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

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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.

KEYWORDS

circular economy, digital technology, literature review, research agenda, sustainability

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, Forti, Gray, Kuehr, & Stegmann, 2017). In 2016, for instance, almost 45 million metric tons—equivalent to 6.1 kg per capita—of waste from electrical and electronic equipment (ie, 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 minimise 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 optimising production, distribution and consumption processes, extending product lifespans and reintegrating waste materials into supply chains (Geissdoerfer, Savaget, Bocken, & Hultink, 2017; Kirchherr, Reike, & Hekkert, 2017; Potting, Hekkert, Worrell, & Hanemaaijer, 2017).

Research on CE first emerged through scientific conversations on waste and resource management that started in the late 1960s (Boulding, 1966; Meadows, Meadows, Randers, & Behrens, 1972; Stahel & 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 & Brennan, 2017). Over the years that followed, the problem-centric narrative on waste handling and prevention shifted toward an opportunity-centric narrative that emphasised 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 (eg, material flow analysis) to sociotechnical discourse (Bocken, Olivetti, Cullen, Potting, & Lifset, 2017; Bressanelli, Adrodegari, Perona, & Saccani, 2018; Prendeville & 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, Uusitalo, & Kivikytö-Reponen, 2018; Casado-Vara, Prieto, La Prieta, & Corchado, 2018; Reuter, 2016; van Schalkwyk, Reuter, Gutzmer, & Stelter, 2018; Wilts & Berg, 2017), but our own community, with its history of sociotechnical, artefact-centric research (Hirschheim & Klein, 2012; Sarker, Chatterjee, Xiao, & Elbanna, 2019) and its mission to explore how IS can be effectively developed and deployed in the human enterprise (Grover & 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, Peters, Collins, & Gupta, 2016), complex urban systems modelling to help develop smart city solutions (Adepetu, Arnautovic, Svetinovic, & de Weck, 2014), collective network of actions to help sustainable development (Braa, Monteiro, & Sahay, 2004), sociotechnical interventions to combat child mortality (Venkatesh, Rai, Sykes, & Aljafari, 2016), and IS solutions for chronic disease management under complex circumstances in rural, developing regions (Bardhan, Chen, & Karahanna, 2020). Second, technological advances in software (eg, predictive analytics, deep learning and quantum instruction sets) and hardware (eg, microprocessors, sensors, 5G and new materials) make infusing traditional economic products and services with digital functionality increasingly possible (Yoo, Henfridsson, & Lyytinen, 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 & Shim, 2016).

To mobilise 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 (ie, pre-use, in-use, post-use) and CE principles (ie, reduce, reuse, recycle)—operationalisable principles conducive to the CE objective. We find that research has primarily examined IS uses for increasing efficiency of isolated intra-organisational 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 emphasise 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 characterise 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.

2 | BACKGROUND

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, Krausmann, Wiedenhofer, & Heinz, 2015; van Schalkwyk et al., 2018).

The CE is an economic model with the goal of minimising 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 realised 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, McLaughlin, & Börger, 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 policy makers and business practitioners alike as a facilitator of eco-industrial development and increased well-being (Ghisellini, Cialani, & Ulgiati, 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 & 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 & Tan, 2011). In business, organisations 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, Kalverkamp, & Pehlken, 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, Yao, Bhada-Tata, & van Woerden, 2018). Further, digitalization has facilitated business model innovations in the sharing economy that have increased product use in the in-use stage (eg, bike sharing) and that prevent waste by extending PLCs (eg, digital platforms offering refurbished technical devices) (Botsman & Rogers, 2011).

These examples show that organisations 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, Galvão, Abadia, & Carvalho, 2018; Merli, Preziosi, & Acampora, 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 & 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, Watson, Hasan, Molla, & Bjørn-Andersen, 2016; Grover & 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, Melville, & Watson, 2013; Seidel et al., 2017) in contexts, such as energy (Ketter et al., 2016; Watson, Boudreau, & Chen, 2010; Wunderlich, Veit, & Sarker, 2019), mobility (Marett, Otondo, & Taylor, 2013; Valogianni, Ketter, Collins, & Zhdanov, 2020), work (Corbett, 2013; Loeser, Recker, vom Brocke, Molla, & Zarnekow, 2017; Seidel, Recker, & vom Brocke, 2013), or urban management (Corbett & Mellouli, 2017). Reviews of this literature attest that this work has advanced our understanding of the complex global issue that is environmental sustainability (Sedera, Lokuge, Tushi, & Tan, 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 synthesise 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 (de Jesus & Mendonça, 2018; Ghisellini et al., 2016; Türkeli, Kemp, Huang, Bleischwitz, & McDowall, 2018).

2.2 | PLC and CE principles

We use two central CE concepts to guide our literature analysis: PLC stages (Fischer & Pascucci, 2017; Herrmann, Hauschild, Gutowski, & Lifset, 2014) and CE principles (Kirchherr et al., 2017; Zhijun & 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 & Pascucci, 2017). The concept of PLC stages is widely used in lifecycle assessment methodology (Alting & 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 minimising resource input and emission output. Over the past decades, a multitude of frameworks in varying levels of granularity—ranging from three principles (Zhijun & 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 & Nailing, 2007). *Reduce* relates to minimising 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 (eg, sharing) and extend use (eg, 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 (ie, PLC stages) certain activities (ie, CE principles) are supportive for achieving a CE (Table 1). We use this framework as the foundation for our literature review.

TABLE 1 Operationalisation 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	Optimise sourcing, manufacturing and distribution processes Plan and design offerings with minimal inputs and outputs	Optimise consumption processes (ie, use of the offering)	Optimise 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*[a]
Recycle waste into secondary raw materials	Plan and design offerings for recyclability and with secondary materials	Optimise product return	Reprocess waste materials into secondary materials for the manufacturing of new offerings

Abbreviations: CE, circular economy; PLC, product lifecycle.
[a]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 | LITERATURE REVIEW

3.1 | Method

Literature reviews can have different foci and goals (Rowe, 2014; Templier & Paré, 2015). We conducted a developmental review with a structured search strategy and concept-centric analysis, which allows building on ideas grounded in previous research (Templier & Paré, 2015), in our case the problem of sustainable development. We opted for this type of review because it allows putting forward directions for further research through synthesis (Rowe, 2014). The main goal of our literature review was thus to understand and make sense of a whole stream of research on the relationship between IS and CE. To that end, our review unfolded in four steps, drawing on guidelines of vom Brocke et al. (2009), Webster and Watson (2002), and Wolfswinkel, Furtmueller, and Wilderom (2011).

3.2 | Literature selection

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 1 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.

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[1] as a guiding frame of reference and 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,

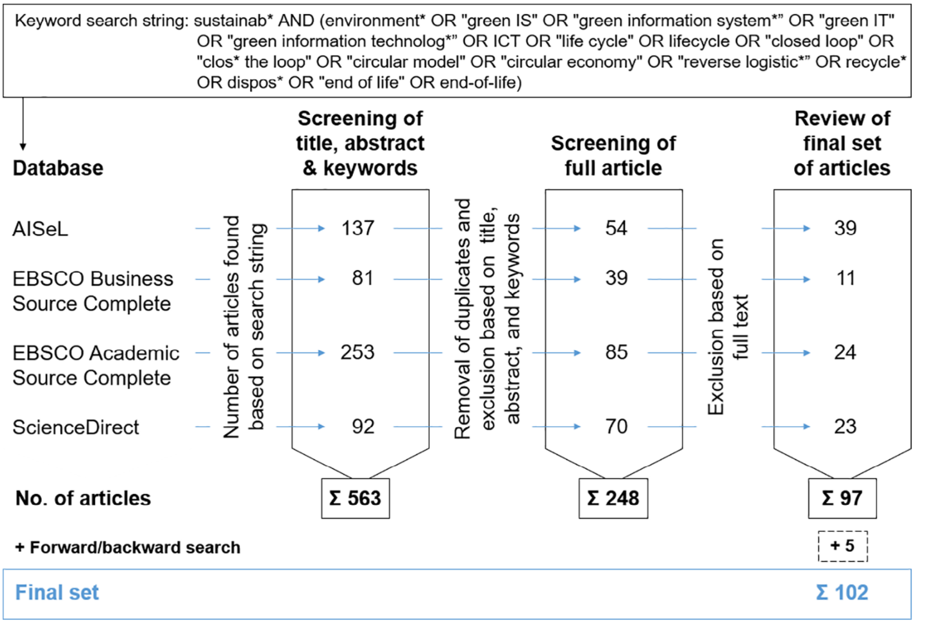


FIGURE 1 Literature selection process [Colour figure can be viewed at wileyonlinelibrary.com]

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 & 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 1).

Keyword search was conducted in titles, keywords, and abstracts of publications with the meta-search tool LitSonar (Sturm & 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 optimising production, distribution and consumption processes, extending product lifespans, and reintegrating waste materials into supply chains. Following careful considerations for journal exclusion (Dubé & Paré, 2003; Elliot, 2011; Karlin, Zinger, & Ford, 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 behaviour and e-waste that emerged from a backward and forward search (Webster & 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). Data S1 summarises outlets and disciplines included in our final sample.

3.3 | Literature coding

Using Microsoft Excel, we coded the 102 articles in line with the coding scheme provided in Data S1. The coding scheme categorises articles according to their *focus* and *unit of analysis* (Dubé & Paré, 2003). To assess the articles' contribution to sustainability, we used as coding categories *PLC stages* (Alting & Jøgensen, 1993; Schrödl & Simkin, 2014) and *CE principles* (Zhijun & Nailing, 2007). Data S1 provides the concept matrix, that is the outcome of our categorisation.

Next, we inductively examined how the studies addressed CE principles and how CE principles were implemented through IS solutions (Schryen, 2015; Wiesche, Jurisch, Yetton, & Krcmar, 2017; Wolfswinkel et al., 2011). Informed by the initial categorisation based on PLC stages and CE principles, we identified prominent first-order descriptive concepts from the analysed articles (eg, ease of disassembly, design for minimum energy-use, toxicity and emissions). In the next step, we synthesised the first-order concepts in higher-order concepts to develop insights about how the identified first-order concepts relate to each other (Gioia, Corley, & Hamilton, 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 analysed 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 &

TABLE 2 Quantitative matching along PLC stages and CE principles

CE principle	PLC stage: Pre-use *(from idea to delivery)*		In-use *(from delivery to end-of-life)*		Post-use *(from end-of-life to next-life)*		No. of articles
*Reduce*energy and material resource input	Optimise sourcing, manufacturing and distribution processes (Process optimization)	63	Optimise consumption processes (ie, use of the offering) (Sustainable consumption)	9	Optimise collection, disassembly, recycling and redistribution processes (Return process optimization)	5	85
	Plan and design offerings with minimum inputs and outputs (Product design for efficiency)	8					
*Reuse*products and components	Plan and design offerings for reparability and upgradability (Product design for reuse)	5	Intensify product use through sharing (Intensified use)	5	*Not applicable*		11
			Extend product and component use through repairing, upgrading, redistribution and remanufacturing (Extended use)	1			
*Recycle*waste into secondary raw materials	Plan and design offerings for recyclability and with secondary materials (Product design for recyclability)	0	Optimise product return (Return behaviour change)	5	Reprocess waste materials into secondary for the manufacturing of new offerings (Material reprocessing)	1	6
No. of articles		76		20		6	102

Abbreviations: CE, circular economy; PLC, product lifecycle.

Strauss, 1990; Wolfswinkel et al., 2011). Coding was performed independently by two authors (Cooper, 1988). Disagreements (eg, 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.

4 | FINDINGS

To present the findings from our coding (Rowe, 2014; Templier & Paré, 2015), we start by indicating the distribution of articles across the categories of PLC stages and CE principles (see Table 2). 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 analysed 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 organisational boundaries were much less frequent. Few articles focused on product design for efficiency (eight articles) and reparability (five articles), and these articles centred on product design for environment and durability aiming at reducing material resource input (CE principles: reduce, reuse).

Research on the *in-use stage* was limited in our sample (20 articles). We found nine articles concerned with motivating sustainable consumption behaviours 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 organisational 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 analyse how the CE principles are implemented in the PLC stages. Rich and detailed accounts of the analysed studies' findings are provided in Data S1.

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 organisational boundaries. We found that in the pre-use stage the literature mainly emphasised increasing *eco-efficiency of business processes* (ie, reducing energy and material resource inputs). The information and transparency capabilities of IS pave the way for sustainability-enhancing concepts such as dematerialization (eg, Bose and Luo (2011)), knowledge dissemination (eg, El-Gayar and Fritz (2006)), workload prediction (eg, Hedwig, Malkowski, and Neumann (2009)) or resource allocation (eg, 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 (eg, sourcing, collection, redistribution) (see Table 3).

Our literature review found no studies on the CE principle *recycle* even though product design for recyclability represents a promising lever to minimise 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 & 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 maximise the utility and value of components and materials (Fischer & 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, Ramudhin, Paquet, & Benkaddour, 2008; Meinrenken, Sauerhaft, Garvan, & Lackner, 2014).

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 behaviour change* (see Table 4).

TABLE 3 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-maximising optimization of manufacturing and distribution processes—sourcing processes are not addressed	Information and transparency capability	Carbon management systems help to promote ecologically responsible behaviours to *improve energy efficiency and material efficiency* of organisations (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, minimises *information asymmetries between collaborating firms* (Grant, Seager, Massard, & Nies, 2010)
		Real cost pricing	IS can improve the information flow on true costs, for example, including the environmental cost of extracting rare earth elements, between stakeholders to ensure that products are ultimately *distributed at real costs* (Desautels & 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, Sharmina, Mendoza, Gallego-Schmid, & Azapagic, 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, Sinha, Singh, & Frostell, 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)

Abbreviations: CE, circular economy; IS, information systems.

A large share of the reviewed literature focused on increasing the eco-efficiency of product use through monitoring and reporting (Krishnan & Teo, 2011; Malmodin, Lundén, Moberg, Andersson, & Nilsson, 2014) and design for environment (Laurenti et al., 2015; Rossi, Charon, Wing, & Ewell, 2006) (ie, on minimising 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, Moberg, & Hochschorner, 2015; Cohen & Muñoz, 2016) and only one study on the remanufacturing of components to extend use (Mazhar et al., 2007). Another small stream of research was

TABLE 4 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-maximising optimization of use processes via monitoring and reporting—sufficiency aspects are not addressed	Monitoring and reporting capability	Smart metre interfaces with user-centred feedback design monitor and report energy-use of households to induce behaviour change toward *efficient energy-use choices* (Dalen & Kraemer, 2017)
		IS capability	Individual technology readiness plays an important role for individuals to actually *apply and make use of supporting technologies* (Krishnan & 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-utilised or unused resources* (Cohen & Muñoz, 2016)
	Core category 6: Extended use		
	Product design for extended lifespans is not addressed and component reuse for remanufacturing is largely disregarded	Extended product and component use	IS can support product optimization, for example, 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, Kara, & Kaebernick, 2007)
Recycle	**Core category 7: Return behaviour change**		
	Research acknowledges the encouragement of individual disposal, collection and recycling behaviour 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 behaviour* (Tong et al., 2018)

Abbreviations: CE, circular economy; IS, information systems.

concerned with motivating individual and organisational recycling activities to optimise collection and recycling (Chen, Fujita, Ohnishi, Fujii, & Geng, 2012).

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* (see Table 5).

The studies concentrate mainly on the implementation and optimization of return logistics to improve the return ratio and dissemination of returned products, thereby minimising the virgin material input according to the *reduce*

TABLE 5 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-maximising 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, Lorena, Costa, Ribeiro, & Ferrão, 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, that is, 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)

Abbreviations: CE, circular economy; IS, information systems.

principle (Manhart, 2011). Extended producer responsibility represents an important policy-induced strategy to lead organisations to internalise disposal costs (Rodrigues et al., 2016; Tong & Yan, 2013) and redesign products that facilitate the reuse of components (Webster & Mitra, 2007). Our review of the literature identified only one article (Haas et al., 2015) focusing on the reprocessing of materials (ie, on the *recycling* of waste into secondary materials that can be used in the manufacturing of new products).

The reviewed studies tackle efficient collection behaviour 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 maximise the utility and value of components and materials (Fischer & Pascucci, 2017; Haas et al., 2015), the circularity of global material flows is often neglected and remains a challenge.

4.4 | Synthesis

The literature we reviewed has focused mostly on maximising efficiency of intra-organisational processes during the pre-use stage (ie, sourcing, manufacturing, distribution). In addition, manufacturing organisations have been the predominant unit of analysis.

This narrow research scope on organisational *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 & Corbett, 2016; Krishnan & 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 realising an intensified and extended use of products and components and close raw material loops at the end of a PLC (Reike, Vermeulen, & Witjes, 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 analyse 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, Zhao, & Sutherland, 2017; Mazhar et al., 2007), or the recycling of valuable resources (Pil & Cohen, 2006; Rocchetti, Amato, & Beolchini, 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 organisational boundaries of a focal manufacturer to include actors that cross supply chains and industry sectors, such as waste managers (Richter & 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-organisational 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 & Lewin, 1990; Dobusch, Kremser, Seidl, & Werle, 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 (eg, 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 & 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., 2016, 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, Nan, Tanriverdi, & Yoo, 2020; Jacucci, Hanseth, & Lyytinen, 2006; Merali, Papadopoulos, & Nadkarni, 2012).

5 | MOBILISING IS SCHOLARSHIP FOR A CE

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., 2016; 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., 2016). Joint technological and managerial innovations can make complex problems tractable (Churchman, 1967; Rittel & 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 organisational 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 mobilised, 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 & 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 (ie, 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.

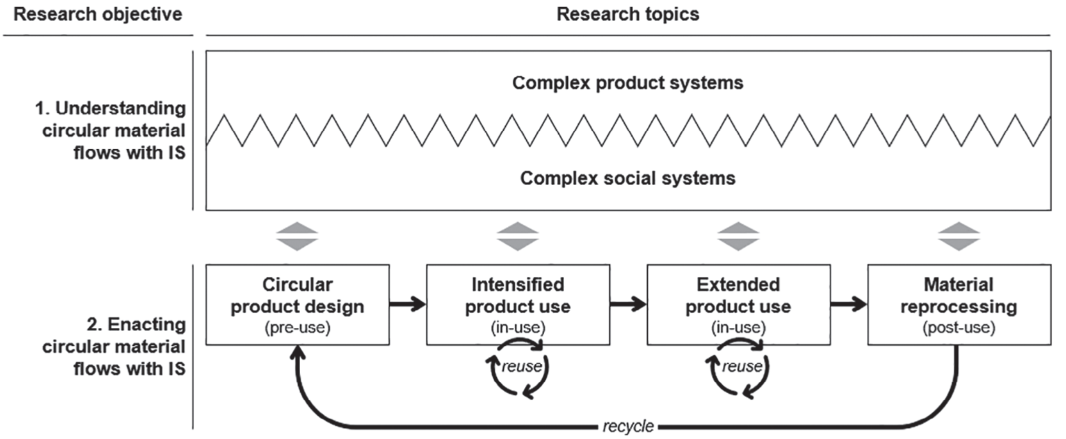
Figure 2 depicts our proposed research agenda and defines its key concepts. It shows two *research objectives* on the left-hand side and six corresponding *research topics* on the right-hand side. In accordance with our understanding of a CE as a complex sociotechnical system, the two research topics 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.[2] 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 2 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 & 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 mobilise research to answer these questions, we highlight selected research streams[3] available in IS literature that in our view provide helpful knowledge traditions for launching into these inquiries. Table 6 summarises research objectives, topics, illustrative research questions and selected IS research programs.

5.1 | Understanding circular material flows with IS

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.



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 & Eppinger, 2001).
Complex social systems	Multi-directional and multi-lateral networks of heterogeneous actors across multiple supply chains and industries (Konietzko, Bocken, & Hultink, 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 & 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, Bocken, van den Hende, & Schoormans, 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 2 Definition of research objectives and topics for IS scholarship for a CE. CE, circular economy; IS, information systems

5.1.1 | Complex product systems

Material complexities in circular material flows emerge from the dynamic and unpredictable behaviour 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, Recker, & Müller, 2019). At their end-of-life, product

TABLE 6 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 behaviour 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

Abbreviations: CE, circular economy; IS, information systems.

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, Recker, Indulska, Green, & Weber, 2017; Weber, 1997). The research program on IS as representational vehicles (Burton-Jones et al., 2017; Recker, Indulska, Green, Burton-Jones, & Weber, 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 (eg, new, used, broken, repaired, unusable) evoked through events alongside the PLC (eg, 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 (eg, 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 (eg, 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 theorised 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, Kourouthanassis, & Pramatari, 2011; Thiesse, Al-Kassab, & Fleisch, 2009; Wamba & 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 optimise 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 & 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 & 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 & 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 (ie, production) and decomposition (eg, 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.

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, Cappellaro, Masoni, & Amato, 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 realising 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 & Pascucci, 2017; Grant et al., 2010; Wilhelm, Blome, Bhakoo, & Paulraj, 2016). Product system data shared across circular value networks can contain sensitive business information and valuable trade secrets (Fraccascia & 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 & Brown, 2010; Otto, 2011; Tallon, 2013). While IS literature has developed a thorough understanding of intra-organisational data governance, less is known about governing collaboration and data sharing in an inter-organisational setting (Abraham, Schneider, & vom Brocke, 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, Trienekens, Kusters, & Grefen, 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-organisational 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 & 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 decentralised 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, Müller-Bloch, & King, 2018) can support the design and implementation of CE data governance solutions. The Dutch start-up Circularise (2019), for instance, developed a blockchain-based decentralised 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 (eg, '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-organisational data governance.

5.2 | Enacting circular material flows with IS

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).

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 & 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 & 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, Harrison, & Billett, 2006; Huang, 2008; Laurenti et al., 2015; Mazhar et al., 2007; Pil & Cohen, 2006; Shuaib et al., 2014). However, only limited research has approached these concepts from a socio-technical 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 & 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 (eg, 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 & Te'eni, 2009; Yoo et al., 2010). Generative capacity is open-ended, creative and innovative but also ambiguous, divergent and unknown (Avital & 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 & Standaert, 2018) before committing to material object production to generate views that 'unravel and challenge' (Jarvenpaa & 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 & Heppelmann, 2014). The IS conversation on the digital augmentation of product offerings has focused on how economic value-in-use can be increased (Kohli & Melville, 2018; Lusch & 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, Babbitt, Tyler, & Babbitt, 2014), negative impacts such as faster obsolescence of interdependent software and hardware (Ixmeier & Kranz, 2020; Jenab, Noori, Weinsier, & Khoury, 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-organisational enterprise IT (Murugesan, 2008; Sedera et al., 2017) through practices such as optimising algorithmic energy efficiency (Mukherjee & Sahoo, 2010), power management (Jenkin, Webster, & McShane, 2011), or server virtualization (Bose & Luo, 2011). These concepts and recommendations could be explored further. For example, goal-oriented requirements modelling language for environmentally concerned organisational systems design (Zhang, Liu, & Li, 2011) could also be leveraged to conceptualise the PLC of digital objects (eg, smartphones) and aid product designers in estimating the environmental impacts of design alternatives.

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 & Muñoz, 2016). Thereby, the service value (eg, mobility) generated by-product systems (eg, a car) is maximised and the overall consumption of natural resources can be lowered (Bardhi & 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, Konsynski, & Bush, 2010). However, our review showed that platform research on intensified product use beyond a purely economic motive is scarce (Achachlouei et al., 2015; Achachlouei & Moberg, 2015; Cohen & Muñoz, 2016; King, Burgess, Ijomah, & McMahon, 2006; Vykoukal, Wolf, & Beck, 2009). Most IS research on collaborative consumption and the sharing economy refers to sustainability only indirectly or spuriously, if at all (Greenwood & Wattal, 2017; Guo, Li, & Zeng, 2019; Mittendorf, Berente, & Holten, 2019; Teubner & Flath, 2019; Weber, 2014, 2016, 2017; Zimmermann, Angerer, Provin, & Nault, 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 & 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, Marton, & Tuunainen, 2017) to investigate how factors like price (Zimmermann et al., 2018) or trust (Mittendorf et al., 2019) affect collaborative consumption behaviour. 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 (eg, the bike-sharing provider Donkey Republic (2019)), while fashion platforms rely on logistics and laundry service providers that ship and clean the apparels (eg, 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, Peters, Solli, & Hertwich, 2005; Hollingsworth, Copeland, & Johnson, 2019; Martin, 2016; Zamani, Sandin, & Peters, 2017). Unintended offline consumption behaviour 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 behaviour, which shortens products' average lifetime and thwarts sustainability efforts (Hildebrandt, Hanelt, & Firk, 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 behaviour can be ‘designed out’ through deliberate interface design choices when building collaborative consumption platforms. In a first step, different forms of unintended consumption behaviour must be empirically documented and underlying social and psychological mechanisms that explain this behaviour 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, Schneider, & vom Brocke, 2016) could be a promising starting point. While originally defined as ‘the use of user-interface design elements to guide people's behaviour in digital [(online)] choice environments’ (Weinmann et al., 2016, p. 433), digital nudging might also be applied to guide real-world (offline) behaviour, such as encouraging energy-efficient behaviour in private households using IS feedback systems (Loock, Staake, & Thiesse, 2013) or invoking change in people's health behaviour (Noorbergen, Adam, Attia, Cornforth, & Minichiello, 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 (eg, ‘Do I park the returned e-scooter where I have to get off letting it block the sidewalk or do I park it 50 metres down the road, where it does not disturb?’) must be nudged a priori in the online world (eg, via an e-scooter-sharing smartphone app). Moreover, existing studies focus on the short-term effects of digital nudges in one-off decisions (Schneider, Klumpe, Adam, & Benlian, 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 summarise, how to design digital nudges for offline choice architectures is still unclear, as is how effective they are.

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 & 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 behaviour has various reasons, ranging from lack of awareness and low trust in repair or upgrade services to lack of economic incentives (Cole, Gnanapragasam, Cooper, & Singh, 2019; Wieser & Tröger, 2018). Moreover, self-repair requires technical knowledge (eg, disassembly instructions), skills (eg, training), and resources (eg, 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, Mosgaard, & Zacho, 2016). This lack of information and guidance leads to ecologically and economically suboptimal dispositions (Atlason, Giacalone, & Parajuly, 2017; Sabbaghi, Esmaeilian, Raihanian Mashhadi, Behdad, & Cade, 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 Section 5.1.1) 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 & Browne, 2000; Staikos & Rahimifard, 2007; Ziout, Azab, & Atwan, 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 (eg, 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 & McEachern, 1998) and, in particular, recommendation agents (Maes, Guttman, & Moukas, 1999; Wang & 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 & Benbasat, 2006; Xiao & Benbasat, 2007; Xu, Benbasat, & Cenfetelli, 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 (eg, consumer electronics), many consumers discard functioning products to replace them with newer models (Welfens, Nordmann, & Seibt, 2016; Wieser & Tröger, 2018). New models and technology innovations drive consumers' perceptions of products' obsolescence, which in turn affects consumers' preferences favouring product replacement over product repair and new products over second-hand products (Jardim, 2017; Ongondo, Williams, & Cherrett, 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 & 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, Coats, & Hazell, 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 & 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.

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; 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 (eg, gold), rare earth metals (eg, yttrium), and hazardous metals (eg, 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, Hait, & Thakur, 2017; Tam, Soulliere, & Sawyer-Beaulieu, 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 (ie, 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 revolutionise 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 & Farrell, 1994; Farrell & 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 standardisation processes. IS research could inform the standard-setting process by, for instance, evaluating the effectiveness of different IT architectural design choices (Baldwin & Woodard, 2009) or investigating the effect of different standardisation processes, such as management-based, technology-based, or performance-based standards (Roca, Vaishnav, Morgan, Mendonça, & Fuchs, 2017) on standard adoption, governance, social welfare, network externalities or standardisation costs (Liu, Gal-Or, Kemerer, & Smith, 2011; Lyytinen & King, 2006; Zhao, Xia, & Shaw, 2011). For instance, IS research could provide dynamic perspectives on standardisation 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 & Yazan, 2018; van Capelleveen, Amrit, & Yazan, 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 & Berg, 2017). Waste producers often lack information on companies in need of recycling derivatives (Aid, Eklund, Anderberg, & Baas, 2017; Golev, Corder, & Giurco, 2015). Further, the quality of recycled materials can vary considerably, resulting in a market characterised 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 & Worrell, 2014).

Online platforms have been recognised as important enablers to form and coordinate markets for secondary resources (Grant et al., 2010; Konietzko, Bocken, & Hultink, 2019). Previous studies have mainly focused on platforms for industrial symbiosis (Halstenberg, Lindow, & Stark, 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 (eg, within industrial parks) with predictable streams of by-products (Ashton, 2008; Bellantuono, Carbonara, & Pontrandolfo, 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 (eg, material purity) and social (eg, trust) complexities that increase with the size of the circular material flows.

Drawing on the extensive knowledge base on multi-sided platforms (Boudreau & Hagiu, 2009; de Reuver, Sørensen, & Basole, 2018; Gawer & 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 & Shapiro, 1985) or the role of intermediaries (Evans, 2003). First, looping secondary resources into new product systems comprises a combination of online (ie, matchmaking) and offline (ie, fulfillment) transactions. Second, supply and demand of secondary materials occur asynchronously and spatially dispersed (Wilts & 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 & Smith, 2000; Forman, Ghose, & Goldfarb, 2009) will be important to consider in future investigations on platforms for secondary materials exchange. For instance, Li, Shen, and Bart (2018) show how online-to-offline platforms 'differ from traditional two-sided online platforms by emphasising 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.

6 | CONCLUSIONS

Many grand challenges affecting economies, societies, and the environment strongly involve IS and need attention from scholars (Davison & 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 realised the full sustainability potential of a CE model. We hope that our article will mobilise 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 & Mellouli, 2017; Elliot & Webster, 2017; Hedman & 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 favour 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 endeavour and networked collaboration across research disciplines will ultimately be needed.

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DATA AVAILABILITY STATEMENT

All data generated or analysed during this study are included in this published article (and its Supporting Information).

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ENDNOTES

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

[2] Core categories 1, 2, 4 and 8 relate to the *reduce* principle (see Tables 3-5).

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

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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