor expects the functionalities provided by the material object (e.g., breaking) to be in a proper and working condition.

Summarizing the previously mentioned examples, we state that material object-related information deficits (a) increase the **ex-ante transaction costs** (i.e., initiation costs), (b) increase **ex-post transaction costs** (i.e., handling costs, adjustment costs, and control costs), and (c) hinder **transaction-free and material flow-free CE practices** (i.e., *refuse* and *reduce*), thereby, decreasing the probability of stimulating pro-environmental behavior change (e.g., foregoing consumption).

4.4.3.4 Activity-related Information Flows

Activity-related information flows concern structured data about **instructions on using and transforming material objects**. We consider this class of information flows separately from the other classes as it does not directly enable market (cf., Section 4.4.3.1) or flow network-related (cf., Section 4.4.3.2 and Section 4.4.3.3) mechanisms in a CE practice. Instead, it is crucial in practices that induce actors to act on material objects directly.

Some practices aim to alter the **use of material objects** to spur eco-effective (i.e., *refuse*) or eco-efficient (i.e., *reduce*) consumption behavior. Here, real-world objects in our sample (e.g., *Evocco* or *Nest Mobile*) provide actors (i.e., consumers) with specific information on how to change for the environmental better (e.g., consumption of alternative products or adapted heating behavior).

Other practices require active participation of actors **transforming material objects** to extend their lifespan (i.e., *repair*, *refurbish*, *remanufacture*) or extract value from their end-of-life (i.e., *recycle*, or *recover*). All transformations require information on how to achieve this, for instance, repair and dismantling instructions for a material object or a list of required tools.

Abstracting from our sample of real-world objects, we state that activity-related information generates knowledge that enables (a) individuals to develop pro-environmental consumption behavior through transaction-free and material flow-free CE practices and (b) organizations to establish business operations that transform material objects in a sustainable manner.

4.5 Discussion

4.5.1 Summary of Findings

We developed a taxonomy of information flows that enable CE practices. We see that all physical components (cf., Chapters 4.4.1 and 4.4.2) are themselves important information carriers that might play a crucial role in the successful application of CE practices (cf., Chapter 4.4.3). To summarize, the taxonomy highlights that information about:

- Supply and demand of material objects is relevant in CE practices that intend to exchange material objects across the boundaries of two actors;
- Location and availability of actors is relevant in CE practices that require a personal involvement of actors in exchanging material objects;
- Properties and condition of material objects are relevant input for all CE practices;

- Location of material objects is relevant in CE practices that involve moving material objects;
- Utilization of material objects is relevant for CE practices that involve sharing material objects;
- Instructions on using material objects is relevant in CE practices that aim to achieve a change in actors' consumption behavior; and
- Instructions on transforming material objects is relevant in CE practices that require actors' active involvement in changing the properties and the condition of material objects.

Considering "information as a resource" in a CE context, our analysis specified *what* classes of information affect which CE principles and where this information arises from. This contributes a basis to speculate *how* IS should collect, process, and disseminate the data and information for CE practices.

4.5.2 Potential Roles of Information Systems in a Circular Economy

We discuss the implications of our taxonomy development in terms of three potential roles that IS can assume to enable the application of CE principles. To stimulate future research on these roles, we provide initial starting points in existing IS research.

4.5.2.1 Information Systems for Sensemaking

A **sensemaking information system** (SMIS) for CE practices supports individual or organizational actors in comprehending, explaining, and predicting (Seidel et al. 2013; Starbuck and Milliken 2006; Weick et al. 2005) their current consumption or sourcing, production, and distribution behavior, respectively.

Successfully involving consumers in CE practices remains to be a challenging endeavor. Environmental Sciences' literature on barriers to sustainable consumption practices collectively reports on missing consumers' awareness and acceptance

(Camacho-Otero et al. 2018; European Commission 2014; Kirchherr et al. 2018). Consequently, a SMIS for individual sustainable consumption practices should act as **educator**, **motivator**, **persuader**, and **decision supporter** enabling actors to make sense of smarter use and lifespan extension of material objects. Our taxonomy points out, that the SMIS, therefore, will rely on information about the **properties** (e.g., hazardous materials) and **conditions** (e.g., historical information about supply chain activities) of material objects and present (i.e., disseminate) it to the right actor in the right moment.

Future research can tap into two types of already existing Green IS research streams, dealing with individual behavior change enabled through IS: First, the well-established concept of **IS-enabled sensemaking** (cf., Baber et al. (2016), Sandberg and Tsoukas (2015), Klein and Moon (2006), Boland Jr. (1984)), nowadays, functions as robust theoretical foundation in Green IS research as well (Seidel et al. 2013; Seidel et al. 2018). The process-oriented nature of this concept (Weick et al. 2005) supports IS research in designing and developing IS for sensemaking of environmental phenomena on the individual and organizational level. Second, scholars have paired theoretical knowledge from the Psychology discipline on pro-environmental behavior (Bamberg and Möser 2007; Steg and Vlek 2009) with IS research on the design of persuasive technology (Oinas-Kukkonen and Harjumaa 2009) to investigate **persuasive environmental sustainability systems** (Brauer et al. 2016; Dahlinger and Wortmann 2016; Mustaquim and Nyström 2014; Shevchuk and Oinas-Kukkonen 2016). Knowledge from this research could essentially also inform design principles for SMISs for CE practices.

4.5.2.2 Information Systems for Matchmaking

A **matchmaking information system** (MMIS) for CE practices supports individual and organizational actors in (a) searching and comparing supply and demand of material objects and (b) negotiating and contracting terms and conditions of the intended transaction. Such an information system is valuable for CE practices that include a change of ownership or the shared utilization of material objects.

Exchanging material objects in secondary or shared markets is challenging as supply and demand are spatially scattered and temporally asynchronous, irregular, and discrete

(Berg and Wilts 2018; Camacho-Otero et al. 2018). In such a context, an MMIS acts as **transparency creator**, **complexity reducer**, **trust builder**, and **legal advisor**. It, therefore, organizes information about the involved **actors' behavior** (e.g., previous transaction fulfilment reliability rating) and the **properties** and **conditions** (e.g., quality, size, ingredients) of the exchanged or shared material objects (cf., Table 14).

Future research on MMIS can draw on valuable knowledge from the **Energy Informatics** research stream (cf., Slavova and Constantinides (2017), Ketter et al. (2016a), Goel (2015), Goebel et al. (2014). Its central objective is to analyze, design, and implement "systems to increase the efficiency of energy demand and supply systems […] [based on the] collection and analysis of energy data" (Watson et al. 2010, p. 24). However, this knowledge reference should be established with caution as there exist some crucial differences between **primary commodity resource markets** (e.g., electric energy market) and **secondary material markets** (e.g., market for reused construction materials): Commodity resource demand and supply systems for primary markets trade homogeneous material objects (e.g., oil, electric energy) in high, continuous frequencies and handle the fulfilment in established, specialized technical infrastructure systems (e.g., oil pipelines or transmission grids). Demand and supply systems for secondary markets, instead, trade heterogeneous material objects (e.g., second-hand windows or mortar) in low, discrete frequencies and handle the fulfilment in ad-hoc sociotechnical infrastructure systems (e.g., individual motorized transportation systems).

These differences come with implications for the design of MMIS for CE practices that are not entirely clear, yet. Future research should evaluate what we can learn from the established Energy Informatics research stream, what must be adapted to the CE context, and what requires completely new approaches.

4.5.2.3 Information Systems for Task Support

A **task-supporting information system** (TSIS) for CE practices enables individual and organizational actors in transforming a material object to extend its lifespan or the lifespan of its components and raw materials. CE practices that include material object transformation expect an active involvement of actors in complex and cognitively challenging tasks, for instance, repairing a smartphone or recycling production waste.

Drawing on empirical observations from our sample of real-world objects, we suggest conceptualizing the underlying tasks of transformational CE practices as a process chain. To illustrate this, a repair scenario (e.g., *kaputt.de*, *ifixit*, *Fairphone*) would consist of (a) defect identification (e.g., defective charger socket), (b) solution alternatives selection (e.g., repair-it-yourself, professional repair service, replacement/disposal), and (c) selected alternative execution. In such a context, the TSIS acts as **motivator**, **complexity reducer**, **decision supporter**, and **procedural instructor**. Considering our taxonomy of information flows, a TSIS organizes and provides **activity-related** information, such as repair and dismantling instructions, cost estimation, or a list of required tools.

We suggest, future IS research on TSIS to start with existing knowledge on **persuasive systems design (PSD)** (cf., Oinas-Kukkonen and Harjumaa (2009)) and **mobile cyber-physical systems (CPS)** (cf., Khaitan and McCalley (2015), Hu et al. (2013), Wu et al. (2011)): we consider (a) PSD as relevant, as the main objective of TSIS, essentially, comprises the goal-oriented and computer-aided execution of complex tasks (e.g., repair), and (b) CPS as relevant, as at the core of these tasks is a physical object (e.g., smartphone) carrying activity-related information (e.g., defect information) itself.

4.5.3 Limitations

Our work is beset with limitations that should not be ignored:

First, we based our taxonomy development on a purposive sample of real-world objects, which does not entail all objects potentially part of CE-driven business models or initiatives. Moreover, our sample exhibits a bias towards small to medium-sized enterprises and service providers and lacks cases from large, established manufacturing enterprises (except for *Patagonia*), thereby limiting the generalizability of our taxonomy. Reasons for this bias are twofold: it might be (a) grounded in a bias of the public databases we used to collect the CE cases from, whilst (b) correctly reflecting a possible population bias (i.e., large manufacturing enterprises are less inclined to participate in a CE). We followed the guidelines for making our taxonomy adaptable (Nickerson et al. 2013), so that it can in future research be applied to a larger dataset that specifically considers established enterprises. Another outstanding activity is theory-testing qualitative empirical research (e.g., case studies) to challenge and refine the current taxonomy.

Second, we did not detail the role of third-party platform providers and collectors in our taxonomy. Both seem to contribute what could be labelled a coordinating function to a CE: the collector as physical and the platform provider as digital broker. It remains unclear, how these powerful functions enable or hinder the development of CE practices and how IS can support these functions.

Third, we did not yet assess the potentials of digital technologies for the collection and processing of data (e.g., internet of things, machine learning). What classes of information (cf., Section 4.4.3) can be collected via which sensor types? How does the level of IS-automation affect the CE practice? Our taxonomy provides a good starting point to theorize about these potentials for the three IS roles in a CE.

Fourth, deconstructing the CE practices into flow networks and material objects and identifying relevant information flows applies a technical lens to the phenomenon. Recent conversations in established CE discourses, however, demand the inclusion of social elements and business perspectives in CE-related research (Bocken et al. 2017; Reike et al. 2018). As our taxonomy essentially classifies CE-driven business models and initiatives, we see an opportunity to further this research trajectory by linking our findings to the social business context.

4.6 Conclusion

The purpose of our paper was to identify and categorize relevant information flows that enable nine CE practices forming the core of the CE paradigm. Based on this analysis, we discussed an initial set of IS roles in a CE. We contribute a taxonomy that supports the classification and analysis of CE business models and initiatives and the identification of relevant information flows underlying these practices.

Our taxonomy allows deconstructing the complexity of the nine CE practices to two constituent components of the physical world: flow networks (i.e., spatially distributed actors with demand and supply requirements) and material objects (i.e., physical artefacts, whose life and use are extended and intensified by CE practices). Both constituent components carry important information classes (i.e., market, material object, actor, or activity-related information) that enable the CE practices differently.

Our taxonomy is deliberately situated at a general, abstract level to facilitate wide applicability in future solution-oriented IS research for environmentally sustainable production and consumption practices. It allows both the Green IS and IS design science communities to (a) better structure and analyze the problem and requirements space of CE practices and (b) better design suitable and impactful solution-oriented artifacts for sustainable production and consumption practices (Venable 2006).

Another goal of our work was to introduce the concepts of sustainable production and consumption and CE into the scholarly conversation of the IS community. Both are timely and intensely debated ideas in other fields that have not yet really entered our own discourse yet. We believe, and expanded on this belief, that IS theory and artefacts can play a focal role in both areas, which in turn allows solution-oriented IS research to become a referent discipline to the emerging discourse in other academic fields.


Original Article

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Digitalization of waste management: Insights from German private and public waste management firms

Rebecca Borchard[1], Roman Zeiss[1] and Jan Recker[2]

Abstract

Keywords

Introduction

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Chapter 5

Digitalization of Waste Management: Insights from German Private and Public Waste Management Firms

Rebecca Borchard
University of Cologne

Roman Zeiss
University of Cologne

Jan Recker
University of Hamburg

Policymakers, practitioners, and scholars have long-lauded digital technologies, such as smart waste containers or artificial intelligence for material recognition and robotic automation, as key enablers to more effective and efficient waste management. While these advances promise an increasingly digitalized future for collecting, sorting, and recycling waste material, little is known about the current extent of digitalization by waste management firms. Available studies focus on firms' digitalization intentions, largely neglecting the level of actual adoption of digital technologies, and do not differentiate the level of digitalization alongside different steps of the waste management value chain. Our study reports on a cross-sectional descriptive survey that captures current digitalization efforts and strategies of 130 public and private waste management firms in Germany. We analyze their levels of digitalization along with different steps of the waste management value chain, explore their different objectives, approaches, and transformational measures with regard to digitalization. Our findings reveal that while the perceived importance of digitalization in the waste management sector continues to grow, the actual adoption of advanced *digital technologies falls notably behind intentions reported in 2016 and 2017. We explore the reasons for this gap, point out so far largely ignored research opportunities, and derive recommendations for waste management firms and associations.*

5.1 Introduction

Waste management has traditionally been a physical and mechanical sector focusing on the collection, sorting, and recycling or incineration of waste material. However, it is increasingly being targeted by solution providers that promise more effective and efficient operations through digital technologies, such as smart bins (e.g., Bigbelly (2020)), on-demand semi-autonomous trucks (e.g., Rubicon (2020)), or artificial intelligence (AI) for material recognition and robotic automation (e.g., AMP Robotics (2020), ZenRobotics (2020)). In recent years, a number of new methods for waste management have emerged that are embodied in and enabled by digital technologies1, such as waste treatment on the basis of image recognition and machine data analysis (Waste Management World 2021) or onsite waste separation through bin-integrated material detection sensors (Green Creative 2018).

Notwithstanding these innovative use cases, little is known about the waste management sector's current extent of digitalization, that is, the conversion of physical or analog processes, contents, or objects into a digital format by help of digital technologies (Fichman et al. 2014; Fitzgerald et al. 2014). Existing literature on the digitalization of waste management has focused on explorations of future digital technologies, such as concepts for digital waste management in sustainable cities (Anagnostopoulos et al. 2017; Esmaeilian et al. 2018), simulations for digital dispatching and routing (Ramos et al. 2018; Shah et al. 2018), smart bin prototypes (Rovetta et al. 2009), or software-enabled image classification for waste sorting (Wagland et al. 2012). Only three quantitative studies exist (Mavropoulos 2017; Mechsner 2017; Sarc and Hermann 2018). However, these studies focus on firms' digitalization intentions, largely neglecting the level of actual adoption of digital technologies, and do not differentiate levels of digitalization alongside different steps of the waste management value chain, such as between customer management &

sales, dispatching & logistics, weighing & sorting, marketing of recyclable materials, recycling, disposal, or container management.

We address these limitations through our study that asks the research question: "What is the status-quo of digitalization by private and public waste management firms in Germany?" We report on a cross-sectional, descriptive survey that captures

5.2 Method

5.2.1 Survey Design

We conducted a quantitative cross-sectional online survey (Pinsonneault and Kraemer 1993). The purpose of our survey was description, not explanation or prediction (Malhotra and Grover 1998). Our aim was to ascertain facts about the status of digitalization such that a systematic basis of empirical data is laid out for future hypothesis development.

To design the survey, we consulted the literature, carried out four practitioner interviews, and visited three waste management firms (Appendix D) to understand the German waste management sector in terms of market structure, industry forces, typical value chain, and digital technologies relevant to the industry. Our unit of analysis were waste management firms (Karanja and Zaveri 2013). We focused on capturing their current levels of digitalization, across (a) all steps of the waste management value chain, and (b) the variety of currently available digital technologies.

Regarding (a), we differentiated the waste management value chain into four successive and one cross-sectional step (Kerdlap et al. 2019; Sarc et al. 2019). Appendix E summarizes our conceptualization of a waste management value chain.

Regarding (b), we identified relevant digital technologies from prior digitalization studies in waste management (Mechsner 2017; Sarc and Hermann 2018) as well as other industrial sectors (Justenhoven et al. 2019; Reker and Böhm 2013) and from our interviews and observations. Appendix F summarizes the technologies we consider.

5.2.2 Instrument Development and Testing

We followed the instrument development procedure by Moore and Benbasat (1991). First, we defined key measurement categories on basis of our understanding of the literature, our interviews, and site observations. To ensure comparability to prior waste management digitalization studies we included key measurements from prior studies, such as perceived impact of digitalization (Mechsner 2017; Sarc and Hermann 2018). In total, we identified seven measurement categories for our survey:

(A) **Firm classification.** We distinguished various waste management roles according to the firms' pursued main value-add activity.

(B) **Digitalization of the waste management industry.** We captured the firms' perceived relevance and impact of digitalization to the waste management industry (Mechsner 2017; Sarc and Hermann 2018).

(C) **Digitalization along the waste management value chain.** For each value chain step, we measured the firms' current implementation status of various digital technologies and their technical interfaces through which data can be exchanged.

(D) **Digitalization strategy and objectives.** We captured the firms' strategic digitalization plans according to their transformational responsibilities, objectives, and measures (Salviotti et al. 2019; van Alphen et al. 2019).

(E) **Digitalization drivers and barriers.** We identified key external and internal factors that drive or hinder the firms' digitalization measures (Pflaum et al. 2017; Reker and Böhm 2013).

(F) **Digitalization outlook.** We captured the firms' digitalization expectations according to their evaluation of innovative digital technologies and their likely investments (Sarc and Hermann 2018; van Alphen et al. 2019).

(G) **Demographic data** of firms to describe our sampling frame.

Second, in total, we created 61 measurement items (43 nominal, 18 ordinal) across these categories. For attitudinal measurements, we used 5-point scale matrices balancing the scales with an odd number of points and a neutral midpoint (Brace 2004). For behavioral measurements, we used a 4-point scale with the pre-codes "not relevant," "planned," "in implementation," and "in use." We ensured that the items were mutually exclusive, as exhaustive as possible, and of appropriate detail (Brace 2004). We incorporated no-response answer options for all questions except for demographics (Dillman 2000; Ryan and Garland 1999). All ordinal scales were controlled for order effects (Artingstall 1978) and acquiescence (Kalton et al. 1980). We rotated some items to prevent bias (Brace 2004).

Third, we ensured content validity and face validity (Straub 1989) by conducting an informal survey pilot with eight practitioners from a medium-sized waste management system service provider (Andrews et al. 2003). Based on the feedback, we revised the survey by adjusting the wording of some items and codes that were unclear and adopted the order of some pre-codes to align them with the value chain logic. The final survey questionnaire comprises 65 items (Appendix G).

5.2.3 Participants and Procedures

We used non-probabilistic convenience plus unrestricted self-selected sampling (Schonlau et al. 2001; Truell 2003). First, we contacted 831 private certified German waste management firms specialized in waste collection with the help of a medium-sized system service provider who distributed the link to the online survey by email. Second, to include public waste management firms, public–private partnerships, and non-certified waste management firms, we published a call for survey participation in German waste management trade magazines (*EUWID Recycling und Entsorgung*, *320grad.de*, *Recyclingmagazin*, *ZfK Zeitschrift für Kommunalwirtschaft*, *e-mag Entsorgungsmagazin*, and *RecyclingPortal.eu*).

The online survey was live between June 15 and July 3, 2020. We sent two reminders, via post on June 22, 2020 and via email on June 29, 2020. Observing response spikes shortly after these dates, we considered the reminders effective.

5.2.4 Data Screening and Cleansing

We received 241 responses. We removed 111 responses from participants who started the questionnaire but did not proceed beyond the first page (94 in total), showed biased response patterns, such as unrealistic survey completion times, extreme tendencies, or systematic answer patterns (5), or did not match our target population (12).

The large majority (91%) of the 130 respondents are commercial waste management firms. Eight municipal waste management firms and four others, such as a public-private partnership, participated in the survey. In total, 120 companies (92%) were certified as specialist waste management firms.

Most respondents (58%) were between 40 and 59 years old. The most often reported positions (28%) were owner, board member, or top manager, followed by other managerial positions (24%). The highest share of respondents (39%) worked for mid-size waste management firms that employ between 50 and 249 employees. Firms with less than ten employees, who make up about 60% of the German waste management sector (Statistisches Bundesamt, 2020), are underrepresented in our study (3%). Contrarily, firms with more than 50 employees are overrepresented in our study.

Before we commenced data analysis, we compared response means for 41 variables between early and late respondents through a Mann-Whitney-U test. Six variables (Management's attitude toward digital change, Relationship between opportunities and risks, Potential impact of digitalization on customer management & sales, Potential impact of digitalization on weighing & sorting, Relevance of online marketplaces for future business model, Sum of the averages of internal drivers) showed a statistically significant difference, with early respondents reporting higher scores on these variables than late respondents. However, since our analysis of our data shows that small firms are on average less digital than larger firms, the difference between early and late respondents may also have emerged from the different distribution regarding the number of employees. We therefore decided to proceed with 130 survey responses in our analysis.

Because our survey's purpose was descriptive, our data analysis strategy primarily relied on identifying relevant summative statistics (such as means, medians, standard deviations) and visualizations (such as box plots, pie charts, bar charts). But where appropriate, we also used inferential statistics to examine the statistical significance of between-group variations and correlations through chi-square, Mann-Whitney-U, and Kruskal-Wallis tests (Tabachnick and Fidell 2014). We also performed cluster analysis based on the k-means algorithm (Ward method) to identify groups of respondents. We computed these tests using SPSS version 27.

5.3 Findings

5.3.1 Perceived Relevance of Digitalization to Waste Management

About 60% of all respondents currently perceive a strong or very strong impact of digitalization on their industry and on their firm (Figure 8). Approximately one out of ten respondents perceive only a small impact of digitalization on the industry and the firm. More respondents expressed a very strong influence of digitalization on their firms (29%) than on the industry (17%). Contrary to that, a strong impact of digitalization is indicated more often for the industry (44%) than for the firm (36%).

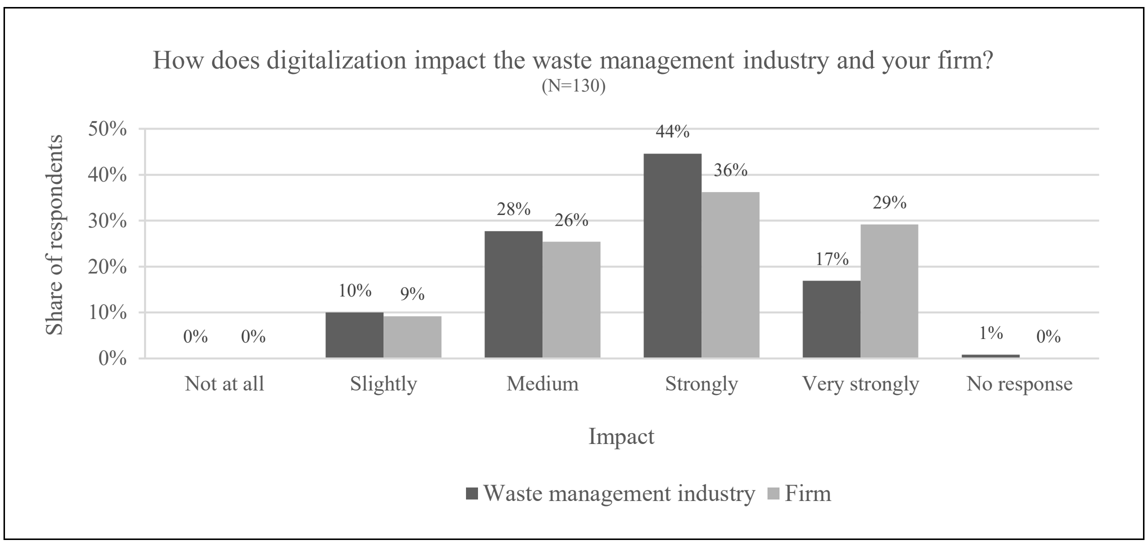


Figure 8. Influence of digitalization on waste management industry and firms

We statistically explored differences in responses by organizational size. Our data shows that respondents with less than 50 employees feel on average statistically significantly less impacted by digitalization than respondents with more than or equal to 50 employees (Mann-Whitney-U test: $z = -2.197$, $p = 0.028$). Small firms are also statistically significantly more dispersed in their responses than larger firms. While about 20% to 30% of the small waste management firms each indicated a small, medium, strong, and very strong impact of digitalization on their firm, larger firms perceive majorly a strong or very strong impact (71%) ($\chi2$ [3, n = 99] = 15.482, $p = 0.001$).

We discovered that 30% of the respondents believe that digitalization impacts their own firm more than the industry. 21% indicate that digitalization has a stronger impact on the industry than on their firm, the remaining 49% see an equally strong impact of digitalization on their firm and the industry. The number of employees has no influence on this distribution.

The majority of respondents (66%) view the digital change with confidence and observe either only opportunities or more opportunities than risks (74%). Approximately one quarter of the respondents has a neutral attitude toward the digital change (28%) and observes balanced risks and opportunities (22%). A small minority observes more risks than opportunities (5%) and feels concerned about the change (7%).

5.3.2 Current Extend of Digitalization in Waste Management

5.3.2.1 Digitalization Along the Waste Management Value Chain

Digitalization has the highest impact on dispatching & logistics followed by weighing & sorting and customer management & sales (Figure 9). Two third of the respondents believe that dispatching & logistics is currently difficult (42%) or even impossible (26%) to be carried out without digitalization. Roughly half of the respondents believe that weighing & sorting and customer management & sales are difficult or impossible to be carried out without digitalization. Marketing of recyclable materials, recycling & disposal was indicated to be less impacted by digitalization. Today, less than 5% assume that this value chain step cannot be carried out without digitalization.

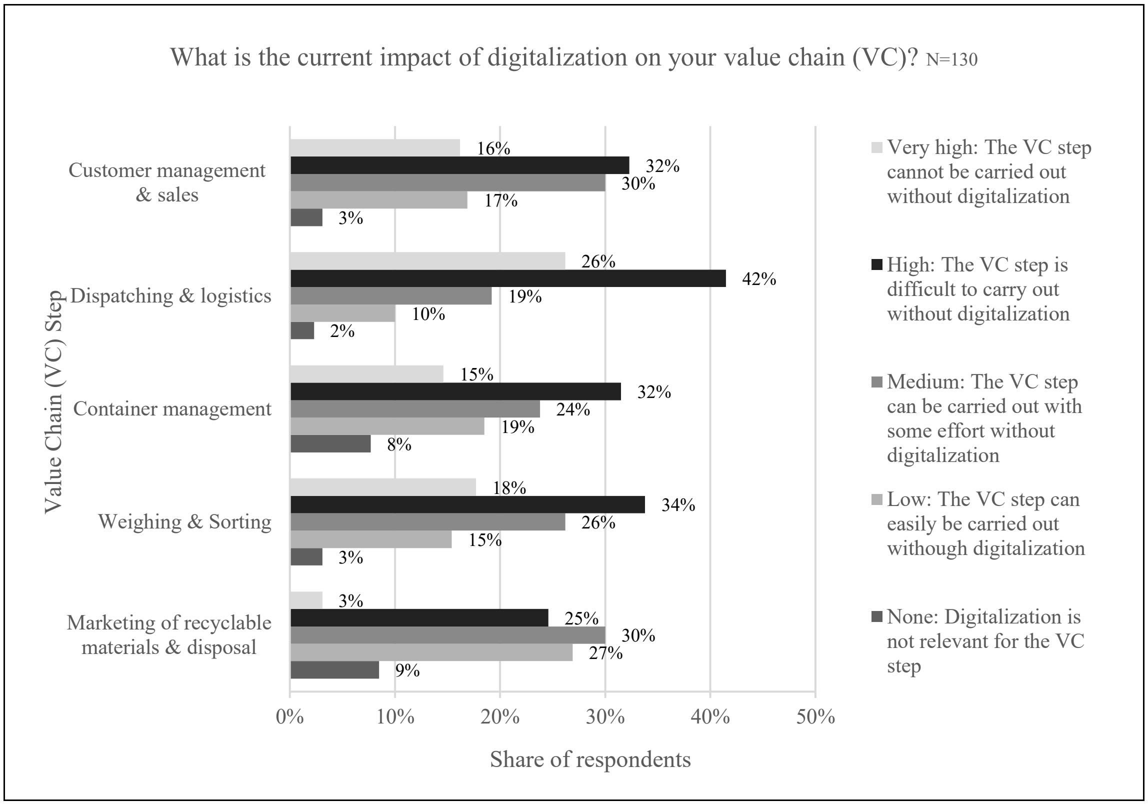


Figure 9. Current impact of digitalization on waste management value chain

Analyzing the impact of digitalization on the five value chain steps in more detail, we discovered statistically significant differences in responses between commercial and non-commercial waste management firms. Commercial waste management firms feel a stronger current impact of digitalization in customer management & sales (Mann-Whitney-U test: $z = -2.501$, $p = 0.012$) and marketing of recyclable materials, recycling & disposal (Mann-Whitney-U test: $z = -1.999$, $p = 0.046$) than non-commercial waste management firms.

For **customer management & sales**, our results show that there is not one single channel used by most waste management firms. Customers frequently order by telephone (90%), followed by e-mail (89%), and fax (46%). Of the respondents, 55% use at least one digital sales channel, in particular external online shops (32%), own online shops (31%), and own apps (15%).

Existing internal online shops differ in their degree of functionality. About half of the respondents' online shops offer digital methods of payment (50%) and real-time information on the price (55%). Real-time information on the delivery date and time and automated offer generation are included by one quarter of the online shops. In contrast to those respondents who use the functions, three out of ten respondents do not regard automated offer generation and real-time information on container availability to be relevant.

While almost 60% of the participants use an Enterprise Resource Planning (ERP) system, only 13% of them have it connected to systems of their customers, system service providers, or other waste management firms. This lack of interfaces and standards can also be noticed when examining the familiarity of the respondents with the standard for the exchange of order-related data, AvaL. Only 31% of all respondents have heard about AvaL. Furthermore, only 24% of the respondents use an automatically processing invoice standard such as ZUGFeRD. Instead, 95% of all waste management firms send their invoices via mail. 82% of the participants send invoices by email.

In **dispatching & logistics**, 61% of the participants currently rely on digital technology. Digital dispatching systems are statistically significantly more used by firms with 250–1000 employees (92%) compared to firms with 50–249 employees (75%), more than 1000 employees (59%), or 10–49 employees (38%) ($\chi 2$ [3, n = 99] = 14.264, p = 0.003). Next to digital dispatching systems, waste management firms plan their routes with online maps services (30%), pen and paper/ whiteboard (17%), or spreadsheets (17%). Besides, not all firms who have a digital dispatching system use it for informing their drivers about the dispatching plan (73%). Instead, drivers are often informed personally (50%), by a plan or stack of orders in the office (42%), or the drivers are called and informed about the dispatching plan (30%).

The most frequently used technology on board of vehicles is a simple navigation system (69%) (Figure 10). Other technologies (e.g., smartphone app for driver assistance, digital status monitoring of the vehicles, real-time transmission of data to office) have been implemented by between 21% and 40% of the respondents. In contrast, between 16% and 40% of the participants do not regard these digital technologies to be relevant.

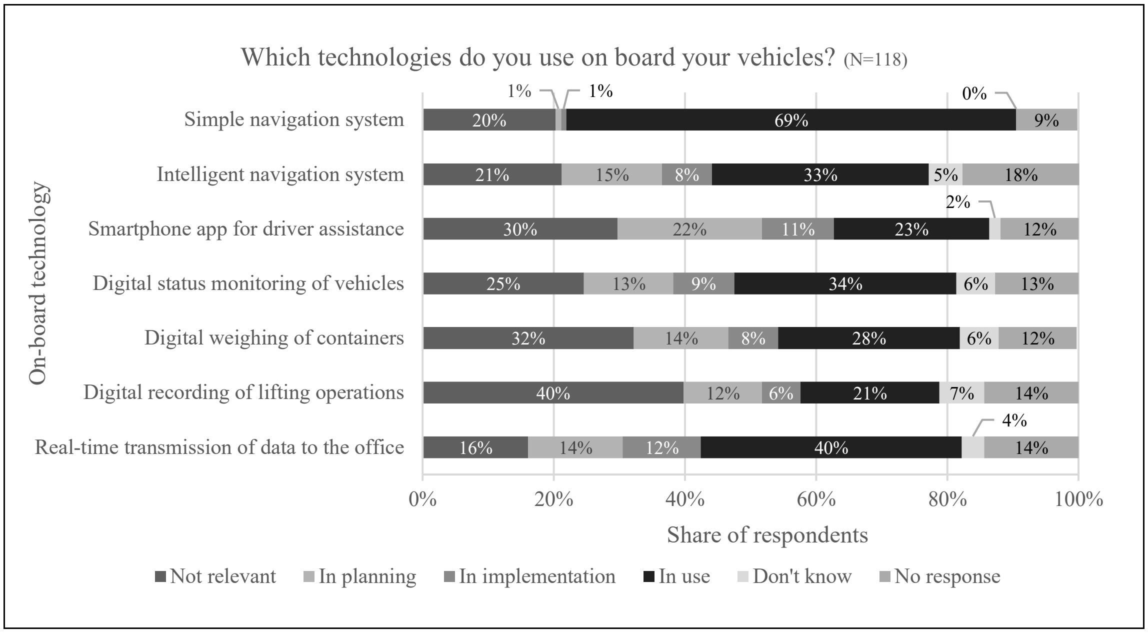


Figure 10. Use of digital technologies on board of vehicles

Of all respondents, 68% use a telematics system, of which 69% use it for process optimizations and 17% for control purposes. 73% of the respondents using a telematics system also use a digital dispatching system. Firms that use an ERP system employ a telematics system statistically significantly more often than firms that do not (Mann-Whitney-U test: $z = -2.192$, $p = 0.028$).

73% of respondents use a printed proof of performance that needs to be signed with a pen; 35% of respondents use geocodes and time stamps; only 29% store the proof of performance on a digital device where the customer provides a digital signature. Often, more than one kind of documentation of service provision is used.

Almost 90% of all respondents indicate they use digital technologies to perform **container management** (Figure 11). The most common digital technologies comprise integrated near-field communication tags, radio-frequency identification chips, and barcodes. The digital technologies are primarily used for the location tracking of containers and less for the monitoring of containers' filling levels. For storing the data gathered from tracking containers, 47% of all respondents use an ERP system, 25% spreadsheet, and 15% pen and paper.

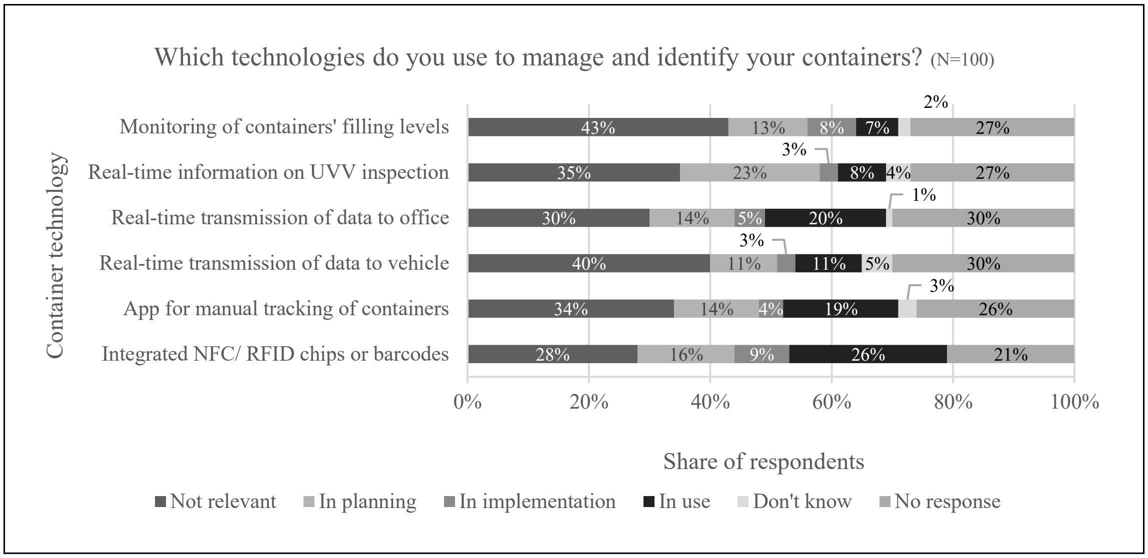


Figure 11. Use of digital technologies to manage and identify containers

UVV: German accident prevention regulation test

For **weighing & sorting**, 27% of the respondents have incorporated a scale into their vehicles. With regard to the proof of weight, 51% of the respondents who own a scale record the weighing note digitally and transfer it to their ERP system. 41% use a printed weight receipt. With regard to sorting, 47% of the respondents who have a sorting plant sort the waste automatically, and 38% sort it manually.

We further investigated the number of digital technologies reported as most relevant by the respondents for customer management & sales, dispatching & logistics, and container management (i.e., digital sales channels, ERP, digital dispatching, telematics, onboard driver app, digital container management).

The distribution of used digital technologies differs considerably with regard to the number of employees (χ^2 (18, n = 99) = 37.234, p = 0.005). While almost 50% of the respondents with 10–49 employees use zero or one digital technology, more than half of the respondents with 250–1000 employees use four or five technologies.

Running a k-means cluster analysis, we could differentiate the respondents based on their use of six digital technologies into three statistically significant (*p = 0.000*) groups: (1) analog waste management firms, (2) firms that use “basic” digital technologies, and (3) digital waste management firms (Figure 12). Group 1 (25% of the respondents) does not use any of the digital technologies. Group 2 (52%) implemented digital sales channels, an ERP system, a digital dispatching system, and a telematics system but no onboard computer and no digital container management. Group three (24%) uses on average all six digital technologies.

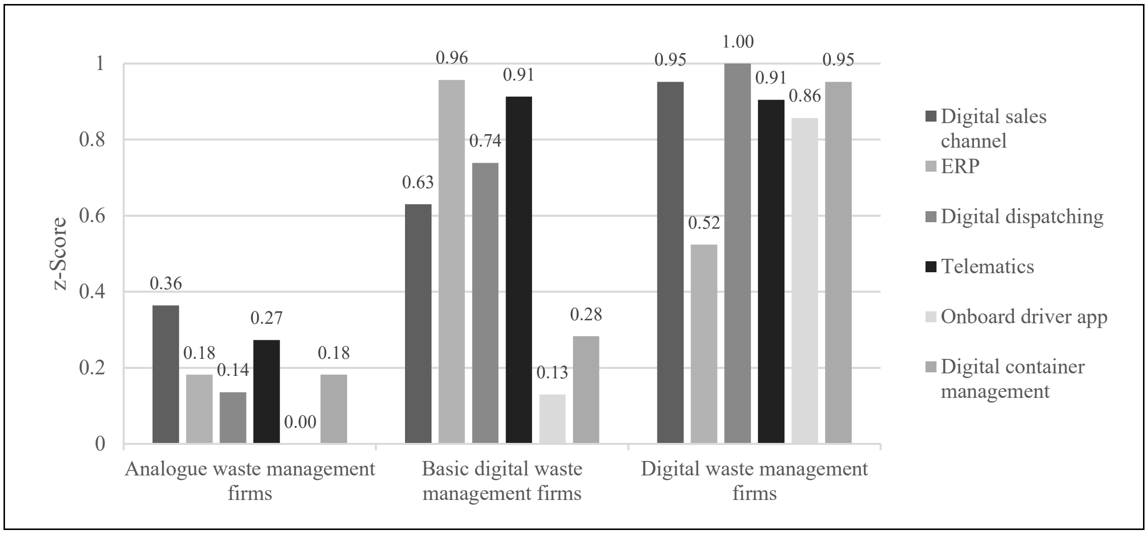


Figure 12. Cluster analysis of current use of digital technologies

5.3.2.2 Digitalization Strategy and Objectives

Figure 13 describes strategic objectives the participants pursued with digitalization. The top-five planned objectives are driven by efficiency and quality gains, comprising faster payment transactions (76%), cost optimization (75%), increased process quality (73%), increased competitiveness (73%), and increased process transparency (67%). Of these top five planned objectives, all but faster payment transactions occur in the top-five achieved objectives. Customer experience and expansion are of medium strategic importance pursued through digitalization. Environmental objectives are the least important objectives pursued.

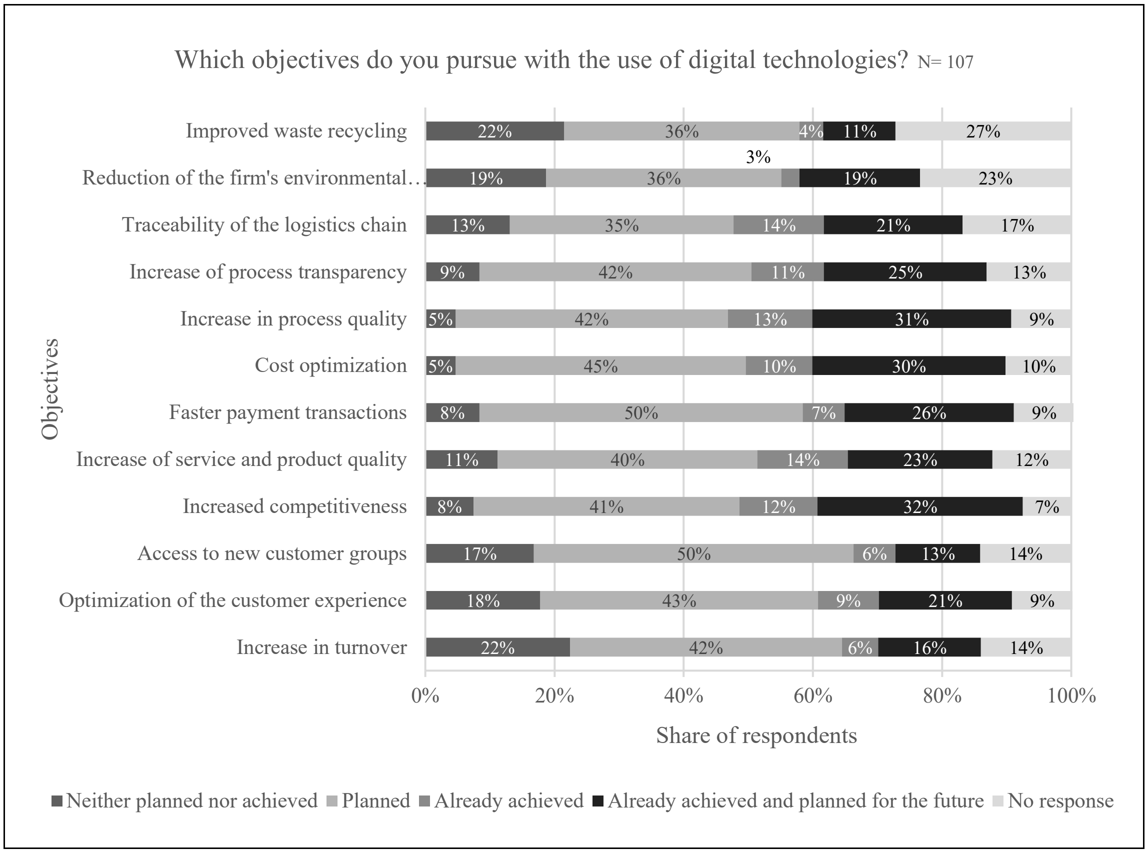


Figure 13. Objectives of digitalization

More than half (57%) of survey respondents felt sufficiently or satisfactorily **prepared for digitalization**. One in three respondents (33%) feel well or very well prepared, about one in ten respondents (9%) feels insufficiently prepared. Firm size does not significantly alter the distribution. Yet, the more digital technologies a firm already implemented, the better a respondent feels prepared for digitalization (Kruskal-Wallis test: $H = 29.387$, $p = 0.000$).

To anchor their digitalization strategies within the firms, the three most preferred **implementation measures** comprise commissioning external service providers (in use: 30%; in implementation: 7%), integrating digitalization into the business strategy (in use: 23%; in implementation 27%), and training employees (in use: 23%; in implementation: 25%). The three least preferred implementation measures comprise cooperating with digital start-ups (not relevant: 52%), establishing a digital business unit (not relevant: 43%), and recruiting new employees with digital expertise (not relevant: 38%).

We found statistically significant differences in the implementation of the measures between firms of different size, except for training employees, which was implemented in all firms. Larger firms significantly more often implement measures to anchor digitalization inside their business (Kruskal-Wallis test: $H = 22.829$, $p = 0.000$).

Finally, our results show that the **responsibility for digitalization** still resides with the managing director or owner of the waste management firm in the majority of the cases (58%), followed by dedicated IT management roles (37%) and individual department leads (27%). 11% of the respondents indicate digitalization responsibility is entirely missing in their firm.

5.3.2.3 Digitalization Drivers and Barriers

Figure 14 displays the top-five **drivers and barriers of digitalization** mentioned by our respondents, distinguishing between internal (I) and external (E) drivers and barriers.

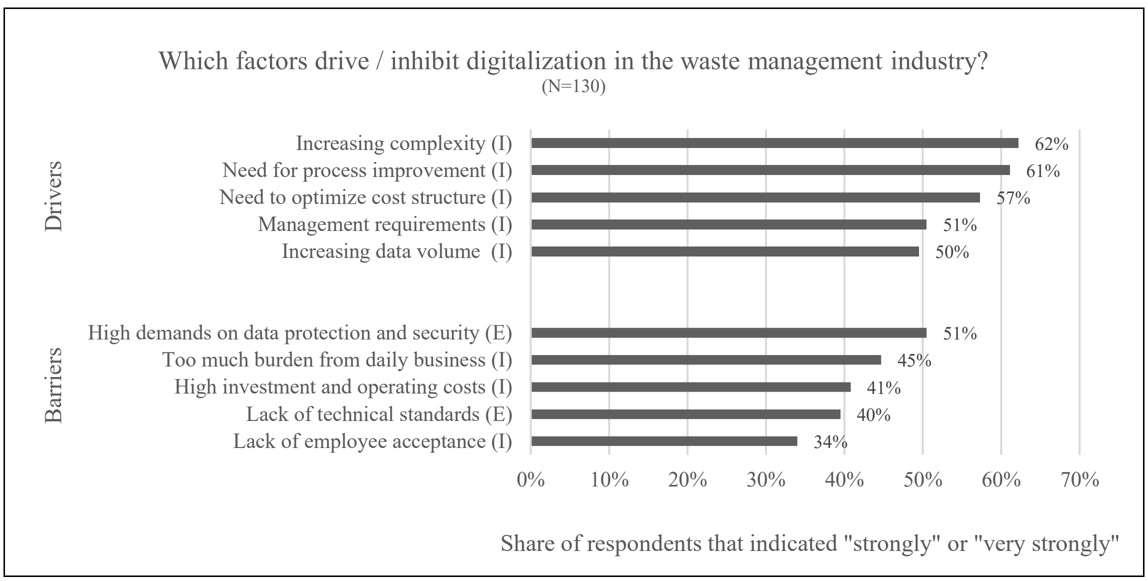


Figure 14. Top five drivers and barriers to digitalization

I: internal; E: external

In general, internal factors drive the digitalization of both small and large firms more than external factors. On average, 30% of the respondents feel strongly or very strongly driven by internal factors, such as an increasing complexity in daily operations, the needs to improve its processes and cost structures, or growing amounts of data that need to be handled. In contrast, respondents specified both internal and external barriers that hinder digitalization. Top barriers concern high demands on data protection and security (strong or very strong: 51%) followed by the burden from operating business (45%) and high investment and operating costs (41%).

Smaller firms feel statistically significantly less driven by internal (Mann-Whitney-U test: $z = -2.153$, $p = 0.031$) and external factors than bigger firms (Mann-Whitney-U test: $z = -2.518$, $p = 0.012$). We could not find any statistically significant differences between small and large firms with respect to internal (Mann-Whitney-U test: $z = -0.038$, $p = 0.979$) and external barriers (Mann-Whitney-U test: $z = -0.893$, $p = 0.372$) to digitalization.

Besides observing already existent drivers, we asked the participants which conditions would need to be in place to further progress digitalization in their firms. 61% of all respondents state that digital standards would need to be available, 49% see the need for a digital culture and management style, 42% regard the pressure on part of the customers as necessary, and 39% indicate that a pressure on part of the competitors would be required.

5.3.3 Future Impact of Digitalization on Waste Management

We examined how survey respondents looked at future digitalization of waste management. Almost 60% of the respondents assume that digitalization will strongly or very strongly change their firm and the industry in the future. 66% of all respondents plan to increasingly deal with digitalization in the future. Notably, our findings show that not all firms who feel a very strong impact of digitalization on their firm and on the industry today also believe that digitalization will very strongly change their industry and firm in the future. 30% of the respondents expect to keep the current level of engagement into digitalization.

Looking into the future, we examined the impact of ten innovative digital technology concepts such as AI or big data analytics on waste management firms. Our frequency analysis revealed that the Internet-of-Things, AI, drones, blockchain, and autonomous driving are not assumed relevant by a large number of respondents. More than 60% consider these technology concepts either not relevant or only relevant in more than 5 years. For the remaining five technology concepts that we investigated (robotics & sensor technology, online marketplaces, predictive analytics, cloud computing, and big data analytics) almost 50% of the respondents consider these technology concepts already relevant or believe that they will become relevant within the next 5 years.

We used a k-means cluster analysis to split the surveyed sample into three statistically significant ($p = 0.000$) groups: Group 1 (42% of the respondents), who on average assumes that the five innovative digital technology concepts big data analytics, cloud computing, online marketplaces, predictive analytics, and robotics & sensorics are relevant within the next 12 months; group 2 (32%), who believes that these technologies will be relevant within the next 5 years (cloud computing and online marketplace) or in more than 5 years (big data analytics, predictive analytics, robotics & sensorics); and group 3 (26%) that either do not know these digital technologies (predictive analytics and robotics & sensorics) or believe that they are not relevant (big data analytics, cloud computing, online marketplaces).

The respondents in group 1 are more aware and informed about digitalization projects in the industry, such as the development of AvaL. 64% of the firms in group 1 have heard about AvaL in comparison to those in group 2 (21%) and group 3 (15%) (Kruskal-Wallis test: $H = 9.639$, $p = 0.008$).

5.4 Discussion

5.4.1 Contributions in Comparison to Prior Studies

Our study complements and expands three comparable prior studies on digitalization of the waste management industry (Mavropoulos 2017; Mechsner 2017; Sarc and Hermann 2018). Our findings suggest a growing **importance of digitalization** in waste management. In 2020, more waste management firms feel stronger impacted by digitalization than 3.5 years ago (+6.5%), more firms perceive opportunities from digitalization than 2 years ago (+10.7%), and more firms report to actively engage with digitalization than 2 years ago (+7.5%).

In terms of implemented **digital technologies**, our findings reveal notable gaps between intentions reported in 2016/17 and today's reality. For instance, while implementation levels of electronic invoicing and digital order processing exceed or almost meet 2016/17 intentions, additional digital customer services, such as live order tracking, are only implemented by 8% of the respondents in 2020 (−42%). Similarly, while our findings confirm advanced implementation levels of disposition and telematics systems, only 40% of the respondents use their telematics system for live vehicle tracking (−25%). Finally, today's implementation levels of digital container identification (55%) do almost meet the intentions from 2016/17 (−5%), but only 7% of our surveyed respondents report an implementation of digital container tracking (-43%).

Our analysis of **digitalization objectives** confirms and expands Sarc and Hermann (2018) who report that in 2017 the three most frequently expected results through digitalization were increased process transparency, increased efficiency, and improved quality. Our findings confirm that waste management firms continue to pursue a cost leadership strategy (Porter 1998) where digitalization objectives focus on the efficiency optimization of internal processes. Such objectives manifest in a limited set of implemented digital technologies with more advanced digital technologies (e.g., sensor-driven live order tracking) remaining irrelevant for achieving cost leadership. This is also reflected in our list of neither planned nor achieved digitalization objectives revealing that environmental optimization and customer-related optimization are largely ignored by waste management firms today.

Three of the top four **barriers** reported in 2016/17 (Mechsner 2017) still hinder the implementation of digital technologies today: daily business burden, high investment and operating cost, and missing technical standards. While in 2020 high demands on data protection and security has been reported as key barrier to digitalization, it was not reported in 2016/17 at all. This development might be explained through the introduction of the General Data Protection Regulation (European Parliament 2016) that in Germany became enforceable in May 2018 and, since then, has been lauded a common digitalization barrier in various industries (Dehmel and Kelber 2020). While digital standards remain the top prerequisite for further digitalization, respondents add “softer” factors, such as digital culture & management style, pressure from customer requirements, or pressure from competitors to the list. These “soft” factors—in particular digital culture & management style—are new to the scientific discourse on digitalization of waste management; yet, they confirm latest industry insights that already highlight the role of leadership in the sector’s digital transformation (AMCS 2018).

5.4.2 Implications

Our findings suggest that waste management firms do not fully exploit the potential benefits of digital technologies available today. These findings lead to two main implications. First, because waste management firms implement digital technologies not to substitute but rather complement existing analog solutions, they need to manage both physical and digital processes, which we call *the burden of parallel worlds*. Second, waste management firms predominantly use digital technologies to reduce costs of operations, which is a risky strategy considering the changing business landscape as well as regulatory and societal requirements for waste management practices. We label this challenge *the efficiency optimization limit of digitalization*.

5.4.2.1 The Burden of Parallel Worlds

When implemented, digital technologies are often used not exclusively for, but rather in addition to, analog tools or processes. For instance, digital sales channels are often used in parallel with traditional, analog sales channels. While 55% of the respondents employ at least one online sales channel, only 3% of them use it in an exclusive manner. Further, only 19% of the respondents who document their provided service via geocodes and time stamps use them exclusively, while almost 75% report that the delivery note is still signed by pen and paper.

Either waste management firms see no need to abolish analog processes because they are part of a well-functioning system or the installed customer base inhibits the exclusive use of digital technologies through existing analog path dependencies. First, the waste management sector can be understood as the epitome of an old, well-functioning system, in which, for instance, the three types of vehicles and containers have not changed over the past 60 years. Further, since the adoption of the first recycling and waste management act in 1996, the fundamental regulatory framework of the German waste management sector has not changed, effectively shielding public waste management firms against private competitors. This history has created a culture of inertia and reluctance to change impeding potentially disruptive digitalization.

Second, customers often demand analog processes, such as a proof of service provision by pen and paper, even though they can also be provided with geocodes and time stamps. As long as customers do not accept or demand a digital service provision, waste management firms are not willing to implement, let alone exclusively use, digital technologies. This "network effect" is particularly detrimental for the adoption of digital standards, such as AvaL or ZUGFeRD, in which a one-sided adoption means failure of the standard essentially impeding an advanced digitalization of customer-related interfaces.

We argue, this non-exclusive adoption of digital technologies risks the unfolding of parallel worlds that impose unnecessary burden on waste management firms. With parallel worlds, waste management firms must not only manage the infrastructure for analog processes but also deal with the operation of less familiar digital infrastructure. Further, both worlds still exhibit touch points, which are more commonly known as "media breaks." For instance, if orders arrive via telephone, an additional step is required where the analog information is digitally recorded in the system, which is prone to potential flaws arising from manual recording (e.g., typos or process delays). Lastly, the burden of parallel worlds risks negative feedback loops, where negative experiences from non-exclusionary adopted digital technologies affect decisions on future digital technologies hampering an ongoing digitalization of the waste management firm.

5.4.2.2 The Efficiency Optimization Limits of Digitalization

Our survey showed that efficiency optimization is the main digitalization driver at present and in the future. Different explanations for this focus on digitalization as an efficiency driver exist. First, waste management firms may not be sufficiently informed about the potential functionality of digital technologies. For instance, only 31% of the respondents have heard about the availability of order-related data exchange standards. Second, perceived barriers, such as high data protection requirements (51%) and the lack of industry standards (41%), may impede the full exploitation of digital solution benefits. Third, waste management firms might see no need to innovate their processes by exploiting more potentials of digitalization. Waste management firms may simply not be incentivized to exploit the full functionality of their online shops or provide customers with live information on the delivery time of their containers.

By focusing on efficiency optimization, however, waste management firms may overlook the optimization limits of digitalization running the risk of pursuing objectives, which in the mid to long-term do not live up to increasing regulatory, societal, and economic requirements. We are not the first to point out this risk; it was also flagged by Mavropoulos and Nilsen (2020) who call for a disruption of "business as usual" optimizations. Three points about such a change appear worth highlighting:

1. Waste management firms have been traditionally understood as economic actors that efficiently take care of the waste of others. Changing regulations (e.g., extended producer responsibility) as well as large-scale societal trends calling for more sustainable production and consumption practices (Vergragt et al. 2014), impose new, more challenging roles on waste management. It remains questionable that digitalization employed as a cost efficiency driver will suffice to meet these growing requirements.

2. Digital-first waste management start-ups (e.g., Rubicon (2020)) occur on the horizon. While incumbent waste management firms feel safeguarded by high regulatory and economic barriers to entry, the digital promises by start-ups

influence the perception of waste producers and policymakers raising the expectations about digitalized waste management.

3. Commercial waste producers start integrating disposal and recycling processes into their own business. This reduces demand for incumbent waste management firms and creates new competitive pressures.

5.4.3 Limitations

Several limitations need to be mentioned. First, we used a nonprobability convenience sampling approach and distributed the questionnaire via the network of the system service provider resulting in a sample primarily representing private waste management firms with more than or equal to ten employees. Our second sampling technique, the unrestricted self-sampling approach, bears the limitation that the survey needed to be openly accessible. We justify this limitation by the fact that we wanted to open our survey to waste management firms other than those in the network of the system service provider.

Second, our findings are limited to the German waste management sector. It would be interesting to investigate, however, how waste management firms from other regions answer our survey.

Third, future research should expand the temporal reach of our study. Our openly available survey instrument (Appendix G) could be used to build a digitalization progress indicator tool that measures progress in the actual digital transformation of the global waste management industry over time, if a survey such as ours were to be repeated in regular time intervals (e.g., annually).

Fourth, data collection was impeded by the concurrent onset of the Covid-19 pandemic in Europe. While our invitations to participate were distributed digitally and via mail, the onset of the pandemic may have contributed to a perceived lack of time or lack of current relevance.

Fifth, our study did not address the entire waste lifecycle. Digital technologies increasingly also feature in new solutions for waste reduction and recycling. For example, image recognition and machine data analysis technologies are being explored to improve waste treatment (Waste Management World 2021). Future research should therefore expand the topical coverage of our survey to study the progress of digitalization not only in waste management but also waste reduction and recycling.

5.5 Conclusion

Our findings show that digitalization is an increasingly important topic on the agenda of waste management firms. Yet, many firms only half-heartedly engage with digitalization resulting in nonexclusive implementations of digital technologies that predominantly aim at the optimization of existing, intra-organizational business processes for efficiency.

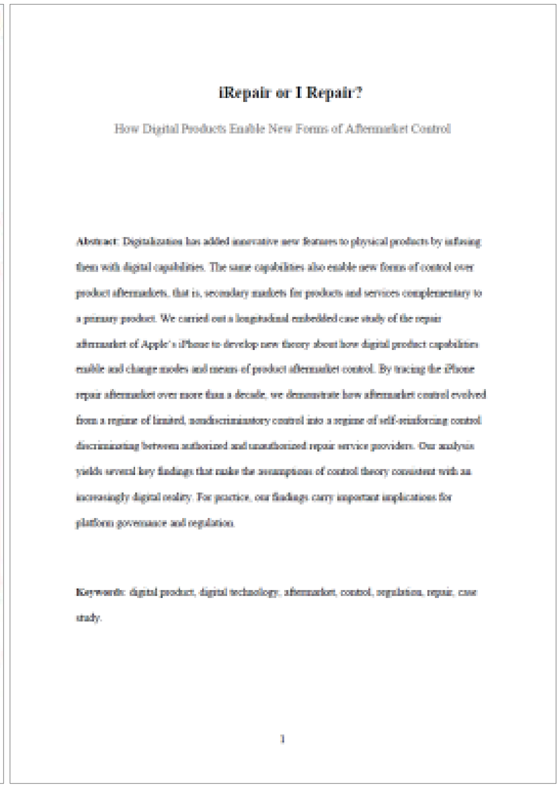
Our findings confirm the need for further research on the digital transformation of incumbent, largely non-digital infrastructures for waste management. Findings from other domains suggest that network effects may play a significant role in the adoption of digital technologies in incumbent infrastructures with multiple actors (Constantinides et al. 2018). It remains to be investigated whether digital technologies will contribute to a platformization of such infrastructures and whether these technologies will change traditional underlying market and governance structures.

Our findings indicate a gap between reported digitalization intentions and actual adoption for advanced digital technologies. Our insights imply that waste management firms may find that the burden of their operative business and high adoption costs are hindering them in pursuing more ambitious digitalization objectives. As a possible lightweight mitigation strategy, we suggest training existing employees and let them engage with digital technology providers, who offer modular solutions that can be quickly ramped up and tested without large financial and operational risks.

Further, advanced digital technologies tend to exhibit increasing returns to adoption (Fichman and Kemerer 1999), that is, their benefits grow with more users adopting the digital technology (Katz and Shapiro 1986). We, therefore, recommend digital technology providers to either employ platform rather than product-centric business models or, at least, ensure that their digital product complies with industry-wide data standards. A platform business logic stresses that digital technology providers are not only selling a digital solution to a waste management firm but essentially to its customers (waste producers) and business partners (waste recyclers) as well. Established data standards ensure that data can flow with the waste stream through the entire waste management value chain, thereby, enabling its end-to-end digitalization.

Our findings also highlight an obligation for waste management associations to continue investing into educating waste management firms about the benefits, barriers, and approaches to digital technologies, and extend these efforts to waste producers as they play an important role in adopting digital technologies as well. New education is required on emergent data protection concerns that hinder many waste management firms in pursuing more ambitious digitalization objectives.

Lastly, we suggest facilitating the exchange between waste management firms and digital start-ups. While digital start-ups were framed as “not very threatening disruptors in the rear-view mirror” in practitioner interviews, we suggest considering them at least as digitalization drivers, valuable informants, and potential technology providers.



iRepair or I Repair?

How Digital Products Enable New Forms of Aftermarket Control

Abstract: Digitalization has added innovative new features to physical products by infusing them with digital capabilities. The same capabilities also enable new forms of control over product aftermarkets, that is, secondary markets for products and services complementary to a primary product. We carried out a longitudinal embedded case study of the repair aftermarket of Apple's iPhone to develop new theory about how digital product capabilities enable and change modes and means of product aftermarket control. By tracing the iPhone repair aftermarket over more than a decade, we demonstrate how aftermarket control evolved from a regime of limited, nondiscriminatory control into a regime of self-reinforcing control discriminating between authorized and unauthorized repair service providers. Our analysis yields several key findings that make the assumptions of control theory consistent with an increasingly digital reality. For practice, our findings carry important implications for platform governance and regulation.

Keywords: digital product, digital technology, aftermarket, control, regulation, repair, case study.

1

Title	iRepair or I repair? How digital products enable new forms of aftermarket control	
Authors and contributions	Roman Zeiss	Conceptualization; Data Curation; Formal Analysis; Investigation; Validation; Visualization; Writing – Original Draft Preparation; Writing – Review & Editing
	Jan Recker	Conceptualization; Supervision; Methodology; Validation; Visualization; Writing – Original Draft Preparation; Writing – Review & Editing
	Mario Müller	Conceptualization; Data Curation; Writing – Original Draft Preparation
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Chapter 6

iRepair or I Repair? How Digital Products Enable New Forms of Aftermarket Control

Roman Zeiss
University of Cologne

Jan Recker
University of Hamburg

Mario Müller
University of Cologne

Digitalization has added innovative new features to physical products by infusing them with digital capabilities. The same capabilities also enable new forms of control over product aftermarkets, that is, secondary markets for products and services complementary to a primary product. We carried out a longitudinal embedded case study of the repair aftermarket of Apple's iPhone to develop new theory about how digital product capabilities enable and change modes and means of product aftermarket control. By tracing the iPhone repair aftermarket over more than a decade, we demonstrate how aftermarket control evolved from a regime of limited, nondiscriminatory control into a regime of self-reinforcing control discriminating between authorized and unauthorized repair service providers. Our analysis yields several key findings that make the assumptions of control theory consistent with an increasingly digital reality. For practice, our findings carry important implications for platform governance and regulation.

6.1 Introduction

Physical products that contain digital capabilities through sensors, connectivity, or algorithmic features, have been growing rapidly over the past decade. The number of digital objects already outnumbered the human population in 2008 and climbed to an estimated 50 billion objects in 2016 (Zhang 2016).

With this advent of digitalized products, we observe a qualitative change in how original equipment manufacturers (OEMs) manage and control aftermarkets, that is, the secondary markets for products and services complementary to their primary product. For instance, printer manufacturers, such as HP, Canon, or Epson, have repeatedly attempted to exclude competitors from aftermarkets by binding original cartridges to the printer via a proprietary software chip (Stoltz 2018). Similarly, special equipment manufacturers, such as John Deere in the agriculture business or Dräger in the medical sector, have reportedly impeded third-party or self-maintenance of their devices through a portfolio of technological protection measures that include digital signatures, passwords, and encryption (Proctor and O'Reilly 2020).

These examples suggest that the digitalization of physical products allow OEMs to increasingly enact control over aftermarkets *through* their digital products. With control we mean the ability of one party to direct, motivate, or encourage other parties to act in a desired way (Eisenhardt 1985; Ouchi 1979). The advent of digital products has marked a fundamental departure from how control has typically been carried out by OEMs: Historically, products would leave the OEMs' sphere of influence once sold to customers. Any value creation after the point of sale, such as product repair, maintenance, or modification, could not be directly observed, let alone intervened, by the OEM. Because of this situation, OEMs have traditionally perused measures such as exclusive dealing of spare parts or contractual tying of products with aftermarket services, in an effort to regulate what type of value could be created by whom in the first place, also because the processes or outputs of aftermarket value creation could not be readily observed or measured by them

We see both assumptions challenged on modern aftermarkets for digital products. We suggest that the infusion of digital technologies in everyday products has spawned new forms of aftermarket control. Digital technologies allow products to be monitored, accessed, and modified long after the point of sale. This is important to understand because these capabilities can potentially facilitate discriminatory and potentially anticompetitive conduct in aftermarkets and thus might need to be regulated. We ask the research question: "*How do digital products enable aftermarket control?*"

We carried out a longitudinal embedded case study of the repair aftermarket of Apple's iPhone. We demonstrate how aftermarket control evolved from a regime of limited, nondiscriminatory control into a holistic regime of self-reinforcing control discriminating between authorized and unauthorized repair service providers. This shift in control has been enabled through two digital product capabilities, remote monitoring and intervention, which have allowed the OEM's control portfolio to progress from singular input control to a blended and interdependent portfolio of input, process, and output controls.

We contribute new knowledge to the literature on control and digital platform governance. Our findings about digitally enabled remote monitoring and intervention reconcile the seemingly contradictory relationship between seminal control theory (Cardinal 2001; Kirsch 1997; Ouchi 1979) and modern aftermarket control practices. Our theoretical model also expands digital platform governance research (Eaton et al. 2015; Tiwana et al. 2010; Tiwana 2015) by stressing the importance of a holistic control view and bringing the 'hardware' element of digital platforms' layered modular architecture into focus (Yoo et al. 2010), which expands the current focus on software platforms.

6.2 Background

6.2.1 Aftermarkets

An aftermarket is a market downstream from the primary product's point of sale where value is created through secondary products and services that are complementary to the primary product (Shapiro and Teece 1994; Wagner et al. 2018), such as repair, modification, or customization. Aftermarkets are prominent in various industries including markets for durable goods (e.g., cars) as well as consumables (e.g., printers).

Aftermarkets comprise tangible (e.g., spare parts or ink cartridges) as well as intangible (e.g., repair or maintenance) secondary products and services, or a combination of both (Gundlach 2007).

OEMs have strong incentives to manage and control aftermarkets (Cohen et al. 2006). Economically, secondary products and services can generate up to 30% of revenue and up to 45% of total profits of OEMs (Dennis and Kambil 2003; Holmström et al. 2011). For example, in 2015 the global automotive aftermarket reportedly generated $760 bn, accounting for approximately 20% of the total revenue in the automotive sector (Breitschwerdt et al. 2017). Strategically, aftermarkets offer cost-efficient ways to retain customers and establish close and recurrent relationships with the installed base (Gebauer 2008; Guajardo and Cohen 2018). Further, the growing awareness for sustainable production and consumption by customers and regulators has induced many OEMs to assume greater responsibility for their products after the point of sale (Kalverkamp and Young 2019; Subramoniam et al. 2009).

On aftermarkets, OEMs tend to face competition by independent service organizations. These independents either create specialized aftermarket value through, for instance, the repair of primary products that are not covered by OEM warranty anymore, or they compete on price with products (e.g., non-original cartridges) and services similar to the OEM's aftermarket offering (Wagner et al. 2018). As a result, aftermarkets tend to split into an OEM controlled network, with internal and authorized service providers, and an independent network, with unauthorized service providers. Sometimes, independent service organizations can tap into OEMs supply chains to obtain original spare parts, causing the boundaries between both networks to blur (Breitschwerdt et al. 2017). In other instances, however, OEMs attempt to defend their aftermarkets against competitors with a variety of control strategies.

Traditionally, key strategies for controlling aftermarkets comprise contractual and technical tying, whereby the OEM would condition the sale of its primary product on the purchase of its own secondary products or services (Bowman 1957; Chen and Ross 1993). Through agreements between the OEM and suppliers or consumers (contractual tying) or through deliberate physical product design (technical tying), the OEM thereby attempts to exclude any unauthorized aftermarket value offered by independent service organizations and bind aftermarket demand to its own product and service portfolio. However, the ongoing infusion of economic products with digital capabilities such as digitization, connectivity, or reprogrammability (Yoo et al. 2010) change contractual and technical tying strategies and also potentially enable new, different strategies for control (Hoofnagle et al. 2019; Yu 2015; Zittrain 2008). Our aim is thus to understand *how* digital products enable new forms of aftermarket control.

6.2.2 Control Theory

To understand how OEMs maintain oversight over product and value creation in digital product aftermarkets, we turn to control theory to build our conceptual vocabulary. Control theory originated in organizational research to understand which mechanisms managers use to guide individuals to act according to organizational goals (Cardinal et al. 2017). Control theory has since been applied and developed in other contexts such as information systems development (Henderson and Lee 1992; Kirsch 1996; Kirsch 1997), outsourcing (Wiener et al. 2016; Wiener et al. 2019), and more recently the governance of digital platforms (Eaton et al. 2015; Ghazawneh and Henfridsson 2013; Tiwana et al. 2010).

Controls refer to mechanisms used to direct, motivate, and encourage actors to act in a desired way (Eisenhardt 1985; Ouchi 1979). *Formal* controls are control mechanisms that are explicitly codified as official written procedures and rules (Cardinal et al. 2004). Three different formal modes of control can be distinguished (Jaworski 1988): input, process, and output control. *Input control* refers to the a-priori regulation of resources (e.g., material, financial, resources) that are relevant to create value (Cardinal et al. 2004). *Process control*, also labelled behavior control, refers to the ad-interim regulation of the value creation procedure (Cardinal et al. 2004; Kirsch 1996). *Output control* refers to the a-posteriori regulation of outcomes of the value creation process (Cardinal et al. 2004; Choudhury and Sabherwal 2003; Wiener et al. 2016). The main difference between these three modes of formal control is the timing of the intervention: Whereas input control relates to measurable actions prior to value creation, process control focuses on the activities required to reach the desired outcome, and output control sets performance standards, and monitors and evaluates the results (Jaworski 1988).

In the literature, two strands of research on control have emerged: the singular and the holistic control view. The singular control view suggests that, for a specific context, only one effective form of control exists (Cardinal et al. 2017). Hence, input, process, and output control are viewed as independent, orthogonal choices of control (Ouchi 1979; Wiener et al. 2016). The holistic control view sees effective control achieved through the combination of different control modes (Cardinal et al. 2017). Here, the focus lies on the interaction, configuration, and joint influence of different forms of control on the desired outcome. This view is in line with studies arguing that the utilization of different control mechanisms is most effective (Henderson and Lee 1992) and that the different forms of control do not exist in isolation but are rather combined to reach a certain goal (Jaworski 1988; Kirsch 1996).

In general, control theory distinguishes between *coercive* and *enabling* control styles (Adler and Borys 1996). Coercive control styles are used to enforce desired controlee behavior to reach desired outcomes, whereby the controlee is supposed to have no influence on the way control is configured and enacted (Wiener et al. 2016). Coercive control thus restricts a controlee using power to achieve alignment with organizational goals (Cardinal et al. 2017). Enabling control styles, while also aiming at achieving compliant controlee behavior, allow controlees to deal with contingencies more effectively by using procedures that allow them to react to unexpected events (Adler and Borys 1996).

To summarize, control theory offers a vocabulary to differentiate how digital product aftermarket control is enacted through different modes and in different styles. This vocabulary allows us to examine empirically who is regulating which aspect of the setting and how the different actors in this setting enact or react to the controls.

6.3 Method

We chose an inductive positivist research approach (Sarker et al. 2018), drawing on qualitative data from one embedded single case (Yin 2014), in which we captured the operations of various actors in the repair aftermarket ecosystem of Apple's iPhone over a period of 13 years and analyzed it through the lens of control theory (Cardinal et al. 2004; Ouchi 1979). The embedded case design allowed us to account for diverging interests, actions, and rationales of the involved actors (Dubé and Paré 2003).

6.3.1 Case Setting

Our setting is the repair aftermarket for Apple's iPhone devices. We chose this setting for four main reasons: First, smartphones are the most widely used digital product in the world (Statista 2018). Apple's iPhone was the first globally successful smartphone and remains one of the leading smartphone products next to Huawei and Samsung. The aftermarket for Apple iPhones is considered the largest and most vibrant (Slinn 2018). Second, regular device releases and operating system updates create sufficient variance in the observed digital product (iPhone) with regard to both hardware and software. Third, we want our theoretical contributions to extend existing knowledge on control in digital platforms (Tiwana 2015). Therefore, we deliberately chose a case setting that is part of the same platform ecosystem as the ones analyzed in previous literature (e.g., Eaton et al. (2015); Ghazawneh and Henfridsson 2013). Fourth, Apple's ecosystem offers a wide and rich range of available data sources allowing for insightful in-depth analysis and triangulation.

In this setting, we identified three types of aftermarket repair service providers as the main actors: internal repair service providers (IRPs), authorized repair service providers (ARPs), and unauthorized repair service providers (URPs).

1. **IRPs** are Apple's technical support staff in Apple Stores or in mail-in repair service centers.
2. **ARPs** are certified technicians of third-party service providers that have exclusive access to training, repair manuals, and original spare parts and tools.

To become an ARP, repair shops must meet certain standards defined by Apple that cover business requirements (e.g., financial stability), operational requirements (e.g., certified personnel), and shop requirements (e.g., Apple-consistent interior design). In addition, ARPs are monitored by Apple against a set of performance metrics including, for instance, repair turnaround time or parts per repair.

3. **URPs** are unauthorized aftermarket manufacturers, resellers, repair shops, and online user communities. URPs range from small suburban mom and pop shops to multimillion-dollar franchise enterprises. All URPs rely on aftermarket spare parts manufacturers primarily located in China, which produce refurbished components from used iPhones or copy components from scratch, and aftermarket resellers, which distribute the aftermarket parts and tools via online marketplaces, such as Alibaba. Finally, online communities—curated (e.g., iFixit) or non-curated (e.g., YouTube and Facebook)—provide URPs with latest information on repair guidelines, spare parts availability, and troubleshooting.

6.3.2 Data Collection

We built a case study database (Dubé and Paré 2003) of empirical data collected from both primary and secondary sources in three waves to establish a rich picture of the iPhone repair aftermarket (Table 15).

With the aim to immerse ourselves in the case setting, our first wave of data collection started in late 2018 when we interviewed and observed URPs and resellers of aftermarket spare parts and tools. Through semi-structured interviews we explored the informants' business models, their self-image, as well as their understanding of independent aftermarket services. We further observed and documented their daily operations, including the sourcing and distribution of spare parts and tools, and several repairs of broken iPhone devices. The empirical evidence gained from the interviews helped us contextualize and better understand the specificities of Apple's repair aftermarket but was primarily of anecdotal character and largely represented the informants' experiences over the last two to three years.

Table 15. Overview of data sources

	Data type	Description
Primary data sources	Interviews	• 8 interviews with unauthorized repair service providers • 4 interviews with authorized repair service providers • 2 interviews with Apple Services from the US and Europe
	Observations	• 5 onsite visits at unauthorized repair service providers
Secondary data sources	Blog entries	• 219 blog entries from tech blogs (e.g., iFixit, MacRumors, Motherboard, engadget, TechCrunch, Wired)
	Vlog entries	• 51 (23h) scripted YouTube videos of known URPs (e.g., by Hugh Jeffreys, Jessa Jones, Justin Ashford, Louis Rossmann) • 30 (6h) unscripted YouTube videos of smartphone repairs and teardowns (e.g., by REWA Technologies or Apfeldoktor)
	Press releases	• Apple Inc., The Repair Association, US Federal Trade Commission
	Public policies	• Apple Inc., US Copyright Office
	Leaked docs	• Emails, internals

In the second wave starting in mid-2019, we followed a more structured, longitudinal data collection approach, with the aim to capture the historical outline of the repair aftermarket since 2007 focusing on aftermarket control. We established this longitudinal perspective with the help of secondary data gathered from tech bloggers and vloggers (Davidson and Vaast 2009). We identified more than 200 relevant blog entries from the blog aggregator Techmeme (Vaast et al. 2013) by querying their curated database with the search string '("Apple" OR "iPhone") AND "repair".' Snowballing references and blog authors, we collected and transcribed more than 20 hours of YouTube vlog entries from the repair community commenting on control events in Apple's repair aftermarket. Where possible, we drilled down to the origin of the blog and vlog entries to verify their credibility and evaluated their temporal occurrence. The sources range from press releases and public policies announced by the aftermarket actors, legal documents, as well as leaked internal files and whistleblower information from current or past Apple employees. At the end of the second data collection wave, we felt better informed about the aftermarket's historical developments and events that marked instances of enacted control. Yet, after analyzing this longitudinal data, we realized two issues: First, while we better understood the evolution of control in Apple's aftermarket through the eyes of the tech community, press, regulators, and URPs, we did not sufficiently understand how URPs reacted to individual control events. Second, we realized that our data sources, up to this point, exhibited a bias towards the position of URPs and lacked the perspective of IRPs and ARPs.

In our third wave of data collection, starting end of 2019, we focused on two aspects: First, we returned to URPs from the first wave and also sampled new ones, to discuss with them the control events identified in our longitudinal analysis. We further collected more than 5 hours of iPhone repair videos from YouTube. Thereby, we gained an in-depth technical understanding of how these control events would unfold in URPs' daily repair activities. Second, we interviewed ARPs with an extensive track record in Apple's aftermarket to (dis-) confirm our understanding of the data based on URP interviews, observations, and the longitudinal data. Third, we discussed our insights with two senior staff at Apple Europe and Apple US who are responsible for the management and operations of repair services. Where our understanding based on URP data was challenged through the information received by ARPs and IRPs, we then returned to URPs and secondary data to probe their perspective further. This back-and-forth between data collection, different sources, and analysis over time helped us generate a holistic and contextualized understanding of Apple's repair aftermarket.

6.3.3 Data Analysis

As our empirical interest was to understand how digital products enable new forms of aftermarket control, we arranged our data analysis around the occurrences of repair and control events. *Repair events* are those actions performed by an actor that aim to create value by restoring a device's deficient functionality, such as the restoration of a deficient touch functionality through the replacement of the broken display. *Control events* are those actions performed by an actor that intentionally or unintentionally constrain or expand the options for action of another actor in achieving a certain outcome.[13] Combining repair and control events, *aftermarket control* comprises occasions where actions of one actor intentionally or unintentionally constrain or expand the options for action of another actor to create aftermarket value. For instance, Apple's decision to solder the connectors of the first iPhone battery to the motherboard constrained the set of options available for battery replacement.

We followed a typical three-stage approach involving open, axial, and selective coding (Strauss and Corbin 1998) to (1) explore repair events, (2) relate technical challenges carrying out repairs to possible control events and identify which control events were digital control events, and (3) relate the subset of digital control events to digital product properties. Table 16 provides an overview of our logical chain of evidence (Benbasat et al. 1987; Dubé and Paré 2003). We explain each step in detail below.

In the first stage of data analysis, we immersed ourselves in the case setting of digital product aftermarkets and openly coded repair events in our first-wave data in terms of involved actions (e.g., disassembly, replacement, reassembly), actors (e.g., URPs, end users, aftermarket suppliers), and objects (e.g., smartphone devices, repair parts, repair tools). During our on-site visits, we observed various iPhone repairs ranging from rather simple battery replacements to more complicated circuit board-level chip repairs. The coded repair event 'iPhone 8 battery replacement,' for instance, includes one **actor**, ten <u>objects</u>, and five *actions*:

Initially, the **URP** *diagnoses* the <u>device</u>'s defect. The diagnosis points towards a <u>drained battery</u> that should be replaced. The **URP,** therefore, *disassembles* the <u>device</u> with the help of <u>two screwdrivers</u>, <u>heat pad</u>, <u>suction cup</u>, <u>spudger</u>, and <u>tweezers</u> and *replaces* the <u>drained battery</u> with a new <u>aftermarket battery</u>. In the end, the **URP** *reassembles* the <u>device</u> with the help of <u>screwdrivers</u>, a <u>spudger</u>, <u>tweezers</u>, and <u>adhesive strips</u> and performs a final acceptance *test*.

[13] Note, that we divert from common definitions of control that predominantly conceptualize control as goal oriented (intended) and manager centric practices in a hierarchical organization to "direct attention, motivate, and encourage organizational members to act in desired ways to meet the firm's objectives" (Cardinal 2001, p. 22).

Table 16. Overview of coding strategies

Data sources	Coding strategy	Outcome
Stage 1: *Exploring repair events in digital product aftermarkets*		
• Two interviews with URPs • Two on-site visits at URPs • Two interviews with resellers of aftermarket spare parts and tools	• Open coding of repair events	• Structured list of repair events classified by actions, actors, and objects • List of technical repair challenges and corresponding workarounds
Stage 2: *Identifying and categorizing control events in digital product aftermarkets*		
• Previous data sources • 200+ blog posts on iPhone repair aftermarket • 20+ hours of scripted vlog posts by URPs	• Axial coding of control events by relating control causes to control effects (= technical repair challenges from Stage 1) • Theoretical coding of control events along control modes and control means • Temporal and logical ordering of control events	• List of 41 control events ordered by control modes (input, process, output control) and control means (regulatory, physical, digital control) • Visualized timeline of control events
Stage 3: *Explaining digital augmentation of product aftermarket control*		
• Previous data sources • Four interviews with URPs • Three on-site visits at URPs • Four interviews with ARPs • 5+ hours of unscripted videos recording iPhone repairs	• Selective coding of relationship between digital control events and digital product properties	• Theory on how digital product properties afford relevant control capabilities that augment aftermarket controls

In our observation of these repair events, we noted that URPs frequently faced technical challenges, such as unclear defect causes or inaccessible components. Correspondingly, a subset of actions during repairs were performed only to overcome these challenges. For instance, sometimes URPs spent considerable amounts of time diagnosing the defect of a device. Due to the absence of accessible log files, they had to reverse engineer actions, such as testing single traces on the printed circuit board with a multimeter, to narrow down the defect's cause and proceed with the repair. As we followed-up with the URPs about such technical repair challenges during interviews, they frequently framed these occasions as barriers induced by external actions of actors, such as Apple, which we marked as control events.

In the second stage of data analysis, we shifted our unit of analysis from repair events to control events to better understand which and how external actions affected the URPs' options for repair. We chose the technical challenges identified in repair events as our analytical departure and re-interpreted them in two steps to understand how control was enacted or responded to.

First, we investigated *which* actions caused technical challenges during repair events. For this axial coding, we relied on our first-wave interview and observation data and also traced root causes of technical repair challenges in our second-wave longitudinal blog and vlog data. Referring to our battery replacement example: Battery replacement was not always as simple as described for the iPhone 8. In the first iPhone generation, for instance, Apple decided to solder the connectors of the battery to the motherboard. This action constrained repairers' options to easily replace a drained battery as this repair could only be performed by knowledgeable repairers with access to solder equipment. Hence, we coded this relationship as '[soldering battery connectors to motherboard] [constrains] [battery repair options]'. In summary, the axial coding of control cause-and-effect patterns yielded a list of 41 control events.

Second, based on this set of control events we developed a categorization to help us differentiate *how* actions caused technical challenges during repair events. For this theoretical coding, we relied on two foundations. Drawing on control theory (Cardinal et al. 2004; Kirsch 1996; Ouchi 1979; Wiener et al. 2016), we adopted the concept of *control modes* to categorize the control events based on their target (input, process, output) in the value creation process. Control theory, however, remains silent about the medium through which the control modes are enacted; a crucial consideration for us to uncover how digital products affect aftermarket control. We, therefore, developed a second concept called *control means* to categorize control events according to the salient medium of enactment that specifies how control is exercised. We distinguished regulatory, physical, and digital control means, acknowledging that digital products are layered (Faulkner and Runde 2019) in that they consist of material bearers (physical components) and non-material bitstrings (digital components) and occupy a social position defined by rights and responsibilities about their use and maintenance (regulatory component). *Regulatory* *control* describes control enacted through legal rights assigned to the social position of a product and its components, such as a warranty or intellectual property rights. *Physical control* describes controls enacted through the design and behavior of material components of the product, such as welded component interfaces that control the accessibility and removability of components. *Digital control* describes those controls enacted through the design and behavior of non-material bitstring components of the product, such as the pairing of two hardware components via a serial number stored as a digital bitstring on both components.

Through this axial and theoretical coding, we developed a timeline of control events from 2007 to 2020 ordered by control modes and means (Appendix J). It shows that Apple—intentionally or unintentionally—not only enacted traditional product aftermarket controls, such as exclusive dealing via contracts (regulatory input control) or technical tying via physical compatibility (physical process control), but increasingly employed new forms of input, process, and output controls, whose enactment specifically relied on digital properties of the iPhone and its repair parts and tools (digital control).

In the third stage of data analysis, we then honed in on elements of salient *digital* products (i.e., iPhone, associated repair parts, and repair tools) as our core analytical category. Building on the third-wave interview data and the in-depth technical repair videos, we re-examined all *digital* control events to understand how they relate to digital product properties. Our selective coding was theoretically sensitized by key characteristics of digital artifacts, three of which we were able to ground as digital product properties in our case data. *Digitization*, "the encoding of analog information into digital format" (Yoo et al. 2010, p. 725), manifested, for instance, when Apple digitally identified physical components through a unique serial number stored on a flash chip located on the physical component itself. *Connectivity*, a digital artifact's ability to link multiple, sometimes spatiotemporally dispersed, social or technical entities via information transmission infrastructure (Leonardi and Treem 2020), manifested, for instance, every time when Apple released an iOS update downloadable to all devices via an internet connection. Finally, *reprogrammability*, a digital artifact's ability of being "accessible and modifiable by a [software program] other than the one governing [its] own behavior" (Kallinikos et al. 2013, p. 359), manifested, for instance, in iOS releases that updated firmware.

Our selective coding revealed that combinations of these three digital product properties provide two relevant control capabilities: Combining digitization with connectivity enables *remote monitoring*; combining connectivity with reprogrammability enables *remote intervention*. These relevant control capabilities equip manufacturers of digital products with the possibility to enact new forms of aftermarket control. Take again the 'battery replacement' example, which was affected by varying controls over time. Initially, Apple controlled battery replacement primarily through trademark law regulating the availability of original repair parts and tools in the aftermarket (regulatory input control) and obstructive physical interfaces regulating the access to the device (physical process control). As the technical repair challenges caused by these traditional aftermarket controls were circumvented by URPs, however, Apple started to enact digital control: First, Apple designed the original battery component with an encrypted storage chip holding its unique component serial number (digitization). Second, once the original battery was initially assembled onto a device, its serial number would be copied and stored in another encrypted chip located on the device's motherboard. Thereby, the original battery was digitally paired to the motherboard. Third, if URPs tried to replace the drained original battery with an aftermarket copy, a firmware bootup procedure would afterwards identify the aftermarket battery as it did not carry the original component serial number. In summary, the digitization of and connectivity between hardware components afforded Apple remote monitoring.

6.4 Findings

We start presenting the findings from our analysis of Apple's iPhone aftermarket from 2007 to 2020 by describing how the three control modes input, process, and output control were enacted and how the enactment changed over time. For each control mode, we present evidence from our case setting that illustrates control enactment through non-digital (regulatory or physical) and digital means. Evidence from blog and vlog data are referenced as {web reference ID}. Appendix H and Appendix I provide blog and vlog reference lists.

6.4.1 Input Control

In repair aftermarkets, the regulation of resources relevant for the repair of the primary product, such as spare parts, repair tools, and repair knowledge, forms the core of input control. In Apple's repair aftermarket, input control can be observed since the release of the first iPhone in 2007 (Appendix J).

Apple has been controlling relevant resources primarily via **regulatory input control**, such as contractual agreements with component suppliers. In supplier contracts, Apple lays the foundation for the tight control over its intellectual property and, thus, the corresponding spare parts and tools {B1}. As a result, to date Apple original repair parts and tools de-facto do not exist outside Apple's supply chain and are, therefore, not available to URPs.

In response to input control, URPs engaged early on in self-resourcing action to gain access to alternative repair parts, tools, and knowledge {B2}. In this regard, a pioneer in 2007 was iFixit, an online supplier of aftermarket repair parts and tools as well as a wiki-based knowledge platform:

> *"We attempted to fix some other [devices] but had trouble finding parts. So we bought a broken [device] on eBay and stole parts from it. Then we decided to start selling the parts ourselves, and iFixit was born. [...] We wrote some [more] instructions the first chance we got. And we posted them online, for free."*
>
> (excerpt from iFixit's 'About Us' statement, 2009)

After each release of a new iPhone generation, iFixit publishes openly available repair guidelines and starts distributing relevant repair parts and tools shortly after. The guidelines are created from so-called 'teardowns,' in which the released iPhone is dissected piece by piece {B3, B4, B5}. This reverse engineering-based approach has endured until today. Nowadays, iFixit has evolved into a wiki-based platform with guidelines resulting from teardowns and community-curated, collective knowledge creation.

Over time, the independent repair aftermarket grew and professionalized and other distributors of repair parts, tools, and knowledge emerged, especially in China {B6}. While initially independent aftermarket repair parts were predominantly refurbished components from broken iPhones, Chinese manufacturers started to produce and sell copy components, such as batteries or displays. This brought more options to the independent aftermarket but created new challenges from a legal, quality, and reliability perspective {B7, V1, V2, V3}:

> *"All the parts originate from China anyway, but quality wise, it's kind of very difficult to judge from a distance what you can get. And so, in the beginning we [worked with domestic] importers exclusively because we had [domestic] laws that protected basically what we buy. But right now, most parts we buy in China."*
>
> (URP 3, 2019)

In light of the magnifying self-resourcing action of URPs, Apple performed two types of input controls (Appendix J). First, Apple relied on its regulatory input control, specified in contracts and backed by public law, and repetitively enforced it with the help of the public executive, e.g., the Department of Homeland Security in the US {B8; V4, V5, V6}.

Second, Apple started enacting **digital input control,** around 2013, that, in comparison to regulatory input control, afforded Apple with a more immediate and selective control power over its repair parts, repair tools, and repair knowledge. Central to this digital input control is Apple's Global Service Exchange (GSX), a web-based repair and order management software tool that provides IRPs and ARPs with access to repair diagnostics and calibration software and original repair parts {B9, V7, V8}. GSX can only be used with a valid Apple Connect ID that only certified repair technicians at IRPs and ARPs possess.

"[The Apple Connect ID] works the same way as an Apple ID, but repairers can use it to log into other programs, such as GSX. GSX gives repairers direct access to Apple's systems and databases. They can retrieve various data via the iPhone's serial number and also order spare parts via it. GSX also ensures that removed components are returned. [...] So, they have more possibilities than we do."

(URP 7, 2020)

As URPs became aware of this form of input control, some tried to illegally gain possession of an Apple Connect ID, which they thought would provide them access to original repair parts and the diagnostics and calibration software. However, this circumvention turned out as unsustainable. As Apple noticed the URPs' responses, they refined and tightened its input control. Today, an Apple Connect ID is necessary but insufficient to gain access to original repair parts, tools, and knowledge:

"There used to be times when you only required an Apple Connect ID to log in [to GSX]. Then, Apple realized that the trade in Apple Connect IDs was growing, and that companies like us get at least three spam emails every day trying to rip off our IDs. [...] [Now,] you need a computer [with installed certificates], the computer needs internet access via a white listed IP, you need software, you need a special cable, and you also need to open a [repair request] in the service console [(i.e., GSX)] at Apple [with your Apple Connect ID]. So that's quite a lot of dependencies: network-related, organizational, hardware-related [...]. Apple wants to make sure that only the people who are allowed to do it do so."

(ARP 4, 2020)

As a result, the majority of URPs diverted to freeware software tools that provide a partial relief to tightly controlled original repair tools {V9}. This freely available repair software mimics repair functionality, such as the software pairing of aftermarket spare parts with the repaired device, that otherwise would only be available via GSX to IRPs and ARPs.

"A lot of things we can work around because there is freeware that we can download. [...] The developers of the freeware are trying to make everything possible for us, but you can't do everything right away. And that is the big problem. With the [iPhone] 11, for example, we still don't have a solution, and it's been on the market for almost half a year. [...] [For a display repair], you definitely have to go through the Apple Connect ID and only Apple Store [(i.e., IRP)] employees or [ARPs] have that."

(URP 7, 2020)

In summary, input control has been ever-present in Apple's iPhone repair aftermarket. It evolved, however, from purely regulatory means to a blend of regulatory and digital means of enactment (Table 17).

Table 17. Summary of salient input control events

Date	Event description	Control mean
Jun '07	Apple does not distribute original repair parts	Regulatory control
Jun '07	Apple does not distribute original repair tools	Regulatory control
Jun '07	Apple does not distribute original repair guidelines	Regulatory control
Jun '10	Apple rolls out software diagnostics tool to IRPs	Digital control
Apr '13	Apple cooperates with US Customs and Border Protection to seize imported displays from URPs	Regulatory control
Jun '13	Apple rolls out display calibration procedure including software and hardware tools to IRPs	Digital control
Sep '15	Apple removes iFixit app from App Store	Digital control
Sep '15	Apple rolls out touch calibration procedure including hardware and software tools to IRPs	Digital control
Jun '17	Apple rolls out touch calibration procedure including hardware and software tools to selected ARPs	Digital control
Jul '17	Apple sues Norwegian URP for trademark violation by importing refurbished original repair parts	Regulatory control
May '18	US Customs and Border Protection seize imported displays from URPs	Regulatory control
Sep '18	Apple rolls out software-only calibration procedure including software tools to IRPs and ARPs	Digital control

The *digitization* of key actors (e.g., identification of authorized repairers via Apple Connect ID) and objects (e.g., serialization of repair parts and tools) involved in repair as well as their *connectivity* via web-based services (e.g., GSX) afforded Apple a so far unprecedented level of *remote monitoring* over its repair aftermarket, essentially enabling it to achieve two outcomes more effectively: In the first place, Apple was able to separate the repair aftermarket in authorized and unauthorized service providers. Subsequently, Apple was able to selectively resource authorized while excluding unauthorized repair service providers.

6.4.2 Process Control

The relevance of resources for a repair is largely defined by the activities carried out in the repair process. For example, any repair process that involves removing the front panel to gain access to the interior of the device relies on the availability of suitable screwdrivers to loosen the screws that secure the front panel to the body of the device. In contrast, a screwdriver is irrelevant if the device is accessed via the rear panel fixed to the body by a clip mechanism.

In repair aftermarkets, process control is primarily shaped through the design of the device that is to be repaired. Through product design choices, rules and repair use cases are inscribed into the product architecture. This type of process control can be observed in Apple's iPhone repair aftermarket ever since the release of the first iPhone in 2007.

Initially, **physical process control** was enacted in that rules supporting or constraining certain repair use cases were inscribed into physical components of the iPhone's product architecture. The teardown of the first-generation iPhone, for instance, revealed that the battery wires were soldered to the motherboard {B10}. This product design rendered battery replacements a challenging endeavor for URPs without appropriate skills and repair tools.

Over time, the URP community repetitively pointed out design choices that allowed Apple to exert physical control over the repair process. Examples include the antenna connector glued to the motherboard in the iPhone 5C {B11}, the display glued to the case since the iPhone 6S {B12}, or two motherboard layers soldered together in the iPhone X {B13}. Albeit, such design choices were not necessarily intended to increase control. For instance, the glued display, which complicates the access to the device, simultaneously increases its water and dust protection.

> *"It started with the iPhone 6S [...]. Then the demands from Apple, as well as from the customer, on the [product's water and dust protection] became higher. That means the iPhone had to become tighter. Of course, this means, in turn, that you have to work more precisely with the tool that you use to open the iPhone. Insert it into the tool, take out the screw, and then carefully cut open the seal. Of course, this has become more complex."*
>
> (ARP 4, 2020)

Other design choices appear to explicitly render the repair process more cumbersome for repairers without access to relevant repair tools, such as the decision to use a special, non-standard screw for securing the iPhone 4 rear panel to the body {B14, B15}. As the corresponding screwdriver was not freely available, URPs could initially not open the device without damaging the screws:

> *"This screw head is new to us. In fact, there isn't a single reputable supplier that sells exactly the same screwdrivers Apple's technicians use—which is Apple's point. They picked an obscure head that no one would have."*
>
> (Kyle Wiens, 2011 {B16})

The repair constraining effect of physical process control seemed limited. First, URPs were able to circumvent physical process control by self-resourcing appropriate repair tools. Once the physical interfaces between components had been understood in teardowns, it did not take long until the first repair tools, such as glue-dissolving heat beds and special screwdrivers for accessing or adhesive strips for resealing the device, appeared on the aftermarket {B16}. Second, its strategic decision to move away from device replacements towards same unit repair {B17, B18, B19, B20} required Apple to rethink their product design making it more repair friendly for IRPs and ARPs, which also benefited URPs {B21}:

> *"'[...T]he fundamental construction hasn't changed since [the iPhone 5]. You can do screen and battery repairs—which are the two most important*

repairs for a mobile device—pretty easily.' We expect this was intentional, since it happened around the same time Apple started doing in-store repairs—after all, repairability doesn't just help you, it helps the techs at the Genius Bar [i.e., IRPs] too."

(Whitson Gordon, 2019 {B22})

As physical process control increasingly reached its limits, Apple moved to digital process control in 2013. In digital process control, rules and use cases are not inscribed into physical but instead digital components of the product architecture.

The first form of **digital process control** manifested in the iOS 8 software update released in September 2014. Shortly after, URP and user reports cumulated in online forums highlighting issues with an unknown 'error 53', which would appear during the software update and result in a disabled—so-called 'bricked'—iPhone {B23}. According to the emerging error pattern, the issue only affected iPhone generations with a fingerprint sensor whose home button had been previously replaced during unauthorized repairs {V10}. This observation was confirmed in February 2016, as negative media coverage {B24, B25, B26} and a class action lawsuit {B27} pressed Apple for an official statement and a subsequent software patch {B28, B29}. The patch unbricked affected iPhones, however, left the fingerprint functionality of assembled aftermarket home buttons' disabled.

"We protect fingerprint data using a secure enclave [i.e., encrypted storage on the motherboard], which is uniquely paired to the touch ID [i.e., fingerprint] sensor. When an iPhone is serviced by an [ARP] or [IRP] for changes that affect the touch ID sensor, the pairing is re-validated. This check ensures the device and the iOS features related to touch ID remain secure. [...] When an iPhone is serviced by an [URP], faulty screens or other invalid components that affect the touch ID sensor could cause the check to fail if the pairing cannot be validated."

(Apple, 2016 {B26})

This software-based serialized pairing of hardware components marked the beginning of digital process control in Apple's iPhone repair aftermarket. Later iPhone product generations did not only include serialization of fingerprint sensors but also of other security-irrelevant hardware components. For instance, iOS 11 (September 2017) {B30} and iOS 11.3 (March 2018) {B31, B32, V11, V12}, both caused touch input failures on non-original aftermarket displays mounted on iPhone 6S and newer generations. In addition, iOS 11.1 (October 2017) {B33}, disabled display functionalities, such as automatic brightness adjustment, on iPhone 8 and newer generations that carried displays replaced during unauthorized repair {B34}. While the touch input failures were resolved by Apple in subsequent patches {B35}, of the two disabled display functionalities only one was reenabled by an iOS update in June 2018 {B36}.

> *"Both [disabled display functionalities] rely on the iPhone's ambient light sensor, a little module embedded at the top of the display that somehow gets disabled on the latest iPhones anytime the display is changed—even if you keep the original sensor, and even if you use a brand-new, authentic Apple display. And if you put the original display back in, suddenly everything works fine again. [...] What's interesting is that if you hot-swap the display [...], the sensor continues to work fine—but it's immediately disabled on restart, which tells us that some sort of hardware check is failing on startup."*
>
> (Jeff Suovanen, 2018 {B36})

Unlike encrypted serialization of security-relevant components, which until today could not be fully circumvented by URPs, the digital process control mechanisms described last did not rely on encryption and therefore yielded less sustaining control effects. Instead, URPs developed a circumvention method to reprogram the storage chips on the display assembly that held the non-encrypted serialization number. When an original component, such as a display, needed to be replaced, the method required the URP to extract the unencrypted serial number from the original component and rewrite it to the aftermarket replacement component {B37, B38, V13}. This would fool the iOS hardware check on startup into thinking the device was still carrying the original component.

Lately, digital process control is increasingly enacted via encrypted serialization again, successfully resisting the URPs' circumvention method. Starting in November

2017, Apple has begun pairing parts of the front sensor assembly (iPhone X) {B33}, battery (iPhone XS) {B39, B40, V15, V16}, display (iPhone 11) {B41, B42, B43}, and parts of the rear camera assembly (iPhone 12) {B44} to the device's motherboard {V17, V18}.

> *"[In the beginning, Apple] started giving us [(i.e., URPs)] more components that have programmable serials. Not that you necessarily have to change them; but if you do not, you lose something else [(i.e., functionality)]. Now, when we look at these [encrypted] serials, we cannot even change [them]. [...] What does that really mean when you are taking over the entire [iPhone device] with reprogrammable serials and they are all turning into encrypted serials? [...] It tells you, we [(i.e., URPs)] are in trouble, we are in big trouble."*
>
> (Justin Ashford, 2020 {V18})

As Apple enacted digital process control by inscribing recalibration as a necessary repair step into software components of the iPhone, it thereby designated recalibration software as a relevant repair tool whose access could then be regulated via digital input control (see previous section). Through this interrelated enactment of input and process control, Apple established an effective way to enable authorized while disabling unauthorized repair value creation.

> *"[Apple] said, '[...] We're putting displays on iPhones that are self-calibrating. The only thing you [(i.e., ARPs)] need is a special cable and a [certified] computer.' And then at the end of the repair, the iPhone is plugged into the computer running special software with the special cable, you push a couple of buttons and say, 'Calibrate, repair end, final check, now.' [...] And since then, vendors [(i.e., ARPs)] like us can also say, 'Yes, we have iPhone service on site and we can change screens, change batteries, change cameras here on site. Because we can do the final calibration.'"*
>
> (ARP 4, 2020)

In summary, process control has been enacted both physically and digitally but digital process control became more prominent (Table 18).

Table 18. Summary of salient process control events

Date	Event description	Control mean
Jun ‘07	Apple solders battery to case	Physical control
Jun ‘10	Apple fixes rear case to body using Pentalobular screws	Physical control
Sep ‘13	Apple glues antenna connector to motherboard	Physical control
Sep ‘13	Apple glues battery to case	Physical control
Sep ‘13	Apple pairs home button to motherboard using encrypted serials	Digital control
Sep ‘15	Apple glues display to case	Physical control
Sep ‘16	Apple fixes internal bracket to case using Tri-point screws	Physical control
Sep ‘16	Apple uses non-mechanical, software-only, home button	Digital control
Sep ‘17	Apple pairs display to motherboard using reprogrammable serials	Digital control
Sep ‘17	Apple hides screw under sticker	Physical control
Nov ‘17	Apple solders two-layered motherboard together	Physical control
Nov ‘17	Apple pairs front sensor assembly to motherboard using encrypted serials	Digital control
Sep ‘18	Apple pairs front battery to motherboard using encrypted serials	Digital control
Sep ‘19	Apple pairs display to motherboard using encrypted serials	Digital control
Sep ‘20	Apple pairs rear camera to motherboard using encrypted serials	Digital control

In sum, the *digitization* of product components (e.g., serialization of battery) afforded Apple new and more effective possibilities to *remotely intervene* in the repair process by inscribing repair procedures (e.g., calibration step at the end of repair) into non-material components of the device. Importantly, this non-material inscription differs from its physical counterpart in its level of tamper resistance: The digital form of instruction was able to withstand a key response mechanism, reverse engineering, that was usually performed by URPs when they encountered technical repair challenges. While a special screw that impedes access to the device (physical inscription) can be rather easily observed and circumvented through reverse engineering, digitally inscribed procedures were inherently more challenging to reverse engineer due to their comparatively limited observability.

6.4.3 Output Control

Even if input and process controls did not subdue unauthorized repair value creation a-priori or ad-interim, Apple could still control the outcomes of repair value creation a-posteriori through two means, regulatory and digital output control.

Initially, Apple's common way to enact **regulatory output control** was to deny any authorized repair under warranty of devices that had been serviced by unauthorized URPs {B45}. Details of this regulatory output control changed step-by-step. In February 2017, Apple excluded screen replacements from the list of third-party repairs that would void the device's warranty {B46}; followed by an exclusion of third-party battery replacements in March 2019 {B47}:

> *"iPhones with aftermarket batteries installed by third-party repair shops are now eligible for service at [IRPs and ARPs.] [...] If the repair is unrelated to the battery, [IRPs and ARPs] are now instructed to ignore the third-party battery and proceed with service as normal [...]. This could include repairs to the display, logic board, microphones, and so forth, with normal fees applying. [...] Apple will still decline service for iPhones with third-party logic boards, enclosures, microphones, Lightning connectors, headphone jacks, volume and sleep/wake buttons, TrueDepth sensor arrays, and certain other components."*
>
> (Joe Rossignol, 2019 {B47})

While regulatory output control diminished, **digital output control** emerged from 2014 onwards. In Apple's repair aftermarket, digital output control was enacted through iOS updates, which were released after a repair had been successfully finalized and the devices were back in the hands of the end user. These software updates controlled the outcomes of repair aftermarket value creation as they affected the materialization of the repair value—a restored and functional device—in a positive or negative way.

The effects of digital output control varied over time. The first enacted form of digital output control relates to the iOS 8 software update that caused 'error 53' {B23}. In this case, the effect of the firmware update was that it entirely disabled devices which contained non-original home buttons. Succeeding digital output controls only disabled selected functionalities, such as touch input or automatic display adjustments. Current digital output controls do not disable the device or selected functionality but inform the end user in on-screen notifications about non-original aftermarket components that had been replaced during third-party repair {B39, B41}.

> *"Currently, we have the problem with the iPhone 11 that you cannot perform a display replacement. If you do, you'll get the message 'your display has been replaced by an unauthorized repair shop.'"*
>
> (URP 7, 2020)

Apple did not only enact digital output controls that constrained but also (re-) expanded the options for URPs to create unauthorized repair value. In the case of the touch input failures caused by iOS 11 and iOS 11.3 (see previous section), Apple initially constrained URPs' repair options as it rendered non-original aftermarket displays inferior to original ones. However, as reports about touch input failures on devices with third-party displays accumulated online, Apple fixed both issues with iOS updates essentially expanding the repair options for URPs to use non-original aftermarket displays again {B35, B36}.

> *"And what about last year, when another iOS update broke touchscreen functionality for many iPhone 7 models that had been repaired with third-party displays? Apple fixed that one within about a week, and gave us all a heads-up right in the patch notes."*
>
> (Jeff Suovanen, 2018 {B36})

Output control is related to process and input control. First, the repair procedures inscribed into hardware and software (process control) are audited by algorithmic checks and rulesets contained in iOS firmware (output control). Yet, this audit depends on physical components that store and execute the algorithms. For instance, the encrypted chip holding the battery's serial number of the iPhone XS was already present in product architectures of previous iPhone generations {V14}. However, the corresponding digital output control—push notifications informing end users about non-original battery replacements—was only enacted with iPhone XS in 2019 {B41}. Apparently, the algorithmic checks and rulesets can be switched on and off at will with software as long as appropriate physical infrastructure is present.

> *"[...] It is like you have this door to your room. Somebody put it in there. It was a really nice door and everything was cool and they put a lock on there. [...] When you get the door, you are like 'Hey, did this door come with a key?' and they [say] '[…] Don't worry about the key.' And then, one day after nobody was paying attention, somebody locked the door. That is exactly what is going on here: Apple is being super sneaky. They literally put this in so long ago."*
>
> (Justin Ashford, 2019 {V14})

Second, as part of output control, the monitoring of authorized and unauthorized outcomes of repair aftermarket value creation also informs the design of future input control. Both sources of information from output control feedforward requirements for adjusting the future set of resources and regulating access to them. On the one hand, it enables the monitoring of unauthorized repairs and modifications.

> *"Apple initially put a lot of emphasis on customer satisfaction, saying, 'Okay if there's a defect, we'll just do a full device exchange.' [...] Nowadays, Apple has moved away from that because, above all things, there were more and more units in the market and [the] aftermarket was thriving. People simply removed things, turned in the cell phone that no longer worked, and got a new one in return. At some point later, in a refurbishment center, it was discovered that the circuit board was missing or the display was not the original one. That's why they started to say, 'Okay, we'll do the same-unit repair now.'"*
>
> (ARP 1, 2020)

On the other hand, it enables the quality management of authorized repairs performed by IRPs and ARPs.

> *"Apple always has control and an overview of what, when, where, by whom, and why was installed in which devices. So, it is always traceable, at any time. [...] After everything is reassembled, time-consuming final diagnoses have*

to be performed: Whether the touch still works, whether the buttons all still work and things like that. That's the most time-consuming thing with the iPhone."

(ARP 2, 2020)

Table 19. Summary of salient output control events

Date	Event description	Control mean
Jun '07	Apple announces any unauthorized modification or repair will void warranty	Regulatory control
Dec '14	Apple releases iOS 8.1 causing devices with non-calibrated aftermarket home button to disable during update ('error 53')	Digital control
Feb '16	Apple releases iOS 9.2.1 fixing 'error 53' but leaving fingerprint functionality disabled for devices with aftermarket home button	Digital control
Feb '17	Apple announces unauthorized display repairs no longer void warranty	Regulatory control
Nov '17	Apple releases iOS 11 causing two display functionalities (TrueTone and AutoBrightness functionality) on devices with non-calibrated aftermarket display to disable	Digital control
Nov '17	Apple releases iOS 11 causing touch input issues on devices with non-calibrated aftermarket display	Digital control
Nov '17	Apple releases iOS 11.0.3 fixing touch input issues on devices with aftermarket display and includes critical message about aftermarket displays in release notes	Digital control
Apr '18	Apple releases iOS 11.3 causing touch input issues on devices with non-calibrated aftermarket display	Digital control
Apr '18	Apple releases iOS 11.3.1 fixing touch input issues on devices with aftermarket display and includes critical message about aftermarket displays in release notes	Digital control
Sep '18	Apple releases iOS 12 fixing one display functionality (AutoBrightness) but leaving second display functionality (TrueTone) disabled for devices with aftermarket display	Digital control
Sep '18	Apple releases iOS 12 causing an on-screen message on iPhone XS and newer generations with non-calibrated aftermarket battery	Digital control
Mar '19	Apple announces unauthorized battery repairs no longer void warranty	Regulatory control
Sep '19	Apple releases iOS 13 causing an on-screen message on iPhone 11 and newer generations with non-calibrated aftermarket display	Digital control
Sep '20	Apple releases iOS 14 causing a camera functionality on iPhone 12 with non-calibrated rear camera to disable	Digital control

In summary, we observe how traditional output control enacted via regulatory means, such as voiding warranties after third-party modifications, was complemented by digital output controls (Table 19).

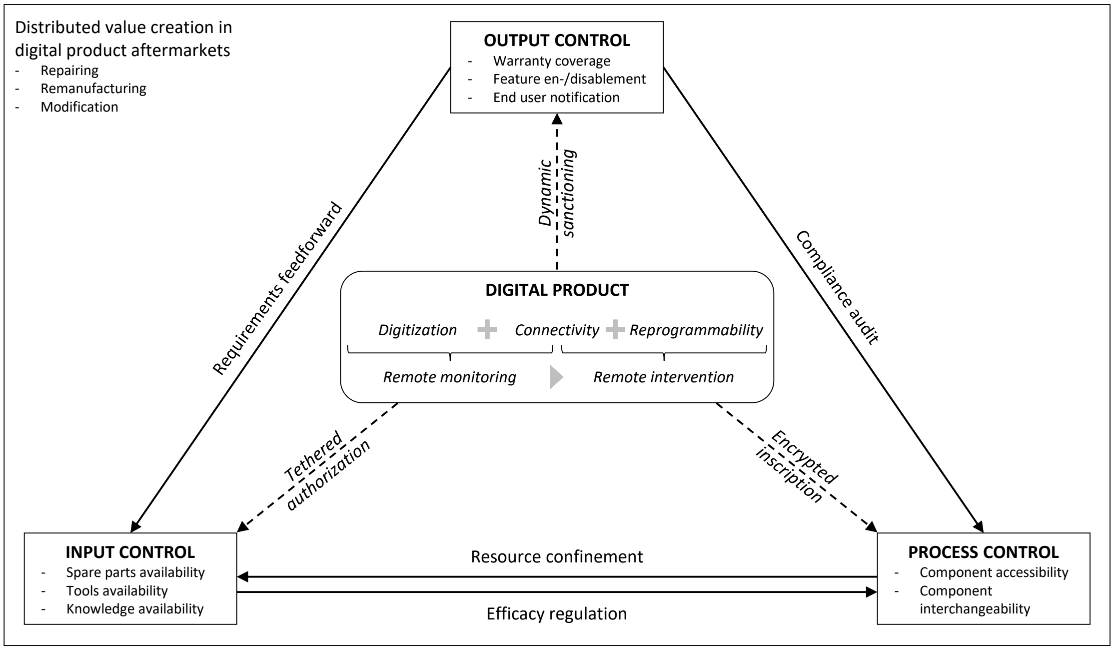
In sum, compared to regulatory output control, digital output control afforded a more effective and efficient compliance audit of authorized and unauthorized repair outcomes. The *digitization* of hardware components (e.g., battery component), the *reprogrammability* of key software components (e.g., firmware), and the product's *connectivity* (e.g., Internet) afforded Apple to *remotely monitor* hardware changes (e.g., unauthorized aftermarket display replacement) and *remotely intervene* at will (e.g., flashing an on-screen notification informing about the non-original aftermarket display).

6.5 Discussion

While much of the attention to digital technology is directed at how infused digital capabilities change the substance and function of economic products (Fichman et al. 2014; Lyytinen et al. 2016), our attention is focused on the question what happens with these digital products after they have been sold, and in particular whether and how the digitalization of products enables new forms of control on aftermarkets, an area largely void of empirical or theoretical knowledge.

6.5.1 Digital Product Aftermarket Control

Our study provides a substantial foray toward understanding control on digital product aftermarkets. Moreover, the picture that emerges from our study is decisively different from the ones we find in the current control literature where input, process, and output control are mostly viewed as three independent, orthogonal choices of control (Ouchi 1979; Wiener et al. 2016), which are not tightly linked to the products themselves. We find these views to be superseded by current reality in which three main digital capabilities of economic products (digitization, connectivity, and reprogrammability) spawn two new relevant control capabilities, remote monitoring and remote intervention, which both enable and synchronize input, process, and output control, making the enactment of product aftermarket control digitally augmented, interdependent, and folded into a holistic, self-reinforcing, and potentially discriminatory portfolio of control. Figure 15 captures our insights in a model that explains how digital products enable new forms of aftermarket control.



Concept	Definition
***Control mode**: Control target in the value creation process*	
Input control	A-priori regulation of the availability of relevant resources for value creation
Process control	Ad-interim regulation of the procedure for value creation
Output control	A-posteriori regulation of the outcomes of value creation
***Blended control portfolio:** Reinforcing relationships between control modes*	
Resource confinement	The definition of relevant resources for value creation through the prescription of the value creation procedure
Efficacy regulation	The modulation of the effect of process control through the availability of relevant resources for value creation
Compliance audit	The review of the conformance with the prescribed procedure for value creation
Requirements feedforward	The corrective information for future regulation of availability of relevant resources for value creation
***Digital product:** A product consisting of hardware and software components with digital product properties*	
Digitization	The encoding of analog information into digital format
Connectivity	The ability to link multiple, sometimes spatiotemporally dispersed, social or technical entities via information transmission infrastructure
Reprogrammability	The ability of being accessible and modifiable by a software program other than the one governing its own behavior
***Digital augmented control:** Enabling new forms of aftermarket control through digital product properties*	
Remote monitoring	The ability to observe actions without the necessity of being spatiotemporally present

Remote intervention	The ability to interfere in actions without the necessity of being spatiotemporally present
Tethered authorization	The individualized online authorization of access to relevant resources for value creation
Encrypted inscription	The tamper-resistant encoding of rules and procedures for value creation embodied in software components of product architectures
Dynamic sanctioning	The temporally delayed and recurrent regulation of outcomes of value creation

Figure 15. A model of digital product aftermarket control

6.5.1.1 Blended Control Portfolio

Our first key insight is that in digital product aftermarkets, all three control modes—input, process, and output control—occur together and interact with one another, resulting in a blended portfolio of enacted aftermarket control.

First, input control is interwoven with process control through two mechanisms, resource confinement and efficacy regulation: Inscribing rules and procedures in product components (process control) restricts which parts or tools can be used to modify the product. This informs the decision about which resources are actually relevant to regulate in the first place (input control)—a mechanism we label *resource confinement*. For instance, fixing two components with a special screw renders the corresponding screwdriver a necessary resource for disassembly. In digital products, OEMs no longer inscribe rules and procedures only in hardware components, but increasingly draw on software components to carry digital process controls. Non-digital resources, such as spare parts and tools, will no longer suffice to comply with digital process controls. For instance, as Apple introduced a digitally serialized fingerprint sensor in the iPhone 5S, they had to ensure that IRPs were still able to replace the home button component holding the sensor. To that end, Apple rolled out a digital calibration tool to IRPs, which would run a software-based calibration to pair the replaced fingerprint sensor with the motherboard again, a couple of months before the release of the iPhone 5S.

Regulating the availability of relevant resources (input control) essentially modulates the effectiveness of the inscribed rules and procedures (process control) by constraining or expanding the available options for carrying out repair, remanufacturing, or customization. We label this mechanism *efficacy regulation*. Efficacy regulation is not dependent on product digitalization, however, the infusion of products with capabilities for digitization and connectivity renders efficacy regulation more feasible. For example, Apple initially controlled the availability of physical repair parts and tools through regulatory means of control, such as exclusive dealing contracts with IRPs. This regulatory control of physical resources, however, was quickly circumvented. Physical resources were too easy to copy. As a result, Apple implemented digital components promising greater tamper-resistance. Since then, new iPhone launches carried repair rules not only in hardware but also in software, rendering physical repair tools—and unauthorized circumventions—ineffective. Thus, software tools became the new instrument to regulate the efficacy of digital process control.

Second, output control is interwoven with both process and input control, through compliance audit and requirements feedforward: While compliance with the prescribed rules and procedures typically cannot be observed during aftermarket value creation (process control), the regulation of the outcomes of value creation (output control) can be used as a form of deferred conformance review—a mechanism we label *compliance audit*. In product aftermarkets, this audit can be performed 'by hand' or in a digital manner. For instance, every repair service at IRPs or ARPs starts with a visual inspection of the iPhone. Thereby, unauthorized value creation, which might have happened weeks or months before, can be identified, allowing Apple to sanction non-compliance (e.g., by voiding warranty coverage). While patent filings show that Apple even looked into possibilities to ease this manual compliance audit through tamper-resistant labels detecting device openings (Hughes 2009), it eventually went for a digitally enabled compliance audit that relies on the digital serialization of hardware components. Any repair service provider without access to calibration software will eventually produce a repaired device that does not contain matching serial numbers between the components, which allows Apple to sanction unauthorized, non-compliant value creation by means of an iOS update at any time.

The monitoring of authorized and unauthorized outcomes of aftermarket value creation (output control) informs the future regulation of the availability of relevant resources (input control)—a mechanism we label *requirements feedforward*. Before 2013, Apple observed a growing number of devices with stripped-off displays, replaced with aftermarket copies. Subsequently, Apple changed its aftermarket strategy from unit replacement to unit repair, which required the provision of appropriate repair parts, tools, and knowledge to authorized repair shops. While the digital infusion of their products renders the feedforward mechanism more responsive, it also allows Apple to improve the quality of its own authorized repairs as well. Any authorized repair runs through an automated final software check capturing and forwarding relevant repair information to Apple headquarters.

In sum, our model suggests that in digital product aftermarkets, input, process, and output control modes not merely add on to each other but also share qualitative dependencies (resource confinement and efficacy regulation) and sustain each other over time (compliance audit and requirements feedforward). They are simultaneously enacted and interact independently. Thus, our model conceptualizes digital product aftermarket control in a *strong holistic* way (Cardinal et al. 2017; Kreutzer et al. 2015), which contrasts much of control research that approached organizational phenomena from a singular control perspective (Cardinal 2001; Ouchi 1979; Ouchi and Maguire 1975).

This holistic conceptualization of a blended control portfolio makes room for two insights to emerge from the data: First, **the interactions between control modes create dynamics** (Wiener et al. 2016) in digital product aftermarket control. These dynamics occur both in short and long-term. Short-term dynamics occur through the interdependent alignment between process and input control. For instance, the release of a novel product with new inscribed rules and procedures for aftermarket value creation (process control) might trigger the adaptation of appropriate input controls in the short-term. Long-term dynamics occur in the relationship between output and input control. Here, output control acts as an audit and learning process which senses the environment (e.g., unauthorized value creation) and feeds forward corrective information triggering an adaptation of future input controls. These dynamics can lead to a constant reconfiguration of the control portfolio resulting in a *self-reinforcing control regime*.

Second, the dependencies between control modes permit the **simultaneous enactment of coercive and enabling control styles** (Cardinal et al. 2017; Wiener et al. 2016). While coercive control styles aim at the conformity of the controlee with the controller's objectives through constraining and forceful actions, enabling control styles seek to support the controlee through guidance and capacity (Adler and Borys 1996). Previous literature has assumed one control style to dominate in organizational settings (Wiener et al. 2016). Our findings show that in digital product aftermarkets both control styles can occur simultaneously. In particular the interplay between input and process control facilitates the simultaneous enactment of coercive and enabling control: First, the inscription of rules and procedures into the product architecture (process control) constrains the options for action to create aftermarket value (coercive control style). Then, the regulation of the availability of appropriate resources (input control) re-expands the constrained option space (enabling control style). If the simultaneous enactment of both control styles purposefully differentiates between two groups of controlees, such as ARPs and URPs, the blended portfolio of product aftermarket control can result in a *discriminatory control regime*.

6.5.1.2 Digital Augmented Control

Our second key insight is that *digital product properties* are relevant to aftermarket control because they enable new control capabilities that qualitatively change the way input, process, and output control can be enacted.

Our findings indicate that three digital properties play an essential role in digital product aftermarkets: Digitization, connectivity, and reprogrammability. With economic goods being infused with these three properties, two digital product-level control capabilities become available: *remote monitoring* and *remote intervention*. Remote monitoring recognizes that digitized and connected primary products enable OEMs to monitor aftermarket value creation without the necessity of being spatiotemporally present. With the introduction of software-based diagnosis and calibration tools, Apple can remotely monitor the access and use of such tools. Remote intervention recognizes that connected and reprogrammable primary products enable OEMs to interfere in digital product aftermarket value creation without the necessity of being spatiotemporally present. Apple can regulate the outcomes of unauthorized value creation through enabling or disabling certain product features remotely via software updates.

Remote monitoring and remote intervention are two new key concepts that help us reconcile an apparently contradictory relationship between seminal control theory (Cardinal 2001; Ouchi 1979) and our empirical observations of control in a digital product aftermarket. In traditional, non-digital product aftermarkets, primary products usually leave the OEM's direct sphere of influence once they have passed the point-of-sale and tend to reappear—if at all—in case of warranty claims. This renders the observability or measurability of aftermarket value creation a challenging endeavor. Consequently, control theory would not expect any process and output control to be salient and instead argue for a preferred enactment of input control, that is, via regulation of resources that remain within the OEM's sphere of influence (Wiener et al. 2016). However, our findings not only show that process and output controls are prominent in digital product aftermarkets but also explain that both control modes fundamentally rely on the digitally enabled control capabilities to remotely observe and intervene in aftermarket value creation. Thus, product digitalization yields new digitally enabled control capabilities, which makes all modes of control applicable to contexts that have traditionally been hard to observe and intervene in, such as distributed value creation in product aftermarkets because of the spatiotemporal segmentation of sales and use.

Remote monitoring and remote intervention augment traditional product aftermarket control in three ways. First, remote monitoring and remote intervention facilitate individualized enactment of input control. In our case, the digital infusion of repair parts (e.g., digitized serialization of components) and tools (e.g., software diagnostics) allows OEMs to selectively authorize the access and use of these resources in near real-time. We, therefore, refer to this digital augmented input control as *tethered authorization*: selected value creators are granted access to key resources; however, their use is constantly monitored. In comparison to traditional input control in product aftermarkets, enacted via exclusive supplier contracts or public law enforced by regulatory institutions (e.g., US Customs and Border Protection enforcing trademark law), the digital regulation of the availability of key resources for value creation can be enforced in a more efficient, targeted, and immediate manner.

Second, digitally enabled remote intervention facilitates a more tamper-resistant enactment of process control due to the way rules and procedures are digitally inscribed into the primary products. Non-digital process control has traditionally been enacted through physical means, as when OEMs inscribe rules and procedures for aftermarket value creation by gluing or welding hardware components together. In contrast, digital process control is inscribed into software components, enabling an additional encryption step (e.g., encrypted serialization of the battery since iPhone X). We refer to this digital augmented process control in product aftermarkets as *encrypted inscription*. As encryption protects more against attempts of reverse engineering than physical inscription, digital process control can be enforced in a more effective and sustained manner than non-digital process controls.

Third, remote monitoring and remote intervention facilitate a dynamic enactment of output control. For instance, the software-based serialization of hardware components and the possibility to release iOS updates afforded Apple to remotely observe hardware changes and remotely intervene at will (e.g., on-screen notification informing about non-original aftermarket display). In comparison to non-digital output control in product aftermarkets, such as the human-based visual inspection in Apple Stores, the digital form renders output control more dynamic as it can not only be enacted in a temporally delayed but also recurrent manner: On day one after repair, a product's restored functionality is available; on day two, it is disabled; on day three, it is available again (similar events happened during Apple's iOS 11 update journey in September 2017). We refer to this digital augmented output control in product aftermarkets as *dynamic sanctioning*.

In sum, our theoretical model suggests that digital product properties enable OEMs to pursue all three control modes to manage their product aftermarkets and design an interactive and blended control portfolio. Thereby, digital product properties potentially catalyze the instigation of self-reinforcing and discriminatory control regimes in digital product aftermarkets. First, digitally enabled remote monitoring and intervention can accelerate the self-reinforcing speed, with which aftermarket control portfolios reconfigure and adapt to remotely sensed events, such as unauthorized value creation (digital output control). Second, digitally enabled remote monitoring and intervention render discriminatory control more effective as the joined enactment of encrypted inscription of aftermarket rules (digital process control) and the tethered authorization to key resources (digital input control) is a powerful practice with the potential to exclude unwanted value creators from aftermarket competition.

6.5.2 Implications for Research

Our study of digital product aftermarkets contrasts several existing assumptions in control literature. First, our findings show that **process and output control can be enacted in settings of distributed value creation**. This implies that the observability and measurability of value creation is not necessarily contingent on the spatiotemporal presence of a human controller in the controlee's environment—a dominant assumption in organizational control research primarily arising from empirical support for the limited use of process control in outsourced projects (Choudhury and Sabherwal 2003; van Fenema 2002). Instead, our model proposes that observability and measurability of value creation can be achieved through digital technology affording remote monitoring capabilities. Abilities for remote monitoring have recently received increased attention also in other IS research streams, such as smart work (Hafermalz 2020; Leonardi and Treem 2020) or health surveillance (De Moya and Pallud 2020; Riemer et al. 2020). However, many aspects remain unclear in this regard, including the limits, antecedents, and (unintended) effects of remote monitoring capabilities. Not everything can be remotely monitored, not everything should be remotely monitored.

Second, our findings show that **not all enacted controls are necessarily complied with**, especially in settings of distributed, non-hierarchical value creation. In our case, URPs have several times been successfully resisting controls enacted by Apple. This implies that control enactment is not a deterministic but dynamic, dialectical, and open-ended process unfolding between controllers and controlees (Wiener et al. 2016)—an assumption that so far has received relatively scarce attention (Chua et al. 2012; Gregory et al. 2013; Heiskanen et al. 2008). We argue that to understand the unfolding of control in complex systems, scholars must engage more explicitly with these dynamic and dialectical processes. One approach to this engagement is to differentiate between attempted and realized control enactment (Tiwana and Keil 2009; Wiener et al. 2016). Some attempted controls do realize; others do not. Depending on the controller's and controlee's capabilities to enact and resist controls, respectively, control consequences tend to converge either in favor of the former or the latter. Our study shows that these capabilities are fundamentally influenced by digital properties vested in the product, on which the to-be controlled value creation takes place.

Eaton et al. (2015)observed in their study of the evolution of Apple's iOS service system that "the power dynamics among actors with different power is balanced by the unique material characteristics [e.g., reprogrammability] of digital technology" (p. 239). We can only partially confirm this argument. Transferred to Apple's iPhone repair aftermarket, Eaton et al.'s (2015)arguments would suggest that the reprogrammability of the iPhone should result in a balanced power landscape between Apple and URPs. This, however, cannot be observed, especially during the last three years of our analyzed time frame. Apple increasingly relies on encrypted flash chips mounted on hardware components (e.g., battery) that hold important serialization data necessary for the successful component replacement. While, per definition, the chip counts as reprogrammable, due to encryption this reprogrammability only holds true for actors with access to appropriate software tools. Therefore, our model of the self-reinforcing evolution of digital product aftermarket control suggests that reprogrammability has a short-term balancing yet long-term centering effect of power dynamics.

Third, our findings show that **the controller's ability to intervene in controlees' non-compliant behaviors cannot be taken for granted**, especially in settings of distributed, non-hierarchical value creation. A controller might be able to remotely monitor non-compliant behavior. However, due to their spatiotemporal distance to the deviant controlee, an intervention might not be feasible. This implies that established antecedents of control, such as observability, measurability, or knowledge of the value creation process (Kirsch 1996; Kirsch 1997), might be insufficient to fully explain the choice of the control portfolio. While extant control literature has collated strong empirical support for the relationships between process observability and the exercise of process control (Choudhury and Sabherwal 2003; Kirsch 1996; Kirsch 1997) as well as between outcome measurability and the exercise of output control (Kirsch 1996; Kirsch 1997; Kirsch et al. 2002), the controller's ability to intervene in non-compliant behavior was so far never under explicit scrutiny. Our model suggests that control intervention can be as important as control monitoring in control enactment. It also highlights how digital product properties enable the controller to remotely intervene through software updates in non-compliant value creation, even if the value was created on hardware-level. We, therefore, recommend future control research to also consider the ability to intervene as a relevant antecedent, especially in settings where the controller is not spatiotemporally located at the controlee's place.

Fourth, our findings show that **coercive and enabling control styles can be enacted simultaneously and selectively**. This finding implies that control can be potentially performed in a discriminatory manner that enables some and disables other controlees—an assumption that so far has received little attention in control research. While both control styles have been explored in literature (Adler and Borys 1996; Gregory et al. 2013), it is commonly assumed that one control style dominates and accounts for all controlees similarly (Wiener et al. 2016). Our model suggests that in particular the interplay between digitally enabled, tamper-resistant input and process controls facilitates a discriminatory control regime. Consequently, and consistent with our case setting, we consider this simultaneous yet selective enactment of both control styles especially tempting for platform owners and ecosystem keystones (Iansiti and Levien 2004) that intend to discriminate the group of potential complementors into authorized and unauthorized ones.

6.5.3 Implications for Practice

Understanding control of digital product aftermarkets carries important implications for the regulation of such markets.

While we note that, with the rise of the digital economy, regulators have expanded their antitrust investigations from brick-and-mortar markets towards digital markets (e.g., Facebook, Google, Amazon) (Holzweber 2018), similar efforts with regards to hybrid markets around digital products remain underrepresented. However, our findings suggest that the digital infusion of everyday consumer products can spawn the instigation of self-reinforcing and discriminatory aftermarket control regimes that, with exclusionary intentions of OEMs, can cause harm to aftermarket competition. Our model highlights that the digitally enabled remote monitoring and intervention capabilities qualitatively change how OEMs can potentially enact restraining activities. Such activities become not only more tamper-resistant and targeted, they also can be carried out with less effort and costs. This insight yields two important implications for antitrust investigations in digital product aftermarkets.

First, restraining activities must not necessarily be only enacted during initial product design. This assumption is common in traditional antitrust investigations where regulators would primarily search evidence for so-called contractual or technical tying arrangements, in which the OEM would condition the sale of the primary product on the purchase of a secondary product or service (Bauer 2007; Holzweber 2018; Yu 2015). As this act was traditionally achieved through contractual agreements or by product design, little attention has been paid to restraining activities beyond the primary product's point of sale. Our findings imply, however, that restraining activities can indeed be enacted via digitally enabled remote intervention capabilities, such as software updates, long after the initial product design.

Second, restraining activities can be enacted dynamically. In contrast to regulators' traditional, static conceptualizations of tying arrangements, technical ties in digital products can vary over time and are less deterministic. Our findings imply that through the digital abilities to remotely monitor and intervene, OEMs can essentially manage important software interfaces in both an exclusionary as well as integrative manner. This, in turn, puts OEMs in a position equipped with unparalleled bargaining power over aftermarket complementors and consumers (Hoofnagle et al. 2019).

Our model also carries implications on how OEMs can use digitally enabled control capabilities to their advantages whilst aligning with principles of competitive markets.

For instance, a key challenge in regulating markets is finding the right balance between safeguarding intellectual property rights and enabling market competition (Stakheyeva 2018). Encrypted inscriptions of digitalized products through tamper-resistant software can both be beneficial to competitive markets and detrimental to monopolized markets. The difference lies in deciding which product component is encrypted and how tamper-resistant encryption is eventually used as a control mean. For example, encryption of security-related software functionality on operating systems or application level can protect against harmful intellectual property attacks. However, the encryption of firmware interfaces may result in anticompetitive moves, such as the restriction of interoperable repair parts and inhibition of possible repair or modification options. Further, our model suggests that tamper-resistant encryption of software rules (process control) and sanctions in response to non-compliance (output control) are interrelated yet distinct practices. Therefore, encryption does not per se lead to interoperable aftermarket components but can also be used for other—societally more beneficial—purposes.

For instance, encryption in combination with digital remote monitoring and intervention capabilities can help tackle fraudulent behavior that might arise from deregulated product aftermarkets. The liberalization of repair aftermarkets can render buying second-hand digital products an increasingly risky endeavor as some actors might use the products' interoperability and accessibility to exchange high-quality with low-quality components and deceptively sell the products as used but original equipment. Digitally enabled remote monitoring (e.g., encrypted serialization of original product components) and intervention capabilities (e.g., automated push notifications) could enable OEMs to offer transparency certificates or similar originality proof instruments to protect against the formation of lemons markets (Akerlof 1978)—a practice, which has been recently pursued by Apple.

6.5.4 Limitations

We carried out inductive positivist research perusing data from a single case, informed by one particular theoretical lens, control. Despite being theoretically informed, one obvious limitation of our study pertains to the external validity of the findings: Our model is substantially grounded in the specific setting of Apple's iPhone repair aftermarket. The nature and structure of other digital product aftermarkets are different. For example, Google, Samsung, and Huawei in the past have been less restrictively using digital controls, and their digital product architecture is different from Apple's (e.g., their products contain more open interfaces). Nevertheless, latest news about Samsung also starting to use serialized displays (Rossmann 2020) indicate that the formal concepts we generated from our analysis of this case provide an abstract analytical lexicon that should be applicable also to other types of digital product or aftermarket structures (Lee and Baskerville 2003).

We also acknowledge that our data might be interpreted differently by other parties. We followed typical guidelines for inductive positivist case study research (Sarker et al. 2018) and exposed our data and emerging concepts constantly to different viewpoints such as those held by Apple versus those held by URPs. Within our team, we ensured reliability of our research approach through maintaining a logical chain of evidence supported by a case study protocol and a central case study database (Dubé and Paré 2003). To increase the internal validity of existing and newly developed concepts, we relied on multiple coders and challenged each other's understanding of the data with rival explanations (Yin 2014).

6.6 Conclusions

Innovative digital products are not only created, sold, and used, but also entertain entire aftermarkets where a variety of actors attempt to create and capture value by modifying, repairing, or customizing primary products. As this setting is receiving increasing attention by policymakers and regulators, it is crucial to understand how OEMs attempt to control how value on aftermarkets is carried out. Our empirical analysis of Apple's iPhone repair aftermarket demonstrates how an understanding of aftermarket control must pay due attention to the different actors and their strategic objectives as well as the evolution and capabilities of the digital components of the products themselves because these enable and augment both new and existing means and modes of control.

Chapter 7

Discussion

In this chapter, I summarize the major contributions of the studies presented and synthesize implications for research and practice that emerge from multiple studies. I point out research limitations that apply at a more general level beyond the individual limitations of each study. I close with an outlook for future research.

7.1 Summary of Contributions

In this dissertation, I explore the relationship between digital technologies and CE from an IS perspective. So far, IS research has addressed the relationship between digital technologies and sustainability, focusing on the design, implementation, adoption, and impact of IS-enabled *energy efficiency* solutions, rather than *resource efficiency* and *material circularity*. Based on the premise that solutions for resource efficiency and material circularity differ from solutions for energy efficiency, I provide a foundation for IS research on digital technologies for a CE—an economic model that seeks resource efficiency and material circularity by narrowing, slowing, and looping material flows—and examine selected phenomena that derive from this foundation.

I conducted four studies. The first study (Chapter 3) serves as a motivation and provides a conceptual foundation in the form of an IS research agenda. The two-part agenda consists of six research topics in which the remaining three studies (Chapter 4, Chapter 5, and Chapter 6) are embedded. Figure 16 visualizes the main contributions of the four studies and shows which research topic of the research agenda the three latter studies start from. In what follows, I will specify the contributions of each study. Please note that study 4 is still under review at *MIS Quarterly* and its contributions should be considered 'expected' and not 'final' in this dissertation.

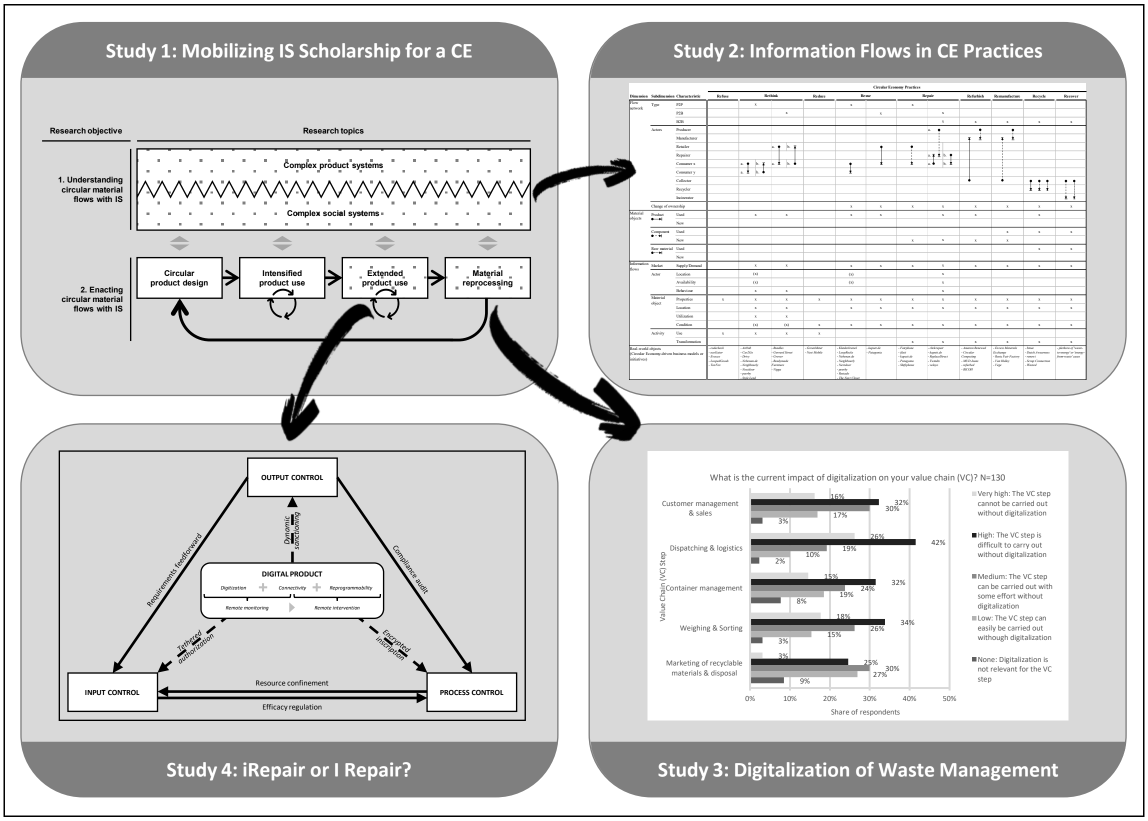


Figure 16. Integrative summary of the four studies within this dissertation

7.1.1 Contributions of Study 1

The goal of study 1 was to outline *how IS scholarship can contribute to CE research* and mobilize future IS research on this topic. It makes the following three main contributions.

First, study 1 introduces the CE idea and key concepts to the IS research discipline. To guide our literature review, we created a framework that combines two concepts from CE literature: PLC stages and CE principles. PLC stages represent different phases that a product and its materials go through, from pre-use (i.e., from idea to delivery of a product), to in-use (i.e., from delivery to end-of-life of a product), to post-use (i.e., from end-of-life to next-life of a product). CE principles, as defined in Chapter 2.1.1, are a set of prescriptive principles that are conducive to the CE strategies of narrowing, slowing, and closing material flows. For our framework, we chose the 3r-framework, which consists of the principles reduce, reuse, and recycle. We consider both concepts—PLC stages and CE principles—and their combination not only relevant to our literature review, but also a helpful guide for future IS research on CE. For example, the PLC concept emphasizes lifecycle thinking and frequently marginalized aspects of a product, such as the origin of its materials or its end-of-life destiny.

Second, study 1 provides an interdisciplinary review of the literature on the relationship between IS and CE and synthesizes its current shortcomings. Compared to the review of Green IS and Green IT literature presented in Chapter 2.2, we used broader and more comprehensive search terms and went beyond AIS journals and conference proceedings. Our results show that the literature reviewed primarily examines IS solutions to increase the efficiency of isolated intra-organizational processes in the pre-use stage. In contrast, IS potentials to slow down and close material loops across all PLC stages have been neglected so far. In addition, our literature review contributes a collection of 102 articles (Appendix B), organized by nine core categories (Appendix C), that address the relationship between IS and CE.

Third, study 1 offers an IS research agenda with research directions focused on IS-enabled solutions for resource efficiency and material circularity. The agenda follows two research objectives that include six research topics. For the first research objective, we propose to develop knowledge on how IS can contribute to *understanding* circular material flows. Our literature review found that implementing reuse and recycle principles involves greater social and material complexity than implementing the reduce principle. We argue that IS are well suited to capture this complexity and help actors make sense of closing the loop of complex product systems (research topic 1) in complex social systems (research topic 2). For the second research objective, we propose to expand our knowledge base on how IS can contribute to *enacting* circular material flows. Specifically, we explored how IS can facilitate the implementation of reuse and recycle principles within and across PLCs by proposing four research topics: circular product design, intensified product use, extended product use, and material reprocessing. We discuss each research topic and pose illustrative research questions that tie into established IS research streams.

7.1.2 Contributions of Study 2

Study 2 aimed to identify *information flows required for the application of CE principles*. From an integrative dissertation perspective, study 2 embeds in the IS research agenda proposed in study 1 by contributing knowledge on which information flows mediate the sociotechnical relationship between complex product systems and complex social systems (Figure 16). Study 2 provides the following three main contributions.

First, study 2 extends the conceptual CE foundation presented in study 1 by introducing a more detailed r-framework consisting of nine CE principles. While the 3r-framework in study 1 was sufficient for the literature review, I opted for a more granular 9r-framework in study 2 because it better reflects specificities among principles that would be classified under the same principle in the 3r-framework. I consider these specificities relevant to the identification of appropriate information flows. For instance, the reuse principle in the 3r-framework splits into four more specific principles in the 9r-framework, all of which address the CE strategy of slowing down material flows by extending the life of products and their components: reuse, repair, refurbish, and remanufacture. While these principles contribute to the same CE strategy, their implementations differ in terms of the actors and material objects involved and therefore require different information flows.

Second, study 2 presents information flows that enable the application of CE principles. I derived these information flows by taxonomizing the nine CE principles along two dimensions: flow networks (i.e., actors with demand and supply requirements that are spatially distributed) and material objects (i.e., physical artifacts, that move through the flow networks and whose lives are extended and intensified by CE principles). Thereby, I was able to deconstruct the underlying complexity of the CE principles by projecting it onto two dimensions. With the taxonomy, I intend to support Green IS and Green IT design science communities in exploring and analyzing the problem-solution spaces that unfold around implementations of CE principles and, in turn, stimulate the design of impactful IS solutions for sustainable production and consumption. To enable broad applicability of the taxonomy, it deliberately resides at an abstract level.

Third, study 2 offers a set of three key roles that IS can play in implementing CE principles. ‘Sensemaking IS’ help individuals and organizations understand past, current, and future production and consumption behavior. ‘Matchmaking IS’ enable individuals and organizations to search, compare, negotiate, and contract material supply and demand requirements. ‘Task support IS’ assist individuals and organizations in complex transformations of material objects (i.e., products, components, or materials) aimed at extending their life. To spur future IS research, I point to existing IS literature streams that seem to be promising theoretical departures for exploring and developing these roles.

7.1.3 Contributions of Study 3

The goal of study 3 was to assess the *status-quo of digitalization by German waste management firms*. It ties in with the second research objective of the research agenda proposed in study 1 by contributing knowledge on the adoption of digital technologies that enable the reprocessing of disposed materials into secondary materials (Figure 16). Waste management firms that collect and reprocess disposed materials play a key role in this context. Study 3 provides the following four main contributions.

First, study 3 provides a snapshot of the actual and planned adoption of digital technologies by 130 public and private German waste management firms. Despite innovative use cases of digital technologies presented in scientific journals and grey literature, the status-quo of digitalization in waste management remains unknown. Existing quantitative studies focus on digitalization intentions and neglect actual adoption levels of digital technologies along the waste management value chain. We therefore surveyed German waste management firms on their current and future digitalization efforts, their digitalization objectives, and their digitalization approaches and measures.

Second, study 3 presents a trend analysis of digitalization efforts compared to reported digitalization intentions from 2016 and 2017. We show that digitalization is becoming increasingly important for waste management firms. More firms feel affected by and actively engage with digital technologies than three to four years ago. However, many waste management firms deal with digitalization only half-heartedly and focus their efforts on the non-exclusive implementation of basic digital technologies with the primary goal of optimizing intra-organizational processes for efficiency. On the contrary, digital technologies are not understood and utilized as innovation drivers for new service offerings or improved recycling rates.

Third, study 3 points out two risks that waste management firms bear if they do not fully exploit the opportunities offered by digital technologies. The complementary but not substitutive use of digital technologies creates parallel worlds of analog and digital solutions, both of which must be managed by waste management firms. We call this ‘the burden of parallel worlds.’ This burden can lead to negative experiences with initial digitalization efforts, thereby, dampening future digitalization intentions. Further, we consider the decision to use digital technologies only as efficiency drivers risky in the face of an increasingly competitive business environment and growing social and legal requirements for waste management. We call this ‘the efficiency optimization limit of digitalization.’

Fourth, study 3 provides the full survey instrument (Appendix G) and invites future research to expand the spatial and temporal scope of the insights. So far, we can only report on and discuss findings that are limited to the German waste management sector. Yet, it would be interesting to see how the actual adoption behavior of digital technologies evolves over time and how it differs to other regions. The openly accessible survey instruments can also be expanded into an annual panel survey that measures digital transformation progress of the waste management sector.

7.1.4 Contributions of Study 4

The goal of study 4 was to investigate *how digital products enable aftermarket control*. It fits into the second research objective of the research agenda proposed in study 1 by providing insights into how digital product properties enable or hinder product lifespan extending principles, such as repair (Figure 16). We adopted a control theory perspective, recognizing that CE principles can potentially be applied by any actor within the lifecycle of a product, and that this set of actors must not always share well-aligned interests, as in the case of unauthorized repair service providers in product aftermarkets. From a CE perspective, the practices of unauthorized repair service providers help extend the lifespan of products. Yet, they do not align with the business interests of OEMs, whose business models are based in part on revenue streams from new product sales and proprietary repair services. Given these diverging interests, we were curious about how digital product properties affect the enforcement of aftermarket control. Consequently, study 4 provides the following three main contributions.

First, study 4 provides a theory of control in digital product aftermarkets. We offer an explanation of how digital product properties facilitate and change modes and means of product aftermarket control. We find that three digital properties (i.e., digitization, connectivity, and reprogrammability) enable two relevant control capabilities (i.e., remote monitoring and remote intervention), which in turn favor the enactment of blended, self-reinforcing, and discriminatory portfolios of input, process, and output control. We consider these enabling mechanisms important as they can shift the power balance toward the OEM, which designs the digital properties into the product and thus has them exclusively available to enact the control portfolio. Actors along the PLC, who do not act in the interest of the OEM therefore potentially face stricter and more tamper-resistant control regimes.

Second, study 4 adds to control theory by challenging some of its established assumptions. We observe that process and output control can be enacted even in settings of distributed value generation. This contrasts with the prevailing assumption that the controller must be physically present to observe and measure the controlee's value generation. We show that physical observability and measurability can be mediated by digital product properties that enable remote monitoring. We also find that not all enacted controls are necessarily complied with. This observation supports the so far widely ignored assumption that control enactment is a dynamic and dialectical process between the controller and the controlee. Lastly, we note that in settings of distributed value generation, controllers cannot always readily intervene in noncompliant behavior of controlees. The spatiotemporal distance between the controller and the controlee makes some interventions infeasible. The controller's ability to intervene has so far not featured as an antecedent to control in literature.

Third, study 4 expands the scope of IS research on digital platform governance and control. To date, scholars have studied governance primarily in the context of software-only platforms, such as Apple's app store or Google's Android OS. We observe that in the context of hybrid product platforms consisting of both digital and physical components, control can be enacted through both digital and physical means. The resulting dialectical control processes between controllers and controlees differ depending on the mean of enactment. While physical control can be circumvented to some extent by controlees, digital control exhibits greater tamper resistance.

7.2 Research Implications

While all four studies make individual contributions, integrative insights across multiple studies emerge. In what follows, I offer a synthesis of these insights and discuss their broader research implications in four parts (Figure 17).

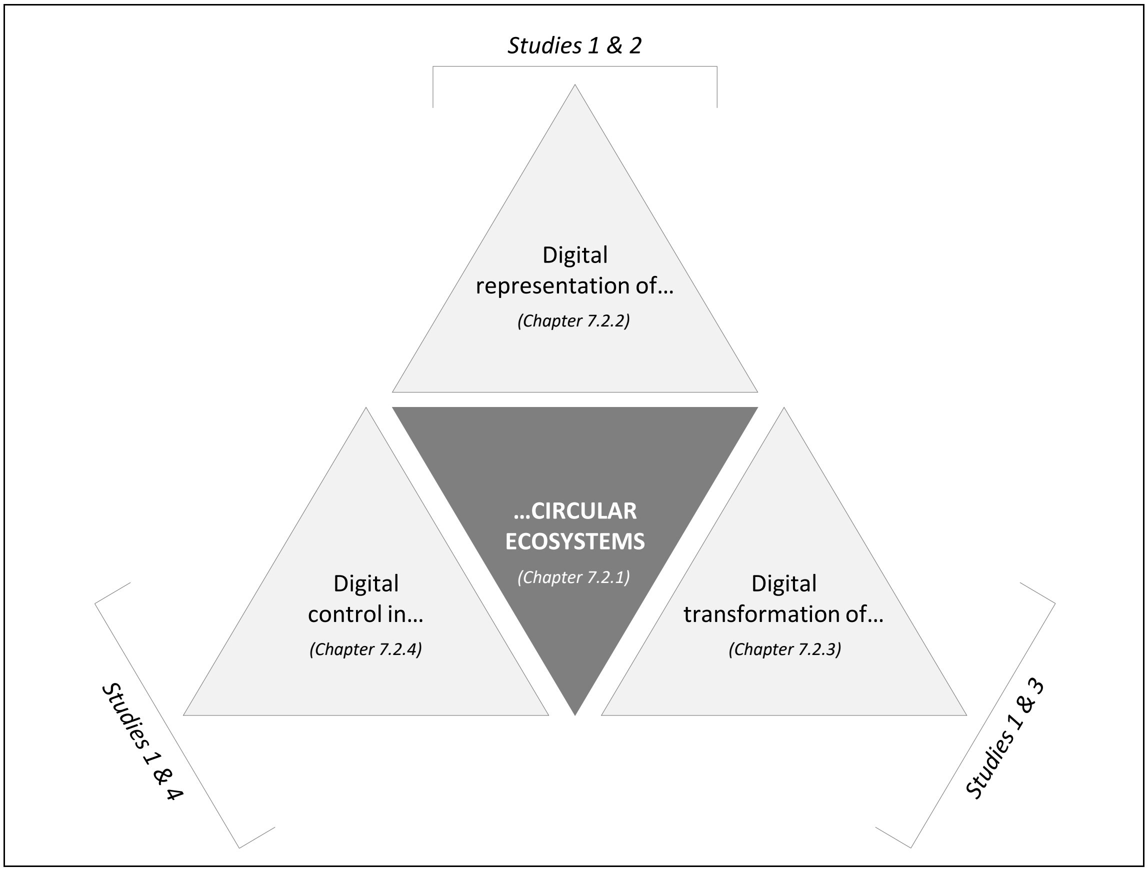


Figure 17. Synthesis of four integrative insights emerging from the studies

7.2.1 Circular Ecosystems

Central to the four insights is the argument that the implementation of circular principle means dealing with complex both social and material systems. Study 1 points out that an intra-organizational or bilateral inter-organizational perspective is insufficient to capture the entire scope of circular material flows as they span supply chains and industry sectors (Chapter 3.4.4).

Our social and material complexity view of CE principles complements recent scholarly considerations of a so-called circular ecosystem perspective (Konietzko et al. 2020). Based on findings from study 1 and study 2, a circular ecosystem can be defined as *a multilateral structure of social actors and material objects that must interact with each other to narrow, slow, and close material flows in an economically viable manner* (Adner 2017; Bocken et al. 2016). It is multilateral in that its structure of interactions cannot be decomposed into a collection of bilateral relationships without compromising its overall value proposition, that is the circular principle the ecosystem plans to realize (Adner 2017). An ecosystem perspective differs from other perspectives, such as the intra-organizational resource-based view (Wernerfelt 1984) or the inter-organizational supply chain perspective (Chopra and Meindl 2013), as it considers relevant actors beyond the boundaries of organizations and direct business partner. Central to a circular ecosystem perspective is the understanding that circularity of material flows is considered a property of a sociomaterial ecosystem rather than a property of resources, products, or business models (Konietzko et al. 2020).

From the taxonomized flow networks in study 2, we know that a circular ecosystem's structure depends on the circular principle being realized and that its complexity can vary depending on the deliberate intent of the researcher or practitioner conceptualizing and making sense of the ecosystem. For instance, a simple repair ecosystem includes different social actors (e.g., consumer, repair service provider) than a simple recycling ecosystem (e.g., consumer, waste collector, waste recycler). Further, a simple repair ecosystem becomes more complex when more social actors are considered, such as authorized and unauthorized providers of repair tools, spare parts, and services (cf. study 4).

This widened social perspective challenges seminal literature on business ecosystems, which focuses predominantly on leaders (Moore 1996), keystones (Iansiti and Levien 2004), or brokers (Gawer and Cusumano 2002). This focus has fostered the assumption that primarily large and financially powerful social actors, such as OEMs, are able to orchestrate an ecosystem. The CE literature also reflects this assumption, as it tends to take an OEM-centric perspective and marginalize less dominant social actors, such as third-party service providers, that can play an important role in the success of the overall circular ecosystem (Konietzko et al. 2020). This bias is particularly problematic for CE research, as CE principles challenge OEMs' linear business models (Kalverkamp and Young 2019). For example, extending the life of a product through repair threatens the sales-based business model of an OEM. As a result, large and financially powerful actors may have no incentive to initiate and orchestrate circular ecosystems. I argue that a more complex circular ecosystem perspective that recognizes the underlying complex social systems (Chapter 3.5.1.2) can help bring marginalized social actors into focus.

Furthermore, business ecosystems have largely been understood as social constructs centered on social actors (Adner 2017; Moore 2006). However, following the concept of complex product systems from study 1 (Chapter 3.5.1.1) and the concept of material objects from study 2 (Chapter 4.4.2), the material fabric of a circular ecosystem structure should be considered as similarly important as its social fabric. Therefore, a circular ecosystem depends not only on social interactions, such as business partnerships, but also on material interactions, such as a physical product architecture whose composition either promotes or prevents repair, remanufacturing, or recycling, and the interactions between material objects and social actors (Leonardi 2011). For instance, a repairer must know and master the decomposability of a product architecture in order to successfully restore a broken product by replacing components. Thus, material and sociomaterial extensions to the current social conceptualization of business ecosystems is critical to making a circular ecosystem perspective useful in CE research.

In synthesis, the circular ecosystem view, which encompasses complex social and material systems, reveals interesting aspects of the relationship between digital technologies and CE. It challenges assumptions of established IS research knowledge that has primarily emerged from less complex intra-organizational or bilateral inter-organizational contexts. In the following chapters, I discuss three of these challenged assumptions based on key insights from the studies presented in this dissertation: digital representation, digital transformation, and digital control in circular ecosystems.

7.2.2 Digital Representation of Circular Ecosystems

In study 1, we argue that "IS can help actors comprehend and accommodate the social and material complexities that unfold around [circular ecosystems]" (Chapter 3.5.1). This assertion is based primarily on two observations: First, technical and economic advances in digital sensor technologies are equipping IS with new capabilities for tracking and tracing material flows. Second, we note that the representation of real-world phenomena is one of the core purposes of IS (Wand and Weber 1995) and that IS research can build on and extend representation theory to contribute digital solutions and new knowledge (Burton-Jones et al. 2017). While we discuss in study 1 the challenges of digitally representing complex product systems (Chapter 3.5.1.1) and how these digital representations need to be disseminated throughout the circular ecosystem to ensure effective decision support (Chapter 3.5.1.2), three implications deserve further attention.

First, the social complexity of circular ecosystems challenges traditional assumptions of representation theory. As Recker et al. (2021) point out, the conceptual modelling of real-world phenomena—the 'design' of digital representations—has traditionally been a professional activity within intra-organizational work settings. In circular ecosystems, however, a variety of actors beyond the intra-organizational boundaries must collaborate to narrow, slow, and close material flows. While study 2 proposes general information flows needed to implement CE principles, information requirements, perceptions of the real-world phenomenon, and interpretations of the digital representation of the real-world phenomenon vary within the heterogeneous set of social actors involved in circular ecosystems (Allen and March 2006); they may even change dynamically over time. If the core purpose of an IS is to represent "someone's or some group's *perception* of the real-world system" (Wand and Weber 1995, p. 206), the question remains as to which actor from the circular ecosystem will take the lead in articulating its perception to design the IS. Further, if the flow and transformation of materials in a circular ecosystem is hardly predictable, it remains unclear who can and must participate in the conceptual modelling of circular material flows.

Second, digital representations of circular ecosystems bring into focus an issue that has received little attention in original representation theory: data generation and availability. Despite the insight that “the faithfulness of a representation is a product of the underlying deep structure and the tokens that populate it” (Burton-Jones and Grange 2013, p. 638), extant literature focuses on the deep structure and neglects the origin of data (i.e., tokens). While scholars debate the advantages and disadvantages of class-based and instance-based designs of the IS deep structure (Lukyanenko et al. 2019; Parsons and Wand 2000), they insufficiently consider the design of the IS surface structure that captures and generates the data in the first place. It remains unanswered how this generational process, which is influenced by the design of the IS surface structure, effects the faithfulness of a representation. As pointed out in study 1, this question is particularly relevant in circular ecosystems where data generation is difficult, availability is poor, and sharing is restricted due to heterogeneous and complex social and material structures.

While study 2 suggests relevant information flows for implementing CE principles, it also ignores the question *how* to collect the required data. In this regard, I argue that tracking and tracing of material flows across re-composable product, component, and raw material levels is an issue of technical, economic, and social constraints. Technically, hardware properties (e.g., size, durability, power requirements) limit the sensing capabilities of sensors (e.g., low spatial and temporal resolution of the sensed phenomenon). Economically, the cost of designing and operating a high-resolution sensor system may still outweigh its representational benefits, despite declining hardware costs. Socially, tracking and tracing of material flows beyond organizational boundaries raises data privacy issues. Consequently, extending existing representation theory literature, I argue that the perceived faithfulness of digital representations of a circular ecosystem depends not only on the role of the modeler (Recker 2010) or the user’s prior knowledge of the phenomenon (Bera et al. 2014; Burton-Jones and Meso 2008) but also on technical, economic, and social constraints imposed by the physical and surfaces structures of the IS (e.g., sensor system). This argument supports recent literature on the blurring boundaries between the different structures of an IS (Recker et al. 2021).

Third, in addition to technical, economic, and social issues of capturing data for digital representation, implications with regard to e-waste generated through sensor technologies should not be neglected. E-waste includes electric and electronic equipment, from large household devices (e.g., refrigerators) to small consumer electronics (e.g., smartphones) and sensor devices (e.g., RFID chips), that have reached their end-of-life (Widmer et al. 2005). While literature on the benefits of sensor technologies for a CE—including our studies 1, 2, and 3—is growing (Awan et al. 2021; Kristoffersen et al. 2020; Sarc et al. 2019), the environmental impacts of the required digital infrastructure in terms of energy and material consumption as well as e-waste remain comparatively under-researched. Therefore, I call not only for greater data availability and a faithful digital representation of material flows, but also for balanced approaches that consider the environmental impacts of the digital sensor systems required to generate these data.

7.2.3 Digital Transformation of Circular Ecosystems

Study 3 presents the status-quo of digitalization in German waste management firms; a contribution which puts into perspective previous research and debates on what is 'digitally possible' in waste management, such as real-time container filling monitoring or AI-based waste sorting (Anagnostopoulos et al. 2017; Rovetta et al. 2009; Shah et al. 2018). Our findings show a gap between what waste management firms reported as adoption intentions in 2016/2017 and the actual state of adoption in 2020. In particular, the actual adoption of advanced digital technologies that go beyond merely optimizing the efficiency of internal business processes falls short of reported adoption intentions.

These findings are not only a snapshot of the current and planned digitalization efforts of the German waste management sector. They also have research implications with regard to our broader understanding of the digital transformation of circular ecosystems, that is large-scale sociotechnical systems. This knowledge has so far been developed mainly in the digital transformation (Vial 2019; Wessel et al. 2021) and information infrastructure literature (Tilson et al. 2010).

The findings from study 3 show that current digitalization efforts of many waste management firms are more akin to an IT-enabled organizational transformation than a digital transformation. Digital transformation is the use of digital technology's computing, communication, and connectivity capabilities to (re-)define a value proposition and identity of an organization, industry, or society (Vial 2019; Wessel et al. 2021). However, current digitalization efforts in waste management focus on optimizing the efficiency of intra-organizational business processes (Vial 2019). This reinforces existing value propositions and organizational identities (i.e., IT-enabled organizational transformation) but does not redefine them (i.e., digital transformation) (Wessel et al. 2021). Consequently, I argue that current digitalization efforts risk perpetuating and solidifying existing value creation structures of the waste management industry. As discussed in study 3 under the notion of 'the efficiency optimization limits of digitalization,' this perpetuation and solidification can prevent a more profound transformation of the waste management sector, which is necessary in light of increasing regulatory, societal, and economic demands (Mavropoulos and Nilsen 2020).

The research context of study 3—and the digital transformation of circular ecosystems in general—challenge the theoretical boundaries of digital transformation knowledge. So far, the majority of digital transformation research adopts an organization-centric perspective (Hess et al. 2016; Matt et al. 2015; Wessel et al. 2021; Westerman and Bonnet 2015). As an exception, Vial (2019) offers a definition of digital transformation that goes beyond the organization including industries and societies. Wessel et al. (2021), however, argue against such a wide-scale, "blurry and hard to grasp" (p. 105) conceptualization. They propose a process model of digital transformation that hinges on organizational identity as a key concept. I question the explanatory power of organization-centric knowledge of digital transformation for the digital transformation of circular ecosystems. For instance, it begs the question if and how organization-centric concepts, such as organizational identity or organizational purpose, transfer to an ecosystem context: Who defines the identity and purpose of a circular ecosystem? How does it evolve? What mechanisms are at play when digital technologies are designed and adopted in an ecosystem? In sum, I interpret these boundaries as a call for research that connects organizational-level mechanisms to ecosystem-level mechanisms.

Partial answers to the above questions can be found in the information infrastructure literature. An information infrastructure is "a shared, open (and unbounded), heterogeneous and evolving socio-technical system […] consisting of a set of IT capabilities and their users, operations and design communities" (Hanseth and Lyytinen 2010, p. 4). An information infrastructure perspective is helpful when dealing with interconnected system collectives rather than stand-alone applications that dynamically evolve over several years (Henfridsson and Bygstad 2013).

On the one hand, study 3 confirms the information infrastructure literature by highlighting that the digital transformation of the waste management sector is largely dependent on the digital adoption behavior of both waste managers and waste producers. This is consistent with the first of Henfridsson and Bygstad's (2013) three generative mechanisms—adoption, innovation, and scaling—that explain the evolution of information infrastructures. Consequently, I argue that for circular material flows, where waste materials are reprocessed into reusable secondary materials, the digital adoption behavior of waste recyclers and secondary material re-processors—both actors not covered by the survey in study 3—is similarly important. The subsequent innovation and scaling mechanisms suggested by Henfridsson and Bygstad (2013), were not observed in findings from study 3.

On the other hand, the implications of study 3 expand the information infrastructure literature by bringing into focus the duality of analog and digital infrastructures that plays out during digital transformations. Based on the insights of study 3, I argue that during the digital transformation of incumbent, largely non-digital infrastructures, analog and digital infrastructures can evolve in parallel and influence each other. So far, the literature on the evolution of information infrastructures has focused on digital-only infrastructures, such as the IT landscapes of an airline carrier (Henfridsson and Bygstad 2013), a hospital (Bygstad and Øvrelid 2020), or a region's healthcare system (Rodon Modol and Eaton 2021). These studies neglect the role of analog infrastructure, which evolves in parallel with digital infrastructure, and disregard interactional effects between the two. That this duality is relevant, however, is shown in Barrett et al. (2012), who discuss how the materiality of analog infrastructure influences the digital transformation of a hospital pharmacy. Such influences are also evident in the findings from study 3, where waste management firms reported that the analog infrastructure of their customer base exerts a delaying effect on the digitalization of their own infrastructure. Similarly, the materiality of the analog container infrastructure poses a challenge to the collection of relevant data, such as real-time filling levels. In sum, I interpret the findings from study 3 as a call for a more hybrid—analog and digital—research approach to studying the digital transformation of circular ecosystems.

7.2.4 Digital Control in Circular Ecosystems

Study 4 proposes a new theory of control in digital product aftermarkets. It explains how digital product properties (i.e., digitization, connectivity, reprogrammability) can change the enactment of control modes (i.e., input, process, and output control), thereby enabling controllers to design blended, self-reinforcing control portfolios that can discriminate between controlees. In study 4, we discuss the research implications for two established research streams: control theory and digital platform governance.

The findings in study 4 update existing assumptions of control theory. First, they expand our understanding of the antecedents of control in terms of their spatiotemporal dependencies. Digitally enabled remote monitoring and intervention capabilities mean that the three established control antecedents—observability, measurability, and enforceability (a so far widely overlooked antecedent)—are no longer spatiotemporal attributes requiring the physical presence of the controller in the controlee's environment, but can be carried out as long as the product architecture is digitized, connected to the internet, and reprogrammable. Second, study 4 shows that the digitization and connectivity of the product architecture enables discriminatory control that distinguishes between authorized and unauthorized value contributors. This can be achieved by encrypting digital components in the product architecture (i.e., limiting the architecture's malleability) and by providing tethered authorization of selected controllers to relevant software tools for decryption (i.e., expanding the architecture's malleability).

The findings in study 4 contribute to the literature on digital platform governance. First, they "widen [the] scope of digital platform research" (de Reuver et al. 2018, p. 129) by expanding the current software focus to the complete layered-modular architecture of digital platforms (Yoo et al. 2010). While IS scholars have previously focused on software artefacts, such as Firefox' web browser (Tiwana 2015) or Google's Android OS (Karhu et al. 2018), study 4 reveals dependencies between hardware and software layers that influence how tightly or loosely coupled product architecture components are. These dependencies provide new control points for platform owners to define how and what value can be generated by third-party contributors. Second, study 4 complements research on the dialectic of control in digital platforms (Eaton et al. 2015; Karhu et al. 2018) by highlighting the shifting of power dynamics to the advantage of the platform owner. While Eaton et al. (2015) argue that "the power dynamics among actors with different power is balanced by the unique material characteristics [e.g., reprogrammability] of digital technology" (p. 239), the findings in study 4 suggest that reprogrammability has a short-term balancing but long-term centering effect of power dynamics in favor of the platform owner, as the power to encrypt digital components and thus tighten control points remains with the platform owner.

The findings from study 4 also have broader research implications for digital control in circular ecosystems. First, digital dependencies between product components increase the complexity of digital product architectures, affecting component de- and re-composability. Circular ecosystems aiming to slow material flows through repair or remanufacturing are thus challenged by additional hybrid—material and non-material—complexity of digital products. The non-material properties of digital dependencies, such as their non-observability to the naked eye, require specialized knowledge and tools to make the dependencies visible and adaptable, hampering repair or remanufacture. I argue that the infusion of digital dependencies into the product architecture raises the barriers to repair and remanufacture for both laypeople and professionals without specialized knowledge and access to software tools, even in markets for repair and remanufacturing that have existed for several decades, such as the automotive industry.

Second, digital dependencies create new control points for OEMs of digital products that can promote or jeopardize the development of circular ecosystems. On the one hand, digital control offers OEMs the opportunity to centrally govern value creation in circular ecosystems (e.g., repair, remanufacturing, recycling). In this course, it can be argued that digital control capabilities help to increase the quality and reliability of circular ecosystems in an efficient manner, with the OEM assuming extended producer responsibility. For instance, study 4 indicates that digital control can ensure the use of authorized spare parts and tools, reduce spare parts logistics costs, and support remote quality management systems. On the other hand, digital control has the potential to exclude third-parties from contributing to a circular ecosystem. Nevertheless, these third-parties can play an important role in circular ecosystems as long as OEMs do not feel obligated to assume extended producer responsibility. As outlined in the conceptualization of circular ecosystems, sales-based OEMs may not be supportive of unauthorized circular ecosystems that unfold around their digital product.

Therefore, it remains unclear when and how digital control is beneficial or detrimental in a circular ecosystem; especially, when economic and environmental outcomes do not align. From the perspective of a for-profit business model, digital control can be environmentally beneficial, if it simultaneously allows OEMs to capture untapped financial returns beyond the point of sale by monetizing additional customer services, such as repair or recycling. However, digital control can become an environmental threat if it is used against environmentally sound third-party rent extraction from opportunities that would otherwise be neglected by OEMs. Metaphorically speaking, I refer to these latter situations as symbiotic relationships, where third-parties generate additional value from outputs—or leftovers—of the activities of other actors. This metaphor fits well with an ecosystem perspective. In sum, while study 4 adds to our understanding of how digital capabilities enable new forms of spatiotemporal independent control modes, we know little about how digital control plays out in sociotechnically complex circular ecosystems.

7.3 Practical Implications

In addition to the research implications already discussed, the four studies in this dissertation have several practical implications, some of which have already been highlighted in the studies themselves and thus are not repeated here.

In general, the findings from this dissertation suggest that the relationship between digital technologies and a CE can be a fruitful one. Yet, the social and material complexities of circular ecosystems must be considered when designing, implementing, and operating digitally enabled circular principles. The following practical implications address incumbent enterprises, digital CE start-ups and technology providers, and regulators alike.

First, the findings from study 1 and study 3 suggest that **incumbent enterprises** tend to employ digital technologies to optimize their linear business processes instead of transforming towards circular business models. This tendency to optimize efficiency risks a perpetuation and solidification of existing linear value creation structures. I suggest that this development can be countered by a circular ecosystem perspective (Chapter 7.2.1). Based on circular material flows as conceptual departure, this perspective helps businesses to locate themselves as actors within a circular ecosystem and to identify other relevant actors and material flows. The circular ecosystem perspective conveys the message that the goal to establish circular material flows cannot be achieved through intra-organizational projects, but in collaboration with other actors who are not necessarily direct business partners (i.e., supply chain neighbors). The taxonomy proposed in study 2 can be used as a methodological tool to launch into the design of circular ecosystems. It offers an abstract collection of social actors and material flows underlying CE principles that businesses can tailor to their specific circular ecosystem, and suggests information flows that businesses can consider when designing and implementing IS.

As outlined in the discussion of the digital representation of circular ecosystems (Chapter 7.2.2), the availability of data can become a critical success factor for digitally enabling circular material flows. Study 2 proposes a range of information that should be captured and shared across the circular ecosystem to support the deployment of circular material flows through digital representation. However, study 3 shows that data privacy and security concerns are high on the list of digitalization barriers and prevent unrestricted data sharing in the waste management sector. Consequently, this barrier should be given greater consideration by digital solution providers, regulators, and the transforming firms themselves. I suggest that concerns can be addressed through a combination of social solutions, such as third-party data curators or bilateral data governance agreements, and technological solutions, such as the distributed ledger technology-based data governance solution from digital start-up *Circularise* (cf. study 1).

Second, study 1 and study 3 show that while **digital-first CE start-ups and technology providers**, such as digital waste management solution provider *Rubicon* in the United States, can act as digitalization drivers of CE transitions, they face several challenges: As conceptualized by study 1, circular material flows come with social and material complexities that must be accommodated and managed. Digital technology providers, especially start-ups, typically do not have sufficient resources to do this. Thus, as long as digital-first CE start-ups not only want to live in a symbiotic relationship with linear industries where they reuse or recycle neglected waste materials, but aim to transform the actual industries, they will need incumbent actors with social (e.g., partner networks) and material (e.g., physical infrastructure) capital to make big impact.

Yet, study 3 reveals a tendency of incumbent actors in regulated industries (here: waste management) not to take digital start-ups and technology providers with ambitious transformative CE goals seriously. Moreover, as theorized in study 4, the digital infusion of products equips OEMs with new forms of control beyond their point of sale, potentially enabling them to exclude third-party actors, such as start-ups, from creating value from their products through CE principles. Such exclusionary control behavior may even prevent symbiotic circular ecosystems. In sum, digital technology alone is not sufficient to transform linear industries into more circular ones; a receptiveness of incumbent actors in these industries for CE transformation is inevitable.

Thus, collaboration with incumbent actors from linear industries that are willing to transform is crucial if digital-first CE start-ups and technology providers are to have a major transformative impact. Examples comprise German start-up *Recyda*, which is developing a digital recyclability assessment tool and has partnered with *Schwarz Group*, the fourth-largest retailer by revenue worldwide, and *Huhtamaki*, a global food packaging specialist; or Dutch start-up *Circularise*, which is developing a distributed ledger technology-based material tracing solution and has partnered with *Porsche*, a German sports cars manufacturer, and *Covestro*, a German chemical materials manufacturer.

Through these collaborations, digital start-ups and technology providers can test and demonstrate their minimum viable product and leverage existing business networks as well as the physical infrastructure of incumbent actors.

Third, the findings in this dissertation imply two major responsibilities for **regulators** to guide and direct the digital enablement of CE principles. On the one hand, regulators must be aware of the potential intrusion of digital technologies into our personal lives if the idea to digitally enable circular material flows is pursued. Note that the information flows proposed in study 2 include geolocation and condition data of products purchased by private customers. While surveillance capitalism has thus far been known primarily from the digital economy, such as social media (Zuboff 2018), a digitally enabled CE implies a growing digital representation of everyday consumer products. I argue that the potential misuse of such data, beyond the original purpose of enabling a CE, can be enticing for businesses.

Thus, regulators need to be proactively involved in developing data standards and governance for a digital CE to strike the right balance between digitally enabling circular material flows and preventing data misuse. Take, for example, the evolving German standard DIN SPEC 91446 (Deutsches Institut für Normung 2021), which aims to specify data quality levels for the classification of plastic recyclates. The consortium consists of firms along the plastics value chain, industry associations, and research institutes. As the recycling standard currently excludes the digital representation of customer-related events (e.g., repair or reuse), it does not deal with data privacy issues. In data standards on component or product level, however, customer-related events will more likely be of interest for digital representations. In these cases, standardization consortia could staff data privacy and security functions with representatives from regulatory agencies.

On the other hand, regulators need to be aware of the shifting power landscapes in product aftermarkets in favor of OEMs instilled through the digital infusion of everyday consumer products. As shown by study 4, this digital infusion has the potential to spawn the instigation of self-reinforcing and discriminatory aftermarket control regimes. With exclusionary intentions of the OEM, such control regimes can cause economic harm to aftermarket competition and environmental harm due to shortened digital product lives.

Economically, digital control enables OEMs to exclude unwanted third-parties from creating value through reusing, repairing, or remanufacturing the digital product or its components, thus limiting competition in the aftermarket. I therefore call for a revision of current antitrust law and investigation procedures with a focus on digitally enabled control capabilities. Environmentally, preventing reuse, repair, or remanufacturing services restricts the options to extend the lifespan of products and components. Given the growing e-waste streams and the proliferation of products with digital control capabilities, I call for a stronger consideration of digital product properties in current legislative proposals aimed at promoting long-lasting products and services by design. As the findings from study 4 show, for instance, repair can be thwarted not only by physical barriers (e.g., inaccessibility or non-dismantlability of components) but is increasingly hindered by ‘digital glue’ as well. Future policies could consider regulating digital interfaces that hinder lifespan-extending repair and reuse of products, for instance through mandatory open-source application programming interfaces.

7.4 Limitations

Aside from the individual limitations of each study, which will not be repeated here, this dissertation is subject to four major limitations that apply at a more general level.

First, the scientific insights into a digitally enabled CE presented in this dissertation are limited by the **immaturity of the phenomenon** under scrutiny. The concept of a CE—despite its nearly five-decade-long scientific history—is not yet widespread in the real business world. The maturity of CE implementations I observed was low in that most actors sought individual CE solutions focusing on intra-organizational initiatives while neglecting more transformational efforts. Thus, the idea of circular material flows across organizational boundaries (i.e., circular ecosystems) remains conceptual rather than empirical within this dissertation. As the CE idea has recently received attention from both policymakers and practitioners, some large-scale research and development projects have emerged that bring together actors from different industries to work on designing circular material flows (DiLinK 2021). I therefore expect that future research on a digital CE will be able to embark on a more mature phenomenon.

Second, the scientific insights presented in this dissertation are limited by the **complexity of the phenomenon** under scrutiny. Circular material flows are scientifically hard to observe and capture in their entirety. As conceptualized in study 1 and in the discussion of circular ecosystems, the phenomenon of material circularity encompasses large social and material systems whose exact manifestations are difficult to predict. In particular, when circular ecosystems are conceptualized as decentralized value creation networks without a structuring hub, social complexity increases even further. This makes the empirical investigation of phenomena within the conceptual boundaries of circular ecosystems challenging.

In this dissertation, all empirical inquiries only partially capture this phenomenological complexity, instead focusing their analysis on selected components of wider circular ecosystems: Study 2’s taxonomy draws on CE-driven business models and initiatives of individual actors without considering their wider ecosystem. Study 3’s survey covers waste management firms as important link between two product lifecycles, but does not consider upstream consumers who generate waste or downstream producers who re-processes recyclates. Study 4’s case study focuses its analysis on authorized and unauthorized repair service providers without considering the suppliers of repair parts and tools or consumers who demand repair services.

Third, the scholarly insights into a digitally enabled CE presented in this dissertation are limited by **disciplinary boundaries**. CE research is an interdisciplinary topic. Consequently, it has been explored from different scientific perspectives with their own conceptual lexica and methods. Besides its scientific origin in Environmental Sciences and Industrial Ecology, Operations Research has approached the topic from a supply chain management perspective and Management Science contributed insights from an innovation and business model angle.

Within this dissertation, not all disciplinary perspectives can be sufficiently reflected. Rather, the proclaimed goal was to provide an IS-specific perspective on the relationship between digital technologies and a CE. This perspective also brings its own conceptual lexicon, which builds on the discipline’s scholarly engagement with the sociotechnical. As a result, the conceptual theme that runs through all studies presented is one of social and material complexity mediated through digitality. Yet, the sociotechnical perspective is limited, in that it does not, for example, evaluate the environmental impacts of digital CE initiatives through detailed lifecycle assessments—an established method in Environmental Sciences (Alting and Jøgensen 1993)—or question the environmental priority of CE initiatives from a waste hierarchy perspective (Chapter 2.1.1). Instead, it is assumed that each CE principle is generally beneficial to the environment.

Fourth, the scientific insights presented in this dissertation are guided by **structural assumptions**. According to Kalverkamp and Young (2019), a CE can be conceptualized from two structural standpoints: as an open or closed-loop supply chain system. While in closed-loop supply chains, products, components, and materials return to the OEMs, in open-loop supply chains, material flows are slowed down and looped by third-parties outside the OEMs' sphere of control. Consequently, the conceptualized and studied circular ecosystems and the scientific knowledge gained from them differ depending on the underlying paradigmatic assumption: a closed-loop supply chain assumes a centralized circular ecosystem in which the OEM plays the role of a governing ecosystem hub; an open-loop supply chain assumes a decentralized circular ecosystem in which third-parties organize polycentric governance structures. In this dissertation, I adopt an open-loop supply chain perspective as previous literature has primarily focused on closed-loop, OEM-centric circular ecosystems—despite empirical observations suggesting otherwise (Kalverkamp and Young 2019). Consequently, this perspective limits the discussed insights on digital representation, transformation, and control to a certain context in which no large and powerful OEMs are transforming their business model towards stronger material circularity, but independent actors, such as unauthorized repair service providers in study 4, are creating value through CE principles without the OEMs endorsement.

7.5 Future Research

With this dissertation, I also aim to stimulate future IS research on the relationship between digital technologies and a CE. As noted in Chapter 2.2, previous Green IS and Green IT research has largely focused on IS-enabled energy efficiency solutions, neglecting IS solutions for sustainable production and consumption, that is digitally enabled CE principles that slow down (i.e., reuse, repair, remanufacture) and close material flows (i.e., recycle). Despite its societal and environmental relevance, the phenomenon of a digital CE remains largely unexplored from an IS perspective. This dissertation suggests two main avenues for future IS research to continue this exploration.

First, future research can build on study 1, which presents an **IS research agenda on a digital CE** with six research topics that align with two research objectives: understanding and enacting circular material flows with IS. The first research objective aims to explore *how IS can help comprehend and accommodate social and material complexities that unfold around CE implementations*. A key challenge, also discussed in the research implications, concerns the digital representation of complex product systems. While recent advances in sensor technologies provide new data capturing capabilities, various constraints of technical (e.g., hardware requirements), economic (e.g., return on investment), and social (e.g., data privacy) nature challenge the digital representation of the dynamic locations and conditions of complex product systems. The second research objective aims to explore *how IS can support the transformation of linear economic activities into more circular activities*. Four corresponding topics are proposed that guide future IS research: IS-enabled solutions for circular product design, intensified product use, extended product use, and material reprocessing.

In this dissertation, I present three studies that are embedded into the research agenda from study 1 and cover some of the research topics proposed therein (Chapter 7.1). Each study provides individual entry points for IS scholars to follow-up with future research. Summarizing the main ones: Study 2 invites future IS research to test and refine the proposed taxonomy of information flows through empirical and design-oriented research. Study 3 publishes the survey instrument (Appendix G) to stimulate the development of a digitalization progress indicator tool that allows future research to quantify the progress of digital transformation in waste management on a regular basis. Study 4 provides an updated understanding of control theory including new concepts, such as encrypted inscription or dynamic sanctioning, that can inform future research on the digital governance of hybrid, that is software and hardware, platform ecosystems.

Note that two research topics from the research agenda have not been covered within this dissertation: IS-enabled solutions for circular product design and intensified product use. I therefore invite future IS research to explore both topics in more detail. As a possible starting point, Table 12 provides illustrative research questions and selected IS research programs on which future research can build.

Second, as synthesized in the research implications (Chapter 7.2.1), future research can further explore the three IS phenomena—digital representation, transformation, and control—in the context of **circular ecosystems**. The circular ecosystem concept builds on study 1's understanding of CE implementations as complex social systems and complex product systems. However, as pointed out in the limitations (Chapter 7.4), insights from empirical research—such as the studies within this dissertation—are limited both by the low maturity of observable circular ecosystems (i.e., phenomenological immaturity) and by research methods that inadequately capture the complexity of circular ecosystems (i.e., phenomenological complexity), in particular when open material loops are involved.

Therefore, I recommend two methodological extensions for future research that go beyond the methods used in this dissertation to investigate digital representation, transformation, and control in circular ecosystems.

In response to limitations that stem from phenomenological immaturity, I consider intervention-oriented research to be a promising complement to empirical methods. By intervention-oriented research, I mean research methods in which the researcher interferes in and shapes the unfolding of the phenomenological event stream while simultaneously contributing new knowledge through experiential abstraction. Intervention-oriented research includes established IS research methods, such as design science research (Hevner et al. 2004; Peffers et al. 2007) or action research (Avison et al. 1999; Baskerville and Myers 2004; Davison et al. 2004). I consider the role of a researcher who is affiliated with an ecosystem, but not to an individual company within that ecosystem, particularly helpful for the orchestration of a digitally enabled circular ecosystems as they require the collaboration of multiple, sometimes competing, stakeholders. Researchers can buffer such competing interests and moderate the collaboration from a scholarly position.

Given the limitations posed by phenomenological complexity, I find mixed methods research (Mingers 2001; Venkatesh et al. 2013)—scientific inquiries that combine qualitative and quantitative research approaches—to be helpful in observing and making sense of the social and material complexities of circular ecosystems. On the one hand, qualitative research methods, such as ethnographic observations or interviews, can help unravel the social complexities that give rise to concerns about data sharing, for example. On the other hand, quantitative research methods can tap into existing digital representations (i.e., data sets) that have been individually generated over time by actors of the intended circular ecosystem, and whose integrative data analysis can yield new insights that benefit the entire circular ecosystem. For instance, in a circular ecosystem aiming to recycle plastic materials, individual actors along the plastic value chain, such as the plastic producers, processors, converters, users, collectors, and recyclers, accumulate digital trace data from their own business activities. However, they do not usually share this data across the value chain. An integrative data analysis of the individual digital representations, conducted by the researcher, can reveal dependencies between non-adjacent actors, such as plastic converters and recyclers.

Chapter 8

Conclusion

This chapter concludes my dissertation. I recapitulate the purpose of my research, state the four research subjects, and summarize the key insights of the presented studies. I close with a call for future research on the relationship between digital technologies and a CE.

In this dissertation, I examined the relationship between digital technologies, as part of larger IS, and a CE. The insights of the four studies presented expand the existing body of knowledge on IS and environmental sustainability, which so far has largely focused on IS-enabled energy efficiency solutions while ignoring IS solutions for sustainable production and consumption. The four studies investigate (a) the potential of IS scholarship to contribute to CE research, (b) information flows relevant to the implementation of CE principles, such as reuse, repair, or recycle, (c) the digitalization of waste management firms, representing a core industry in a CE, and (d) control in digital product aftermarkets that may negatively impact repair or remanufacturing services.

My research comes to four main conclusions. First, the **relationship between IS and a CE** can be prolific. Study 1 (Chapter 3) shows that IS can help comprehend and accommodate social and material complexities that unfold around CE implementations and support the transformation of linear economic activities into circular ones. Second, the **design of IS for a CE** must correspond to the particular structure of social actors and material objects that underlies implementations of CE principles. Study 2 (Chapter 4) analyzes the social actors (i.e., flow network) and material objects of each circular principle to derive general information flows relevant to the implementation of the principle. Third, the **adoption of IS for a CE** tends to follow an efficiency paradigm and neglects innovation potentials for slowed down (i.e., reuse, repair, remanufacture) and closed (i.e., recycle) material flows. Confirming study 1, study 3 (Chapter 5) shows that despite a growing awareness of digital opportunities, waste management firms focus their digitalization efforts on the non-exclusive implementation of basic digital technologies with the primary goal of optimizing intra-organizational processes for efficiency. Fourth, the digital infusion of products can benefit or thwart the **use of IS for a CE**. Study 4 (Chapter 6) shows how digital product properties provide OEMs with new control capabilities that can be employed for remote monitoring and intervention in repair aftermarkets to enable authorized third-party service providers (i.e., beneficial for a CE) and disable unauthorized third-party service providers (i.e., detrimental for a CE).

This dissertation is just a first yet incomplete attempt to explore a 'circular economy in the digital age.' The idea of a CE is broad and the opportunities for digital technologies to support a CE are vast. I hope that the four studies presented, as well as the synthesized discussion of digital representation, transformation, and control in circular ecosystems, will stimulate future IS research on this socially and environmentally relevant topic.

Appendices

Appendix A: Literature Outlets and Coding Scheme

Appendix A.1: Classification of academic outlets by research disciplines

Discipline	Academic outlets included in final sample (number of articles)
Information systems (55)	• Proceedings of the Americas Conference on Information Systems (8) • Business & Information Systems Engineering (3) • Communications of the Association for Information Systems (7) • Proceedings of the European Conference on Information Systems (2) • Proceedings of the International Conference on Information Systems (6) • Information Systems Journal (4) • Journal of the Association for Information Systems (3) • Proceedings of the Pacific Asia Conference on Information Systems (12) • Proceedings of the Hawaii International Conference on System Sciences (1) • The Journal of Strategic Information Systems (5) • Management Information Systems Quarterly (4)
Sustainability management (36)	• Journal of Cleaner Production (12) • Journal of Industrial Ecology (24)
Logistics, operations, and production research (6)	• Journal of Operations Management (6)
Strategic management (2)	• Academy of Management Review (2)
Marketing (2)	• Journal of Product Innovation Management (1) • Journal of the Academy of Marketing Science (1)
Technology, innovation, and entrepreneurship (1)	• Research Policy (1)

Appendix A.2: Summary of coding scheme

Category	Selected criteria
Focus	What is the stated *research goal*?
Unit of analysis	Which *unit of analysis* does the paper deal with? • Individual: Private actor level • Organizational: Intra- and inter-organizational process level • Regulatory: Public authority level
PLC stage	Which *PLC stage* does the paper essentially address? • Pre-use: From idea to delivery • In-use: From delivery to end-of-life • Post-use: From end-of-life to next-life
CE principle	Which *CE principle* does the paper essentially address? • Reduce: Minimization of energy and material resource input • Reuse: Intensification and extension of use • Recycle: Reprocessing of waste into secondary materials

Appendix B: Literature Coding Overviews

Appendix B.1: Concept matrix of articles by PLC stage and CE principle

PLC stage	CE principle	Article (Unit of analysis[14])
Pre-use	Reduce	**Core category 1: Process optimization** Alaraifi et al. (2011b) (O); Babin and Nicholson (2009) (O); Bengtsson and Ågerfalk (2011) (I); Bose and Luo (2011) (O); Butler (2011) (O); Chaabane et al. (2008) (O); Chen et al. (2009) (O); Condea et al. (2009) (O); Cooper and Molla (2017) (O); Corbett (2013) (O); Dekker et al. (2002) (O); Desautels and Berthon (2009) (O); Desautels and Berthon (2011) (O); El-Gayar and Fritz (2006) (O); Elliot (2007) (O); Elliot and Binney (2008) (O); Erek et al. (2009) (O); Erek et al. (2011) (O); Fischer and Pascucci (2017) (O); Gholami et al. (2016) (O); Gholami et al. (2017) (O); Grant et al. (2010) (O); Hanelt et al. (2017) (O); Hartmann and Moeller (2014) (O); Hasan et al. (2009) (I/O); Hedman and Henningsson (2016) (O); Hedwig et al. (2009) (O); Henkel et al. (2017) (O); Heyes et al. (2018) (O); Hilpert et al. (2013) (O); Katsikeas et al. (2016) (O); Linton et al. (2007) (O); Loeser et al. (2017) (O); Loos et al. (2011) (I/O); Mann et al. (2009) (O); Meinrenken et al. (2014) (O); Molla (2009) (O); Molla et al. (2009) (O); Molla and Abareshi (2011) (O); Molla et al. (2011) (O); Moreno et al. (2011) (O); Niero et al. (2017) (O); Nishant et al. (2011) (O); Nishant et al. (2017) (O); Park et al. (2010) (O); Pernici et al. (2012) (O); Pitt et al. (2011) (O); Poles and Cheong (2009) (O); Posch (2010) (O); Røpke (2012) (O); Rosen et al. (2003) (O); Sarkar and Young (2009) (O); Sayeed and Gill (2008) (O); Sayeed and Gill (2009) (O); Schmidt et al. (2009) (O); Sedera et al. (2017) (O); Seidel et al. (2013) (O); Wang et al. (2015a) (O); Wang et al. (2015b) (O); Watson et al. (2010) (O); Wei and Li (2009) (O); Wilhelm et al. (2016) (O); Wu and Pagell (2011) (O)
		Core category 2: Product design for efficiency Chang and Lu (2014) (O); Cooper (2005) (I); Frey et al. (2006) (O); Huang (2008) (O); Laurenti et al. (2015) (O); Ryen et al. (2014) (I); Shuaib et al. (2014) (O); Sihvonen and Partanen (2017) (O)
	Reuse	**Core category 3: Product design for reuse** Cong et al. (2017) (O); Eppinger (2011) (O); Pil and Cohen (2006) (O); Rossi et al. (2006) (O); van Schalkwyk et al. (2018) (O)
In-use	Reduce	**Core category 4: Sustainable consumption** Bjørn and Hauschild (2013) (O); Dalén and Krämer (2017) (I); Kranz and Picot (2011) (I); Krishnan and Teo (2011) (I); Loock et al. (2013) (I); Malhotra et al. (2013) (I/O); Malmodin et al. (2010) (O); Malmodin et al. (2014) (O); Takase et al. (2005) (O)
	Reuse	**Core category 5: Intensified use** Achachlouei and Moberg (2015) (I); Achachlouei et al. (2015) (I); Cohen and Muñoz (2016) (I); King (1995) (I); Vykoukal et al. (2009) (O)
		Core category 6: Extended use Mazhar et al. (2007) (O)

[14] In parentheses, we indicate the unit of analysis of each paper. I: individual (private actor) level; O: organizational (intra- and inter-organizational process) level; R: regulatory (public authority) level.

	Recycle	**Core category 7: Return behavior change** Chen et al. (2012) (I); Richter and Koppejan (2016) (O); Rocchetti et al. (2018) (O); Tong et al. (2018) (I); Zeng et al. (2013) (R)
Post-use	Reduce	**Core category 8: Return process optimization** Leigh et al. (2012) (I); Manhart (2011) (O); Rodrigues et al. (2016) (O); Tong and Yan (2013) (O); Webster and Mitra (2007) (O)
	Recycle	**Core category 9: Material reprocessing** Haas et al. (2015) (O)

Appendix C: Rich Accounts of Literature by PLC Stage

Pre-use

The foci of the 76 articles focusing on the pre-use stage were on **process** and **product design** optimization (Appendix C.1).

Appendix C.1: Literature review findings for the pre-use stage

CE principle	Higher-order concept	Description
Reduce	**Core category 1: Process optimization**	
	Information and transparency capability	Tracking of material and energy flows, automating tasks, and monitoring and evaluating environmental impacts to establish eco-efficient business processes
	Supply chain extension and collaboration	Inter-firm collaboration to trade by-products
	Real cost pricing	True cost economics to include the cost of negative externalities into the pricing of goods and services
	Product-service system	Offering product functionalities as a service to customers rather than offering the product itself
	Core category 2: Product design for efficiency	
	Design for environment	Systemic concept to minimize the environmental impact and address lifecycle concerns already in the development phase
Reuse	**Core category 3: Product design for reuse**	
	Design for environment	Systematic concept for value recovery through built-in reparability and disassembly options

Process Optimization

Research on the optimization of business processes to minimize energy and material resource input in sourcing, manufacturing, and distribution is comprehensive. Studies highlight the *information and transparency capabilities* of IS to improve energy efficiency (Bose and Luo 2011; Pernici et al. 2012; Pitt et al. 2011; Sedera et al. 2017; Watson et al. 2010) and material efficiency (Erek et al. 2009; Gholami et al. 2016; Hasan et al. 2009; Loeser et al. 2017; Mann et al. 2009; Pitt et al. 2011).

The reviewed literature gives attention to automation potential for optimized planning and logestics, such as resource tracking (Alaraifi et al. 2011a; Hilpert et al. 2013; Moreno et al. 2011; Sedera et al. 2017), workload prediction (Hedwig et al. 2009), and dematerialization (Bose and Luo 2011; Loeser et al. 2017; Mann et al. 2009). El-Gayar and Fritz (2006) address environmental management IS (EMIS) to optimize business processes by making critical information on environmental performance more salient. IS can further assist the monitoring and evaluating of behavioral impacts (Elliot 2011). Examples are carbon management systems (Corbett 2013) and sensemaking that influences individual attitudes, awareness, and ecologically responsible behaviors (Henkel et al. 2017).

Beyond intra-organizational sustainable practices, inter-organizational and inter-lifecycle material and energy considerations are essential to the CE concept (Heikkurinen et al. 2019; Korhonen et al. 2018). Literature focuses on *supply chain extension* to reinforce inter-firm *collaboration* between up- and downstream partners within or across industries. Cooperation target synergistic collaboration on materials, energy, and services to exploit wastes produced by one firm as inputs by another firm and optimize offerings from a total cost standpoint (Chen et al. 2009; Grant et al. 2010; Niero et al. 2017; Posch 2010). To minimize information asymmetries and optimize resource flows be-tween collaborating firms, research emphasizes technological enablers and standardized resource taxonomies for planning, tracking, and recording (Chaabane et al. 2008; Grant et al. 2010). To protect against chain liability, firm management is required to work toward sustainable behavior throughout the supply chain (Babin and Nicholson 2011; Hartmann and Moeller 2014; Wilhelm et al. 2016).

At the same time, research highlights process optimization intricacies due to a lack of holistic management thinking, standards, metrics, and measures, as well as increasing complexity of regulations and stakeholder expectations (Pernici et al. 2012; Wu and Pagell 2011). Technologies, policies, governance, attitudes, and beliefs are found to bring advantage (Bose and Luo 2011; Molla 2009; Molla et al. 2011; Sayeed and Gill 2009) to the practicality and commitment of process optimization. Examples include IS for sensemaking of work practices aligned to sustainability goals (Bengtsson and Ågerfalk 2011; Butler 2011; Seidel et al. 2013) and business process modeling (Meinrenken et al. 2014).

Real-cost pricing and product-service systems (PSS) are the key approaches to internalizing environmental and social lifecycle costs. *Real-cost pricing* builds on true cost economics (Stern 2007) to include the cost of negative externalities into the pricing of goods and services, such as the environmental cost of extracting rare earth elements that are essential for many electrical products (Desautels and Berthon 2009, 2011). IS can improve the information flow on true costs between stakeholders. Just as for service models, cost models have to be specified before entering the market, but show their effectiveness in later stages of lifecycles. This requirement also applies to *product-service systems* that allow purchasing the service of a product for a defined user period rather than purchasing the product itself. Since ownership can remain with the firm that offers the service, knowledge on customer behavior and product characteristics can inform reverse logistics in the post-use stage (Bjørn and Hauschild 2013; Fischer and Pascucci 2017; Heyes et al. 2018). Diminished uncertainties in quantity, quality, and timing of returns allow firms to improve decision making for the optimal recovery option of post-retail (Condea et al. 2009; Dekker et al. 2002; Poles and Cheong 2009; Wei and Li 2009).

Product Design Optimization

We found that from the perspective of product design optimization, the literature focused on the reduction and reuse of material resources through *design for environment* (DfE) (Laurenti et al. 2015; Rossi et al. 2006). The systemic DfE concept addresses lifecycle impacts of a product or service already in the development phase (Huang 2008; Sihvonen and Partanen 2017). Design paths to minimize the input of virgin physical components and extend life spans include using recyclable, recycled, or renewable parts or designing products that can be easily disassembled (McDonough and Braungart 2002; Sedera et al. 2017; Sihvonen and Partanen 2017). The literature emphasizes the importance of computer-aided design tools to assist designers in evaluating products' aggregated sustainability performance and designing for circularity, for example by providing suggestions for reducing the toxicity and improving the ease of disassembly (Chang and Lu 2014; Laurenti et al. 2015; Shuaib et al. 2014; van Schalkwyk et al. 2018).

Further, research highlights design for dematerialization—that is, designing products for multifunctionality with convergent device design (Ryen et al. 2014). For example, one smartphone device integrates several functionalities (e.g., phone, camera, computer). Drawing on this analogy, Ryen et al. (2014) point to the potential of designing offerings with multiple functionalities to decrease re-source use. As such, multifunctional device design also affects the use phase since it intensifies use of (multifunctional) products while minimizing the total number of products owned.

DfE not only reduces negative environmental impacts, but additionally enables efficient value recovery through built-in reparability and disassembly (Cong et al. 2017; Huang 2008; Jensen et al. 2019; Mazhar et al. 2007). To enable products to become useful input for other products instead of becoming waste, design takes into account products' reparability, upgradeability, and recyclability. Modularity and ease of disassembly have received attention as a means to facilitate repair and in-crease product variety in favor of extended product life spans (Cong et al. 2017; Eppinger 2011; Pil and Cohen 2006).

IS can support product optimization, for instance, by detecting the optimal life span of components (Mazhar et al. 2007), or by trustfully exchanging reliable, fine-grained information that decision makers need to assess products' eco-impact (Mazhar et al. 2007). The reviewed literature thus emphasizes the need for IS solutions to support the design and analysis, as well as collaboration, regarding offerings that are less toxic and easier to disassemble, and allow for effective circularity with less time and effort (Chang and Lu 2014; Eppinger 2011; Laurenti et al. 2015; Rossi et al. 2006; Shuaib et al. 2014; Sihvonen and Partanen 2017).

Pre-use

The foci of the 20 articles focusing on the in-use stage were on **sustainable consumption**, **intensified and extended use**, and **return behavior change** (Appendix C.2).

Sustainable Consumption

Our review found that the literature is concerned with motivating a sustainable consumption behavior change to curb operational inefficiency of products (Malmodin et al. 2010). The literature analysis highlights opportunities for behavior change via *monitoring and reporting* energy use to support efficient operational behavior and reduce demand (Hasan et al. 2009; Kranz and Picot 2011; Malmodin et al. 2010; Malmodin et al. 2014). User-centered feedback and personal goal choice were found to enhance sensemaking in favor of sustainability actions (Dalén and Krämer 2017; Loock et al. 2013; Malhotra et al. 2013; Seidel et al. 2013). Further, individual technology readiness to use supporting technologies (*IS capability*) was found to play an important mediating role, since any technological advantage depends on individuals having digital literacy and making use of it (Blut and Wang 2019; Chipidza and Leidner 2019; Craig et al. 2019; Krishnan and Teo 2011). However, behavior change involves not only bottom-up individual actions but also top-down government-driven actions to better educate and engage community groups and citizens in the public sphere under con-sideration of their individual motivations as well as consumption and income rebound effects (e.g., Alakeson and Wilsdon (2002), Frenken (2017), Heikkurinen et al. (2019).

Appendix C.2: Literature review findings for the in-use stage

CE principle	Higher-order concept	Description
Reduce	**Core category 4: Sustainable consumption**	
	Monitoring and reporting capability	Track energy-use to support efficient operational behavior and demand reduction
	IS capability	Individual technology readiness and literacy to use IS
Reuse	**Core category 5: Intensified use**	
	Collective use and sharing	Digital platforms enable intensified use
	Core category 6: Extended use	
	Extended product and component use	Assessment of the remaining useful life of components for remanufacturing
Recycle	**Core category 7: Return behavior change**	
	Extended consumer responsibility	Consumer awareness for and implementation of waste separation and recycling activity

Intensified and Extended Use

Regarding intensified or extended use of products and components by multiple users, a small part of the reviewed literature addresses digital platforms that provide an opportunity for *collective use and sharing* activities (Cohen and Muñoz 2016; King 1995) and the exploitation of underutilized or unused resources (Achachlouei et al. 2015; Achachlouei and Moberg 2015; Vykoukal et al. 2009).

Return Behavior Change

In terms of efficient disposal, collection, and recycling behavior, the activation of *extended consumer responsibility* by downward informating is emphasized by the literature review. Individual self-efficacy and convenient, local return points were found to significantly contribute to an individual return behavior change and the actual implementation of waste separation and recycling activity (Chen et al. 2012; Richter and Koppejan 2016; Rocchetti et al. 2018; Tong et al. 2018; Zeng et al. 2013).

Post-use

The foci of the 6 articles focusing on the post-use stage were on the implementation and optimization of efficient **return process optimization** (Appendix C.3).

Appendix C.3: Literature review findings for the post-use stage

CE principle	Higher-order concept	Description
Reduce	**Core category 8: Return process optimization**	
	Extended producer responsibility	Policy-induced strategy to lead firms to internalize disposal costs
Recycle	**Core category 9: Material reprocessing**	
	Circularity of global material flows	Accounting of material flows from resource inputs (imports and extraction) to outputs (wastes, emissions, and exports)

Return Process Optimization

Organizational return process optimization can be advanced by public policies as well as the awareness of manufacturers, retailers, and consumers (Leigh et al. 2012). Besides incentives such as lease contracts, product service agreements, and promotion programs for returned products, tracking technologies and recycling cooperation allow for digital control and improved dissemination of returned products (Manhart 2011). In terms of efficient collection behavior, *extended producer responsibility* represents an important policy-induced strategy to lead organizations to internalize disposal costs (Rodrigues et al. 2016; Tong and Yan 2013) and redesign products that facilitate the re-use of components (Webster and Mitra 2007). However, the *circularity of global material flows* remains a great challenge and we have identified only one study that takes a materials perspective on reprocessing to use materials in the manufacturing of new products (Haas et al. 2015; Rossi et al. 2006).

Appendix D: Data Sources Used for Contextual Immersion, Survey Development, and Validation

Appendix D.1: Data sources used for contextual immersion, survey development, and validation

	Source type	Sources	Intention for using source
Primary sources	Interviews	Four interviews (IP1, IP2, IP3, IP4) with employees at a German waste management systems provider One interview (IP5) with a digital officer at a large waste management firm (>1,000 employees) One interview (IP6) with the Head of Business Unit Products and Equipment & Business Unit Waste and Packaging of a waste management technology provider	Understand the waste management market structure and VC Get an impression of the status quo of digitalization Validation and discussion of survey findings
	Observations	Three observations (O1, O2, O3) based on visits of German waste management firms	Get to know the processes and activities of a private German waste management firm Get an impression of the status quo of digitalization Examine the firms' attitudes towards digitalization
Secondary sources	Digitalization surveys on the German waste management industry	Lacher and Ziss (2019), Mechsner (2017)	Uncover the status quo of digitalization Identify discrepancies and research gaps Adopt items
	Digitalization surveys on international waste management	Mavropoulos (2017), Sarc and Hermann (2018)	Recognize areas of digitalization that have not yet been studied in the German waste management industry
	Academic papers on digital technologies and solutions in waste management	Anagnostopoulos et al. (2017), Bakici et al. (2013), Esmaeilian et al. (2018), Faccio et al. (2011), Johansson (2006), Ramos et al. (2018), Sarc et al. (2019)	Understand and get to know digital technologies and digital solutions in waste management Gain insights into how digital solutions and technologies can change the traditional VC

	Digitalization studies on other industries	Berger and Volkmar (2020), Deutsche Telekom AG (2018, 2019), Justenhoven et al. (2019), Kersten et al. (2017), Pflaum et al. (2017), Reker and Böhm (2013), Saam et al. (2016), Salviotti et al. (2019), Schäfer et al. (2017), Schug et al. (2007), techconsult GmbH (2020a, 2020c, 2020b, 2020d)	Observe the structure of other digitalization studies Become aware about aspects of digitalization that were neither included in the study on the German waste management industry nor on the international waste management Adopt items and scales

Appendix E: Waste Management Value Chain

Appendix E.1: Waste management value chain

Value chain step	Description
Customer management & sales	Waste producers approach the waste management firm to order a container. Typically, the waste management firm documents and confirms the order, issues a delivery of an empty container, and performs invoicing after waste has been collected.
Dispatching & logistics	Waste containers are picked up—either regularly on a predetermined collection day or on customer demand. A dispatcher of the waste management firm plans when and on which tour the container is collected and informs the drivers. Tour routes are either planned by the drivers themselves or a dedicated dispatcher. On collection, a delivery note is handed out to and signed by the customer.
Weighing & sorting	Collected waste is weighed and sorted into recyclable and non-recyclable waste. If the waste management firm owns a scale, the weight can be determined at the firm's site. Otherwise, the driver uses the weighing services of a third-party provider. Subsequently, the full container is treated on-site or by a third-party waste treatment firm. Sorting is often done by hand and mechanically relying on wind sifting or magnetic separation.
Marketing of recyclable materials, recycling, or disposal	The waste management firm decides on where to channel the collected, weighed, and sorted waste. The firm can either sell recyclable waste to material recovery (i.e., recycling) firms, sell non-recyclable waste to incineration plants, or dispose of waste via dumpsites or export.
Container management	Represents the spatial and temporal coordination and maintenance of waste containers. Central to this step is knowledge about the number of containers and their current location as well as their condition. Container management is cross-sectional, because it connects to the sequential value chain steps described above at various points of the value chain, for instance when deploying or collecting containers at customer sites.

Appendix F: List of Digital Technologies Considered in the Survey

Appendix F.1: List of digital technologies considered in the survey

Value chain step	Digital technologies	Description	Reference
Customer management & sales	Online customer portal	The online customer portal represents the point of contact to the customer. Here, customers can e.g. order containers, receive invoices, access the status of their orders, make reclamations and get information on their waste.	Piel et al. (2018)
	Enterprise resource planning (ERP) system	An ERP system integrates back-office functions (e.g., sales, procurement, asset management, finance, etc.) into a standard IT application platform with a uniform database.	Weill and Vitale (2002)
	AvaL (data standard)	AvaL is an open standard for the exchange of order-related data between waste management firms, their customers, authorities and other partners. It aims to simplify the communication across firms through a uniform language.	BDE (2020)
	ZUGFeRD (data standard)	ZUGFeRD is a hybrid cross-sector data format for the exchange of electronic invoice data. It integrates structured invoice data in XML format into a PDF document. This enables electronic processing of invoices.	AWV (2020)
Dispatching & logistics	Dispatching system	A digital dispatching system carries out order scheduling, the personnel allocation, and route planning.	IP2, IP3, IP4
	Telematics system	A telematics system enables the transmission of vehicle-related data to the back-office and customer. The scope of application reaches from driver assistance, vehicle tracking, transition of position data, to automatic storage of arrival and departure times.	Osińska and Zalewski (2020)
Dispatching & logistics, Container management, Weighing	Onboard computer	The onboard computer is the central processing unit in the vehicle that supports the driver at every step of the waste collection. Over the touchscreen, drivers access functions such as orders, navigation, maps, container management, scale, camera, transponders or eANV. The onboard computer stores information such as the weight or digital signatures and transfers them on to the back-office.	Piel et al. (2018)
Weighing & sorting	Robotics	"Robotic waste sorting systems are autonomous, multitasking, learning and scalable systems […] [,] capable to separate specific materials"	Mavropoulos (2017, p. 36)
	Digital watermarks	A digital watermark is an optical code applied on an item. If read by sorting systems, it informs about sorting ways.	Belder (2019)

Container management	Barcode	"Barcode is an electronic data interchange medium that contains machine readable dichromatic mark that encodes information for objects labelling using an arrangement of geometric symbols"	Hannan et al. (2015, p. 514)
	Radio Frequency Identification (RFID)	RFID is a data collection technology "used for the identification or tracking of objects or assets and people. The most usual method […] involves storing a specific serial number […] and other information on an RFID tag. An RFID reader can scan and read the tag", convert radio waves into digital information that is then shared with computers, e.g., onboard computers to process the data.	Hannan et al. (2015, p. 515)
Container management, Dispatching & logistics	Sensor	"A sensor is a device that perceives and measures real-world features, such as physical quantities […], and converts them into signals that can be directly observed or adopted by another device"	Hannan et al. (2015, p. 516)

Appendix G: Survey Instrument

Appendix G.1: Survey Instrument

Code	Item	Reference
Classification		
A1	How would you describe the **activity** of your company? (multiple answers possible)	Practitioner interviews
A2	Are you certified as a specialist disposal company according to **EfbV**?	Practitioner interviews
Digitalization of the waste management industry		
DE1	How strongly does the subject of **digitalization** influence the **waste management industry** in general and **your company** in particular?	Justenhoven et al. (2019), Mechsner (2017), Studer et al. (2019)
DE2	How would you describe your company's **approach to digitalization**?	techconsult GmbH (2020b)
DE3	How does the management of your **firm feel about digitalization**?	van Alphen et al. (2019)
DE4	How do you assess the relationship between **opportunities and risks** of digitalization for your company?	Kersten et al. (2017)
DE5	What is the current **significance** of **digitalization** in the various areas of your **value chain**?	Practitioner interviews
DE6	What is the potential **significance** of **digitalization** in the various areas of your **value chain**?	Practitioner interviews
Actual use of digital technologies along the value chain: customer management & sales		
WKB1	Through which **sales channels** does your customer order from you?	Justenhoven et al. (2019), Practitioner interviews
WKB2+ WKB3	Does your **online shop** have one or more of the following **functions**? Follow-up: Please name **other functions** that your **online shop** has that have not yet been queried.	techconsult GmbH (2020d), Practitioner interviews
WKB4	Which of the following e**xternal online shops** do you know?	Practitioner interviews
WKB5	Which of the following **external online shops** do you use?	Practitioner interviews
WKA1	Do you use an Enterprise Resource Planning (**ERP**) system (e.g., SAP)?	Reker and Böhm (2013), Practitioner interviews
WKA2	Is your **ERP system connected** to that of your customers, system service providers or other waste management companies?	Practitioner interviews

WKA3	The **BDE** Federation of the German Waste, Water and Raw Materials Management Industry e.V. is currently developing a standard for the electronic exchange of order-related data (**AvaL**). Have you already heard of it?	Practitioner interviews
WKA4	Are you willing to use the standard?	Practitioner interviews
WKA5	Why are you not willing to use the standard?	Practitioner interviews
WKA6	How do your customers receive their **invoice**?	Practitioner interviews
WKA7	Do you use an automatically processing invoice format, such as ZUGFeRD?	Practitioner interviews
WKK1+ WKK2	Do you notice a **change in customer requirements** in the following areas? Follow-up: Please name **other customer requirements** that you perceive and that have not yet been queried.	Practitioner interviews
Actual use of digital technologies along the value chain: dispatching & logistics		
WDL1	How do you **plan** the **routes** of your vehicles?	Practitioner interviews, onsite visits
WDL2	How do you **inform** your drivers about the **dispatching plan**?	Practitioner interviews, onsite visits
WDL3+ WDL4	Which of the following **technologies** do you use **on board** your vehicles? Follow-up: Please name **other technologies** that you use **on board** of your vehicles that have not yet been queried.	Practitioner interviews
WDL5	Do you have a telematics system?	Practitioner interviews, onsite visits
WDL6	What is the **main reason** for using a **telematics system** in your company?	Practitioner interviews, onsite visits
WDL7	How do you **document the service** you provide to the customer?	Practitioner interviews
Actual use of digital technologies along the value chain: container management		
WKBV1	How to identify and manage your containers?	Practitioner interviews, onsite visits
WKBV2+ WKBV3	Which of the following **technologies** do you use to manage and identify your **containers**? Follow-up: Please name **other technologies** that you use to **manage** your **containers** that have not yet been queried.	Practitioner interviews, onsite visits
Actual use of digital technologies along the value chain: weighing & sorting		
WKW1	Do you own a **scale**?	Practitioner interviews
WKW2	What kind of **proof of the weight** do you use?	Practitioner interviews
WKS1	Do you own a **sorting plant**?	Practitioner interviews, onsite visits
WKS2	How do you sort your waste?	Schug et al. (2007), onsite visits
WKS3	What chances do you see in a further digitalization of your sorting plant?	Practitioner interviews

Digital technologies along the value chain: actual interfaces		
WKV1	Which of the following value chain steps is your **ERP system linked** to?	Practitioner interviews
WKV2	Which of the following value chain steps is your **digital dispatching system linked** to?	Practitioner interviews
WKV3	Which of the following value chain steps is your **telematics system linked** to?	Practitioner interviews
Digitalization strategy and objectives		
SZ1	Based on your company's previous activities, how well is your company prepared for digitalization?	van Alphen et al. (2019)
SZ2+ SZ3	What **measures** do you implement to **anchor digitalization** in your company? Follow-up: Please name **other measures** that you are implementing to anchor digitalization in your company that have not yet been queried.	Salviotti et al. (2019), van Alphen et al. (2019)
SZ4	Who in your company is responsible for digitalization?	Vogl (2020)
SZ5+ SZ6	Which of the following **objectives** have you been able to achieve through the use of digital technologies or which of them do you aim to achieve in the future through the use of digital technologies? Follow-up: Please name **previously unasked-for objectives** that you have been able to achieve or are striving for through the use of digital technologies.	Berger and Volkmar (2020), Deutsche Telekom AG (2018), Saam et al. (2016), Sarc and Hermann (2018), Studer et al. (2019), Practitioner interviews
Drivers and barriers to digitalization		
TH1+ TH2	Which of the following **external factors** are currently **driving** digitalization in the waste management industry? Follow-up: Please name **other external factors** that have not yet been queried and that are currently **driving** digitalization in the waste management industry.	Pflaum et al. (2017), Reker and Böhm (2013), Saam et al. (2016), van Alphen et al. (2019), Practitioner interviews
TH3+ TH4	Which of the following **internal factors** are currently **driving** digitalization in the waste management industry? Follow-up: Please name **other internal factors** that have not yet been queried and that are currently **driving** digitalization in the waste management industry.	Reker and Böhm (2013), Practitioner interviews
TH5+ TH6	Which of the following **external factors** currently **inhibit** digitalization in the waste management industry? Follow-up: Please name **other external factors**, which have not been queried so far, which currently **inhibit** digitalization in the waste management industry.	Berger and Volkmar (2020), Justenhoven et al. (2019), Mechsner (2017), Saam et al. (2016), Sarc and Hermann (2018)

TH7+ TH8	Which of the following **internal factors** currently **inhibit** digitalization in the waste management industry? Follow-up: Please name **other internal factors**, which have not been queried so far, which currently **inhibit** digitalization in the waste management industry.	Berger and Volkmar (2020), Deutsche Telekom AG (2019), Justenhoven et al. (2019), Mechsner (2017), Saam et al. (2016), Sarc and Hermann (2018), Schäfer et al. (2017), Studer et al. (2019)
TH9	Which conditions would have to be in place to ensure that the **digitalization** of your business continues to progress?	Saam et al. (2016), Practitioner interviews
Outlook		
AB1	How will the **waste management industry** in general and **your company** in particular **change** in the future due to digitalization?	van Alphen et al. (2019)
AB2	Will you **deal with the digitalization** of the waste management industry in the **future**?	Sarc and Hermann (2018)
AB3+ AB4	What **concrete investments** in one or more of the following digital solutions are you planning in the future? Follow-up: Please name **other digital solutions** you have not yet queried, in which you plan to invest in the next 12 months or in the next 5 years.	Practitioner interviews
AB5	How has **COVID-19** influenced your investment planning?	Practitioner interviews, Review rounds with research team
AB6	Which of the following **innovative technology concepts** will have an impact on your **business model** in the future?	Justenhoven et al. (2019), Mavropoulos (2017), Sarc and Hermann (2018)
Demographic data		
PD1	To which **gender** do you assign yourself?	Brace (2004)
PD2	To which **age group** do you belong?	Brace (2004)
PD3	How many **employees** does your company have in Germany?	techconsult GmbH (2020c)
PD4	Which **position** do you have in your company?	Studer et al. (2019), techconsult GmbH (2020a)

Appendix H: Blog References

Appendix H.1: Blog references

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Appendix I: Vlog References

Appendix I.1: Vlog references

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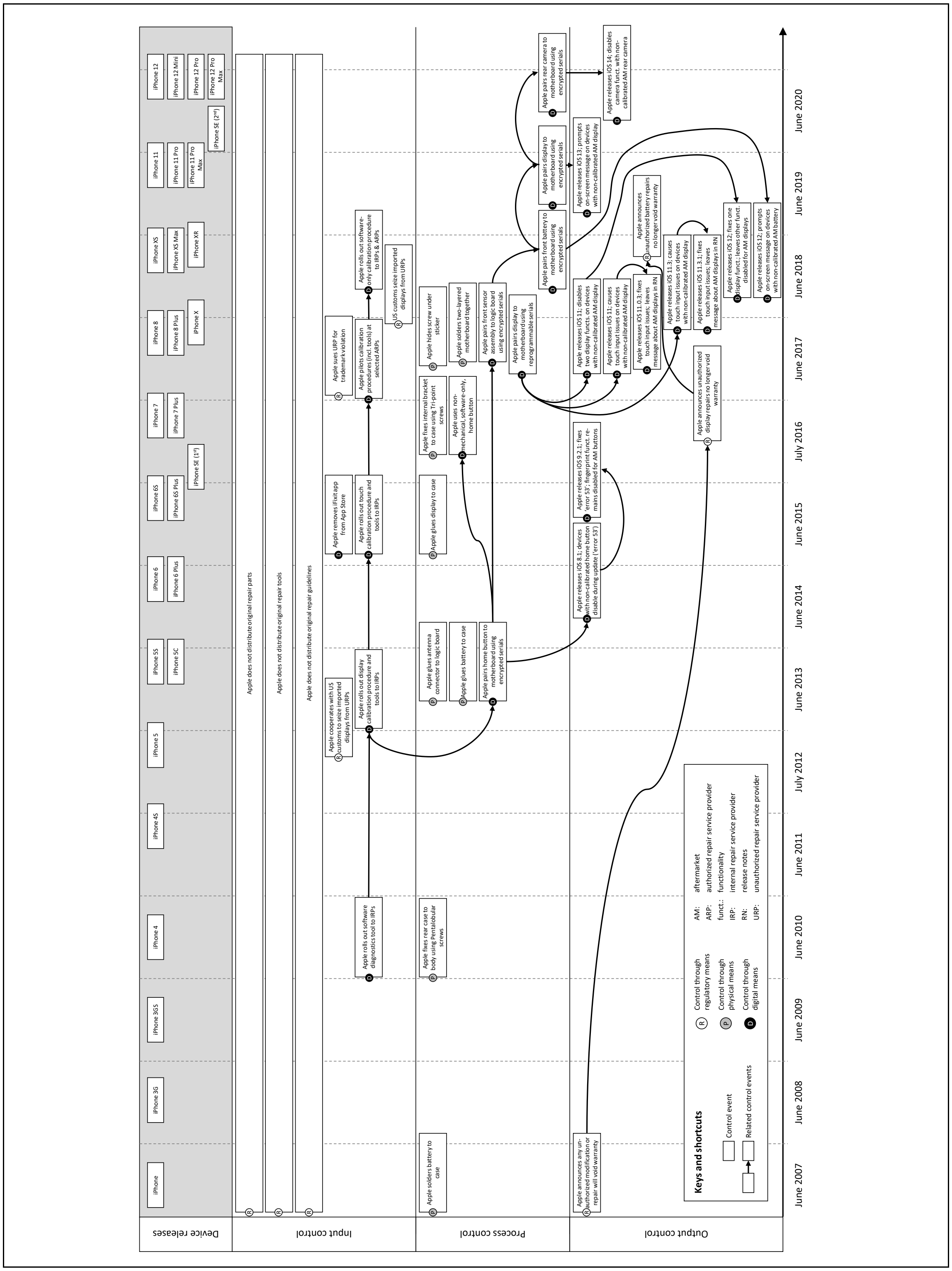
Appendix J: Timeline of Salient Control Events in Apple's iPhone Repair Aftermarket



Appendix J.1. Timeline of Salient Control Events in Apple's iPhone Repair Aftermarket

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