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Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations

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Abstract This work makes a case for the integration of the increasingly popular and largely separate topics of Industry 4.0 and the circular economy (CE). The paper extends the state-of-the-art literature by proposing a pioneering roadmap to enhance the application of CE principles in organisations by means of Industry 4.0 approaches. Advanced and digital manufacturing technologies are able to unlock the circularity of resources within supply chains; however, the connection between CE and Industry 4.0 has not so far been explored. This article therefore contributes to the literature by unveiling how different Industry 4.0 technologies could underpin CE strategies, and to organisations by addressing those technologies as a basis for sustainable operations management decision-making. The main results of this work are: (a) a discussion on the mutually beneficial relationship between Industry 4.0 and the CE; (b) an in-depth understanding of the potential contributions of smart production technologies to the ReSOLVE model of CE business models; (c) a research agenda for future studies on the integration between Industry 4.0 and CE principles based on the most relevant management theories.

Keywords Smart manufacturing · Circular economy · Digital manufacturing · ReSOLVE framework · Internet of things · Sustainable operations

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1 Introduction

The circular economy (CE) is claimed to be a new business mind-set that can help organisations and society move towards sustainable development (McDowall et al. 2017). For example, China, some European countries and Japan have implemented incentive regulations to encourage organisations to pursue CE principles (Geng et al. 2013; Ghisellini et al. 2016; Mathews and Tan 2016; Winans et al. 2017). In addition, a substantial amount of recent literature deals with this subject (e.g. Liu et al. 2012; Nasir et al. 2017).

The CE offers a new and different perspective on the organisational and operational systems of production and consumption, one which is focused on restoring the value of used resources. The CE proposes that a circular approach to energy and materials can provide economic, environmental, and social benefits (Geissdoerfer et al. 2017) to organisations when they replace the traditional perspective of 'take, make, use and dispose'—also known as the linear economy—with the CE. However, there have been barriers to the full adoption of CE principles within organisations and supply chains. It has been identified, for instance, that a lack of information on the life cycle of products, as well as a shortage of advanced technologies for cleaner production, have diminished the reach of CE principles (Geng and Doberstein 2008; Su et al. 2013). Furthermore, the perceived uncertainty regarding costs, return on investments and timeline for implementation often results in initial reluctance from corporations to adopt such an ambitious goal. Nevertheless, since emerging technologies based on the principles of Industry 4.0 have spread, it may now be feasible to overcome barriers to the CE by adopting emerging technologies related to smart manufacturing.

Industry 4.0—also known as smart manufacturing—is based on manufacturing systems driven by information technology (IT) (Lasi et al. 2014). It involves a combination of smart factories and products and the Internet of Things (Stock and Seliger 2016; Lasi et al. 2014; Shrouf et al. 2014), and aims to provide real time information on production, machines, and flow of components, integrating this information in order to help managers to make decisions, monitor performance, and track parts and products (Lu 2017).

It can certainly be argued that Industry 4.0 technologies have the capability to pave the way for CE principles, for instance by tracking products post-consumption in order to recover components. However, due to the very recent emergence of these ideas, the relationship between the CE and Industry 4.0 technologies has not been widely explored in the literature, and the two topics have largely been analysed separately. This work makes a case for integrating these emerging topics by:

- Identifying technologies and resources from Industry 4.0 that are suitable for advancing the CE;
- Exploring how the ReSOLVE framework of the CE can be applied and further developed by linking it to Industry 4.0 approaches;
- Discussing the relationship between the CE and Industry 4.0 in order to achieve sustainable operations management;
- Developing a pioneering roadmap to enhance the application of CE principles in organisations by means of Industry 4.0 approaches;
- Proposing an original research agenda to further understanding of this topic.

This article contributes to the literature by discussing how a variety of Industry 4.0 technologies can underpin CE strategies, and to organisations by addressing those technologies on which they can base sustainable operations management decisions. This work is unique as it addresses a significant gap in the knowledge of this topic and provides insight into the relationship between smart manufacturing and the CE. For instance, while some literature has addressed the relationship between Industry 4.0 and organisational sustainability (e.g. Stock and Seliger 2016; Trentesaux et al. 2016; Waibel et al. 2017), the connection between the CE and Industry 4.0 technologies has not been extensively discussed.

The article is organised as follows. Section 2 presents the key concepts of the CE and smart manufacturing. Section 3 encapsulates the fundamentals of integrating the CE and Industry 4.0. Section 4 contains the original roadmap that can further understanding on the co-evolution of the CE and Industry 4.0, and Sect. 5 presents a research agenda and draws some conclusions.

2 Theoretical background

2.1 The circular economy: concepts, principles, and business models

In the context of sustainable production and consumption (Fahimnia et al. 2017), the Circular Economy is an emerging approach aimed at the sustainable use of natural resources (McDowall et al. 2017). The CE focuses on maximizing the circularity of resources and energy within production systems, based on the fact that natural resources are scarce, and that waste at the end of its life may retain some value (Ghisellini et al. 2016).

The CE is based on two key cycles: one biological and one technical (MacArthur et al. 2015). The biological cycle regenerates ecosystems by reducing excessive extraction of natural resources, using renewable materials and reusing energy and organic waste by means of anaerobic digestion. The technical cycle emphasises the extension of a product's lifespan through a hierarchy of circularity strategies, which include reuse, repair, refurbishment, remanufacturing (Zhao and Zhu 2015) and recycling; technical cycles seek to turn what is regarded as waste into resources for other production systems (Bocken et al. 2017; Murray et al. 2017).

Three principles govern the CE cycles, namely: (1) conservation of natural capital, which means creating an equilibrium of consumption between renewable and non-renewable resources; (2) increasing the lifespan of resources through both biological and technical cycles, i.e. enhancing the circularity of resources and energy; and (3) reduction of the negative effects of production systems (MacArthur et al. 2015).

The Ellen MacArthur Foundation, a leading global charity in establishing the CE's position on the agenda of decision-makers across business, government and academia (MacArthur 2015), has proposed the following six business actions—the ReSOLVE framework—to guide organisations through implementing the principles of the CE:

- *Regenerate* This is based on a shift to renewable energy and materials. Biological cycles are used to enable the circulation of energy and materials, and to convert organic waste into sources of energy and raw material for other chains.
- *Share* This is embedded in a shared economy perspective, in which goods and assets are shared between individuals; ownership thus loses importance. As a consequence, products should be designed to last longer, and maintenance should be available to allow re-use and extension of product life.
- *Optimise* A technology-centred strategy. This model requires that organisations use digital manufacturing technologies, such as sensors, automation, radio-frequency identification (RFID), big data, and remote steering to reduce waste in production systems across supply chains. Organisations will benefit from increased performance; for instance,

a predictive maintenance scheme can be planned based on real-time data reporting the conditions of machines (MacArthur and Waughray 2016).

- *Loop* This is based on biological and technical cycles. Biological cycles, for example anaerobic digestion, are important to recapture the value of organic waste; technical cycles can restore the value of post-consumption products and packaging by means of repair, reuse, remanufacture, and recycling. Operations research approaches have been used to study these options (e.g. Loomba and Nakashima 2012).
- *Virtualise* A service-focused strategy which replaces physical with virtual and dematerialised products.
- *Exchange* This involves substituting old and non-renewable goods for advanced and renewable ones. Keilhacker and Minner (2017) show, by means of a system dynamics model, that substitution has significant potential to mitigate supply chain unavailability caused by rare earth elements.

Lieder and Rashid (2016) carried out a comprehensive systematic literature review on the CE in order to identify the research themes that have been studied so far. The finding was that three main CE-related topics were studied; namely, resource scarcity, environmental impact, and economic benefits. The authors also stated that most business and economic aspects have not yet been addressed; this lack of research and unavailability of evidence of its advantages could reduce CE initiatives implemented by industry.

Winans et al. (2017) identify exchange of information as one of the major constraints on the effectiveness of CE. Additionally, the authors also highlight that it is critical to know the quality of materials circulating within production systems after their collection.

By and large, it seems that new research is needed that is capable of shedding light on how organisations can gain competitive advantages by mitigating constraints on the effectiveness of the CE. Therefore, the potential contribution of Industry 4.0 to CE is emphasised in the next section.

2.2 Industry 4.0: concept and available technologies

The concept of Industry 4.0 is quite new; it was launched in Germany in 2011, and represents the current production paradigm, which combines information and communication technologies with digital manufacturing technologies (Kang et al. 2016).

According to Shrouf et al. (2014), the core feature of Industry 4.0 is connectivity between machines, orders, employees, suppliers, and customers due to the internet of things and electronic devices; as a consequence, firms are able to produce products using decentralised decisions and autonomous systems (Lasi et al. 2014). Trentesaux et al. (2016) add that Industry 4.0 enables smart factories and products, with the result that components, machines and digital devices can communicate with each other in order to self-manage production lines and provide high performance in terms of product design, production, and logistics systems. To summarise, the main characteristics of Industry 4.0 are integrated, adapted, optimised, and interoperable manufacturing processes (Lu 2017).

The application of Industry 4.0 technologies enables the real-time monitoring and controlling of important production parameters such as production status, energy consumption, flow of materials, customers' orders, and suppliers' data. Additionally, these technologies facilitate relationships and communication with customers due to the connectivity between customers and products; as a consequence, organisations are able to develop products that meet real customers' needs (Shrouf et al. 2014).

An overview of the core technologies of Industry 4.0 is provided in Table 1. This table was developed based on data compiled by Kang et al. (2016), in response to the fact that the

Table 1 An overview of the core technologies of Industry 4.0. *Source*: Based on Kang et al. (2016)

Technology	Brief description	Example of resources
Cyber-physical systems	Enables automation, monitoring, and control of processes and objects in real time (Wang et al. 2015)	Controllers and sensor systems (Wang et al. 2015; Yu et al. 2015)
Cloud manufacturing	Virtual portals which create a shared network of manufacturing resources and capabilities offered as services (Yu et al. 2015)	The internet
Internet of things	A computational system which collects and exchanges data acquired from electronic devices (Kang et al. 2016)	Radio-frequency identification (RFID) technology tags, sensors, barcodes, smart phones (Da Xu et al. 2014; Atzori et al. 2010)
Additive manufacturing	Represents agile and connected prototyping of parts of products on a large scale, enabling customisation (Holmström et al. 2016)	3D printers

literature in this field has not reached clear consensus on the types of technologies included. Zhong et al. (2017) identify the key technologies in the context of Industry 4.0 as cyber-physical systems, the internet of things, big data, and cloud manufacturing.

Cyber-Physical technological systems enable the integration of cyber space, physical processes and objects in order to connect machines and devices in production lines as a network, thus making real data available for decision-making, such as for the prioritisation of production orders, optimisation of tasks, reporting of maintenance needs, etc. (Ahmadov and Helo 2016; Lee et al. 2015). Sensors and actuators are responsible for gathering and distributing this data in real-time (Yu et al. 2015).

Cloud manufacturing is a technology that creates a virtual and global space for enabling a shared network of manufacturing resources and capabilities through the internet. The logic of cloud manufacturing is service-based, meaning that suppliers and customers interact in order to sell and buy services—for instance, design, simulation, manufacture, and assembly of products. Cloud manufacturing is recommended for its e-commerce features (Yu et al. 2015), and also involves other technologies from Industry 4.0, such as additive manufacturing.

The internet of things (IoT) refers to the interconnectivity between things, such as electronic devices, smartphones, machines, modes of transportation, and the internet, through unique identification codes which allow these things to communicate with one another to achieve common aims (Atzori et al. 2010; Da Xu et al. 2014). By means of the IoT, cyber-physical systems can be connected to companies and individuals, enabling interoperability with them (Hermann et al. 2016). As a consequence, real-time data collection and sharing are able to occur among all parties (Zhong et al. 2017). The exchange of information between the things will generate a large quantity of data which can be subsequently analysed to improve added value for organisations (Roblek et al. 2016). In this sense, the big data approach enables analysis of the high volume and variety of data that comes from the application of the internet of things (Akter and Fosso Wamba 2017; Witkowski 2017). Big data has been used, for instance, to improve product development (Zhan et al. 2016), demand forecasting in supply chains (Li et al. 2016), and green production policies (Du et al. 2016). Radio-frequency identification (RFID) technology tags, sensors, barcodes, and smartphones are the most common resources used in implementing the internet of things (Atzori et al. 2010; Da Xu et al. 2014).

Additive manufacturing is based on the manufacture of parts of products without the need to acquire and use specialised tools; additionally, production occurs through digital design, which enables both a shortened lead time on production and connectivity between designers, engineers, and users (Holmström et al. 2016). 3D printers are the main resources associated with additive manufacturing.

Some literature has addressed the relationship between Industry 4.0 and organisational sustainability (e.g. Stock and Seliger 2016; Trentesaux et al. 2016; Waibel et al. 2017). However, the connection between CE and Industry 4.0 technologies has not been thoroughly explored, and this theme is therefore developed in the next section.

3 Connections between the circular economy and Industry 4.0: implications for sustainable operations management

Recently, PricewaterhouseCoopers (PwC) published a news item in order to highlight synergies between CE and Industry 4.0. However, their announcement merely introduced the topic without developing it in depth (Van den Beukel 2017). A McKinsey Global Expert Survey, exploring attitudes towards Industry 4.0, determined that a limited number of respondents had a clear roadmap for implementing Industry 4.0 (Bauer et al. 2016). It can therefore be argued that a knowledge gap exists related to how organisations should build the path towards sustainable operations management and the achievement of CE strategies, taking into consideration the current technological tendencies of Industry 4.0. According to Man and Strandhagen (2017) and Stock and Seliger (2016), Industry 4.0 technologies contribute to sustainable operations management decisions and new business models by means of integrating value chains through data collection and sharing. Therefore, sustainable operations management decisions contribute to implementing the connection between the principles of CE and Industry 4.0 approaches.

Sustainable operations management refers to the integration of the traditional perspectives of efficiency and profit from operations management, with a simultaneous awareness of the environmental impacts of production operations (Kleindorfer et al. 2005). According to Gunasekaran et al. (2014), sustainable operations management can be divided into sustainable products, production/processes, and logistics decisions. Therefore, taking into account the concept of sustainable operations management—which is paramount for implementing organisational strategies based on CE principles—the ReSOLVE framework of CE is proposed, and its implementation, based on the effective adoption of the technologies/resources of Industry 4.0, is discussed.

By constructing the matrix in Table 2 we relate sustainable operations management decisions (design of products, production of products, and logistics/reverse logistics) to the six business models proposed by the ReSOLVE framework; we also present the Industry 4.0 technologies that could be applicable to each relationship. The matrix was developed based on Sect. 2 of this article. An explanation of the relationships proposed by the matrix follows Table 2.

The *Regenerate* business model could benefit from Industry 4.0 by applying the internet of things in the form of sensors and apps; for example, to plan, monitor, and control factors related to land management between rotation of harvests, to automate irrigation systems based on weather conditions in real time, and to manage the use of pesticides according to the health of plantations (MacArthur and Waughray 2016). The design and production decisions of sustainable operations management could be adapted based on data provided by the

Table 2 Matrix of the relationships between CE, Industry 4.0, and sustainable operations management. *Source*: Authors

ReSOLVE	Design of products	Production of products	Logistics/reverse logistics
Regenerate	✓ Internet of things	✓ Internet of things	–
Share	✓ Cloud manufacturing	✓ Cloud manufacturing	✓ Internet of things
	✓ Internet of things	✓ Internet of things	
Optimise	–	✓ Cyber-physical systems	✓ Internet of things
		✓ Internet of things	
Loop	✓ Internet of things	✓ Internet of things	✓ Internet of things
		✓ Cyber-physical systems	✓ Cloud manufacturing
Virtualise	✓ Cloud manufacturing	✓ Cloud manufacturing	✓ Internet of things
	✓ Internet of things	✓ Internet of things	
		✓ Additive manufacturing	
Exchange	✓ Additive manufacturing	✓ Additive manufacturing	–

resources of the internet of things. As a consequence, it would be possible to reduce resource consumption (of water, nutrients, energy, etc.), to improve the productivity of harvests, and to extend the life cycle of the land.

The *Share* business model could reach its full potential through the use of both cloud manufacturing and the internet of things, since these technologies enable people to connect and share information related to supply and demand. Websites and apps are important resources for connecting people with organisations. Additionally, these technologies are able to collect information on consumers' behaviour; organisations can therefore improve both product and service design for better utilisation or replacement of equipment, and increase customers' satisfaction (Rymaszewska et al. 2017). Moreover, the use of sensors in products allows performance monitoring—for instance, monitoring maintenance requirements—thereby allowing organisations to proactively provide a high quality of service to customers. Furthermore, as a consequence of monitoring products during consumer use, organisations can invest in extending products' life spans by applying the 3Rs strategy (reduce, re-use, and recycle) due to shifting ownership of products. The design, production, and logistics decisions of sustainable operations management can be adaptable, based on the data provided by the resources of cloud manufacturing and the internet of things.

The *Optimise* business model could be supported by cyber-physical systems and the internet of things. These technologies are able to collect data from processes and objects, such as machines; it is therefore possible to identify failures, which might create waste. Additionally, based on the parameters of production and consumption of resources—for example, energy—managers could monitor and control the performance of operations; the use of sensors would enable them to intervene in processes, even during production of components/products. Efficiency of machines could also be assessed in real time in order to plan maintenance, thus avoiding excessive use of resources. Moreover, delivery routes could be optimised according to operational and environmental indicators. Suppliers could be involved in managing their own performance in terms of production planning, quality, deliveries (Hofmann and Rüsch 2017), and environmental compliance by using RFID tags and the internet of things; this would entail optimisation of resource usage. The production and logistics decisions of sustainable operations management would be adaptable, based on the data provided by the resources of cyber-physical systems and the internet of things.

The *Loop* business model represents a broad perspective on the CE, as its overall aim is for significant extension of the circularity of materials and energy. As a result, design, production, and logistics decisions should be adapted. The Industry 4.0 technologies which could support the Loop approach are the internet of things, cyber-physical systems and cloud manufacturing. Design could include chips or sensors informing users of the components and materials contained in the product, and how they can be disassembled and recycled at the end of the product's useful life. This concept is called 'product passport' (European Commission 2013). Provision of 'product passport' information would facilitate CE cycles. Production decisions could gain the same advantages from the internet of things and cyber-physical systems as highlighted in *Optimise* business model. Logistics and reverse logistics could improve their processes through the internet of things due to the fact that post-consumption products and packaging can be tracked and traced using sensors, RFID tags, and barcodes. As a consequence, organisations are able to reuse, remanufacture, or recycle components of products and packaging (Vanderroost et al. 2017). Cloud manufacturing could support organisations in this business model by finding buyers for reused or refurbished components (MacArthur and Waughray 2016).

The *Virtualise* business model could be advanced using cloud manufacturing, the internet of things, and additive manufacturing technologies. Both cloud manufacturing and the internet of things enable connection between organisations, suppliers, and customers in order to offer services rather than physical products. Additionally, these technologies are able to collect information on consumers' behaviour, which organisations can use to improve service design. There are businesses that, based on interaction between organisations and customers, are able to manufacture customised products by using 3D printers. The role of cloud manufacturing in this case is to link supply and demand. Since service is a core focus of the Virtualise business model, tracking deliveries is important to enhance customers' experience. Thus, the design, production, and logistics decisions of sustainable operations management would be adaptable based on the data provided by the resources of cloud manufacturing and the internet of things.

The *Exchange* business model could gain advantages by adopting additive manufacturing and the internet of things. 3D printers are able to advance renewable and sustainable production. According to Despeisse et al. (2017), the characteristics of additive manufacturing lead to reduced use of material; further, it enables the recycling of small quantities of waste because of the portability of 3D printers. The design and production decisions of sustainable operations management would thus be able to approach CE principles.

To conclude, the relationships discussed here represent the current situation identified by the authors, and other relationships could certainly emerge in future. The next section will introduce a pioneering roadmap to guide an organisation on the journey to Industry 4.0-based CE, taking the discussion from this section into account.

4 Proposed pioneering roadmap, integrating Industry 4.0 and CE

Figure 1 illustrates the roadmap proposed in this work.

As outlined in Sect. 3, the ReSOLVE framework proposes six different business models for pursuing CE principles. Therefore, the first step for organisations that aim to move toward CE is to decide which models are suitable to their production processes and purpose—organisations may have definite capacity levels for the circularity of resources, which influences the extent to which they are able to develop CE cycles.

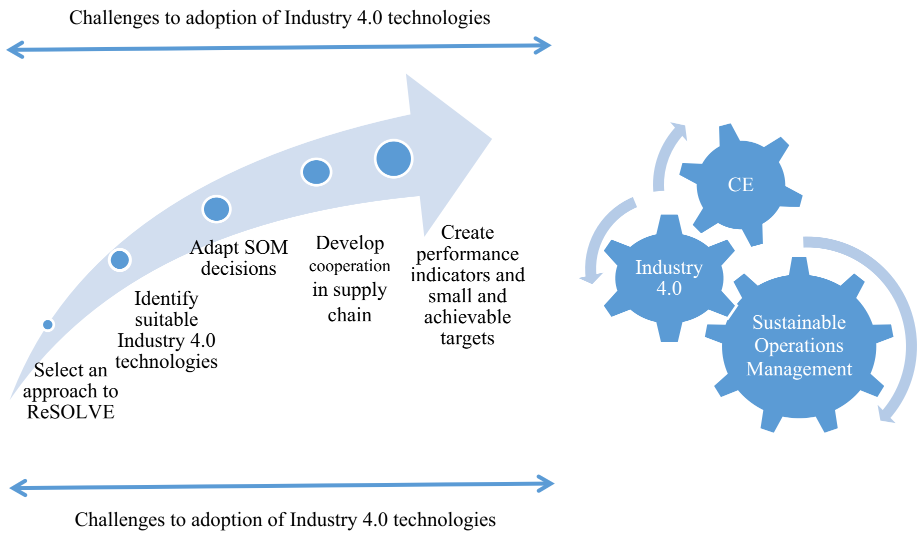

Fig. 1 Roadmap towards Industry 4.0 and CE. *Source*: The authors

The second step would be the identification of the Industry 4.0 technologies and resources that are viable for them, considering factors such as availability, costs and technical constraints. Tables 1 and 2 could assist organisations in this assessment.

The third step for organisations would be the adaptation of sustainable operations management (SOM) decisions for the design, process, and logistics of products. It was mentioned that the selected ReSOLVE approach would impact the tracking, tracing, and managing of post-use products and packaging, from the conceptualisation to the development of products, the latter including extended product life cycles. Thus, the breadth of SOM-related change will depend on the first step.

The fourth step for organisations would be the development of integration between tiers in supply chains in order to connect technologies and resources and share information pertaining to demand, supply, deliveries, and customers' behaviour in real time. According to Fischer and Pascucci (2017), one of the most relevant challenges faced by an organisation engaged in CE transition is facilitating collaboration and developing business relations. Thus, it is important to plan the transition towards the CE and Industry 4.0 within an organisation as well as externally.

Finally, the fifth step for organisations would be the creation of indicators of performance in order to measure progress towards the CE (Elia et al. 2017). Additionally, small and achievable targets should be designed when planning organisational actions, based on resources and capabilities.

Every journey of change involves potential challenges; therefore, organisations should be aware that the implementation of Industry 4.0 technologies presents barriers, as found by the Global Expert Survey. The main challenges are the following: coordinating actions across different organisational areas; concerns about cybersecurity; lack of necessary talent (Bauer et al. 2016). Sung (2017) and Tupa et al. (2017) also highlight other challenges related to Industry 4.0 adoption, which include reliability of connectivity between machines, integrity of maintenance-related data, and/or available information.

In addition to these inherent challenges to Industry 4.0 adoption, organisations may face additional difficulties in following the proposed roadmap due to a lack of trust when integrating IT systems between supply chain partners and a lack of technical and technological knowledge of CE cycles and Industry 4.0 approaches.

Schumacher et al. (2016) state that utilization of a roadmap is a critical success factor to the maturity level of Industry 4.0. Furthermore, the McKinsey Global Expert Survey found that only a limited number of users had a clear roadmap for implementing Industry 4.0 (Bauer et al. 2016); thus, the roadmap proposed in our study can help and guide managers to success with Industry 4.0 approaches, due to the fact that simple steps based on SOM are recommended here in order to analyse the prospect of integrating advanced technologies into CE business models.

5 Final remarks and proposed research agenda

This article aims to develop a pioneering roadmap to enhance the application of CE principles in organisations by means of Industry 4.0 approaches, since the connection between CE and Industry 4.0 technologies has not previously been thoroughly explored. Further, the business models presented in the ReSOLVE framework have overcome technological hurdles, thereby offering a myriad of opportunities to improve organisational competitiveness. Therefore, discussion on technologies/resources from Industry 4.0 suitable to the implementation of a CE perspective was developed, and sustainable operations management decisions—which must be involved in adopting a CE approach—were selected.

The original roadmap presented consists of five key steps, which guide managerial decisions toward sustainable operations management and aim to position organisations at the forefront of the digital manufacturing era. The proposed roadmap is the first to combine novel concepts from the ReSOLVE business models and Industry 4.0 technologies, thus providing new directions for future research. It represents a thorough and important advance in this emerging field. Additionally, this article is innovative in addressing a technological theme—Industry 4.0/digital manufacturing—from a managerial perspective.

Based on the features of the roadmap, some recommendations are provided for scholars, policy makers, and managers.

For *scholars*, there are key suggestions for avenues of future research. These are based on the most frequently cited organisational theories in the field of sustainability, following the ideas of Sarkis et al. (2011) and Touboulic and Walker (2015) (Table 3).

For *policy makers*, it is suggested that infrastructural plans could be developed to address the current threats to adoption of Industry 4.0 technologies, such as cybersecurity and lack of necessary talent. Governments around the world should develop a common vision on the CE and industrial policy. As Industry 4.0 can unlock the CE, the industrial strategies of national sustainability plans should be integrated and discussed simultaneously.

For *managers*, it could be argued that testing the proposed roadmap may be a starting point for implementing Industry 4.0 technologies. The proposed roadmap sheds light on the potential of Industry 4.0, not only in terms of expanding productivity and profit, but also in terms of advancing CE.

This work could be developed further in order to overcome some limitations. First, the roadmap can be presented to key stakeholders for refinement. The application of the roadmap to different cultures, nations, and continents should further highlight cultural aspects and implementation challenges that should be considered when adopting the ideas of this work. We also suggest conducting in-depth case studies in order to understand the 'soft side' of integrating Industry 4.0 and the CE, by qualitatively exploring subjects such as resistance

Table 3 Research agenda for scholars based on selected theories. *Source*: Authors

Theory	Brief definition	Research agenda
Resource-based view	Resource-based view theory is centred on the perspective that internal resources and capabilities are sources of sustainable competitive advantage and organisational profitability (Grant 1991; Hart and Dowell 2011) if they are unique, not imitable, and rare	(a) To investigate the organisational resources and capabilities which are necessary to underpin strategies towards the CE, based on technologies from Industry 4.0
		(b) To identify potential organisational barriers to following the proposed roadmap and to propose ways to overcome them
Stakeholder theory	Through the lens of stakeholder theory it can be understood that, due to changes in the external context, organisations need to contingently adjust their responses to stakeholders in order to avoid underperformance (Freeman 1984)	(a) To map the expectations of primary stakeholders with regards to CE performance, in order to prioritise the implementation of Industry 4.0 technologies
		(b) To identify and analyse mechanisms to facilitate integration between organisations, suppliers and customers for implementing ReSOLVE business models
Institutional theory	Institutional theory states that organisations operate within a regulated environment (organisational field) and its associated demands, and pressure for conformance to social and legal requirements (DiMaggio and Powell 1983). As a result, organisations adapt processes, structures and practices in order to ensure the legitimacy of their actions within the environment (Hsu et al. 2014)	(a) To explore the extent to which different institutional environments (e.g. whether in Germany or in Africa) impact initiatives to apply the technologies of Industry 4.0
		(b) To investigate the role of competitors and customers in putting pressure on organisations to adopt technologies of Industry 4.0 in order to enable CE strategies
Ecological modernisation	This theory is used to explain governmental environmental initiatives, by means of policies and technological innovation, to reconcile economic and environmental development (Sarkis et al. 2011)	(a) To study how national technological development polices from different countries have contributed to the emergence of the fourth industrial revolution, and how these polices are aligned with CE principles
		(b) To propose indicators to measure the economic and environmental gains due to the application of technologies from Industry 4.0

to change, industrial human relations, and customer preferences. This ‘soft’ understanding should prove in valuable to better promote and encourage adoption of the various results from quantitative studies resulting from the roadmap. Adoption remains a major challenge at this early stage in various industries and contexts; the support of regulators or policy makers may also be reinforced by further studies demonstrating the potential impact of the CE and Industry 4.0. For corporations, a determined strategic approach can only benefit from additional research work at both the theoretical and practical levels.

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