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HOW CAN INFORMATION AND COMMUNICATIONS TECHNOLOGY SUPPORT THE LINK BETWEEN CIRCULAR ECONOMY AND PRODUCT LIFE CYCLE MANAGEMENT? – A REVIEW

C. Villamil Velasquez [1,✉], N. Salehi [2] and S. I. Hallstedt [1]

[1] Blekinge Institute of Technology, Sweden, [2] KTH Royal Institute of Technology, Sweden
✉ dcv@bth.se

Abstract

Linear production is related to resource scarcity and negative environmental impacts. Circular Economy (CE) emerged for society transition towards sustainability, based on regenerative systems and multiple life cycle products. Product Life cycle Management (PLM) supports the whole life cycle with the aid of Information and Communication Technology (ICT). A literature review analyzed the role of ICT enabling CE based on PLM, identifying challenges and opportunities, active and passive PLM, system perspective, stakeholder's role, and sustainability. Concluding that ICT enables the CE transition.

Keywords: circular economy, product lifecycle management (PLM), information and communication technology (ICT), product development, sustainability

1. Introduction

Global population increment, economy growth and the rise of living standards in society have accelerated the mass production significantly. Where the linear production systems are unsustainable causing negative environmental impacts, which indicates the necessity to shift to Circular Economy.

Circular economy (**CE**) is an approach designed intentionally to be restorative and regenerative, to maximize the produced service by using cyclical flows, renewable energy and cascading energy flows (Ellen MacArthur Foundation, 2013). In CE, the end of life management is focused on restoration, eliminating waste production by redesigning the products and planning to choose materials which will not cause problems. CE contributes to the three sustainability dimensions: economic, environmental and social (Korhonen et al., 2018). Therefore, implementing CE requires modification in various stages of a product life cycle, such as redesigning the product in its beginning of the life (BoL), providing better service and maintenance while the product is in use in the middle of the life (MoL) and avoiding disposal by remanufacturing it at the end of life (EoL) (Li et al., 2015). These changes require a holistic and multi-disciplinary perspective, stakeholder's collaboration and circulation of information flow, Product Life cycle Management supports the CE transition.

Product life cycle management (PLM) is defined as an integrated business approach using Information and Communication Technology (ICT) to manage a product through its whole lifecycle, from idea generation to disposal, in a collaborative and cooperative way. PLM helps companies to increase revenue and value, reduce production costs, manage stakeholders and support product development (Oliveira and Soares, 2017; Tavčar and Duhovnik, 2004; Chapotot et al., 2008). Although, this

approach is challenging when there is 1) a shift from mass production to personalized, 2) customer-driven and knowledge-based products, 3) complexity and variability of products, and 4) continuous change of customers' needs. On the other hand, CE is linked to PLM as support to develop sustainable products, meet customer needs, and compete at the market, by collecting, analyzing and transforming data into knowledge to be used along the whole product lifecycle with a sustainable perspective (Lungi et al., 2006). Therefore, the development of ICT presented potential capabilities in connecting PLM and enabling CE in industries. ICT tools are the key enablers of PLM with CE perspective, where ICT devices supports the communication and the collection of information to be transmitted, analyzed and used to control or improve the system (OECD, 2003). ICT establish a smart information along the whole product life cycle, in order to enhance collaboration and make effective decisions in real-time (Oliveira and Soares, 2017), e.g. at BoL, manufacturers can analyze the data of customers behavior to design innovative products.
The aim of this study is to determine the link between CE and PLM with ICT focus to enable manufacturing systems to CE transition. The study is a systematic literature review that is described in the methodology section. The PLM stages are described and supported with examples from the literature. Moreover, the discussion section presents different aspects to link CE with PLM with ICT focus, such as the opportunities and challenges, active and passive PLM, system perspective, sustainability and the stakeholders' role.

2. Methodology

A systematic literature review was performed to understand the state of art of CE and PLM with an ICT focus, following the guidance proposed by Gill and Johnson (2002). First, few papers were analyzed to plan the research: scope, aim, key words, etc. With this, understanding was possible to define the search query: a) CE and Sustainability: Circular*, "Circular economy", Eco*, efficien*, Sustainab*, "Clos* loop*", b) LCM or PLM: "Life*cycle management", "Product life*cycle" and c) ICT: "ICT" "IoT", "Internet of things", AI "Artificial intelligence", ML "Machine Learning", Big data, "data mining", digitaliz*, Industry 4.0. The research is limited to journal and conference papers related to the manufacturing field and published from 2000 to 2019. SCOPUS, Web of science and Science Direct were the databases used to identify the papers. It was complemented with a snowballing process, where some useful papers mentioned by other authors were reviewed. A total of 48 papers were selected by their contribution to the field, which were organized by title, author, year, description, key concepts, product life-cycle stages, study cases. The results were linked to other studies in the field, helping to draw the discussion, the main research contributions and the future work. Figure 1 presents the methodology used in the systematic literature review. Most of the papers are from 2015 to 2018, showing a growing interest in recent years about the field. The most studied stage is the EoL. 27 papers had a system perspective and 15 papers used a case study. Table 1 presents the number of papers by publication year and the main reviewed topics.

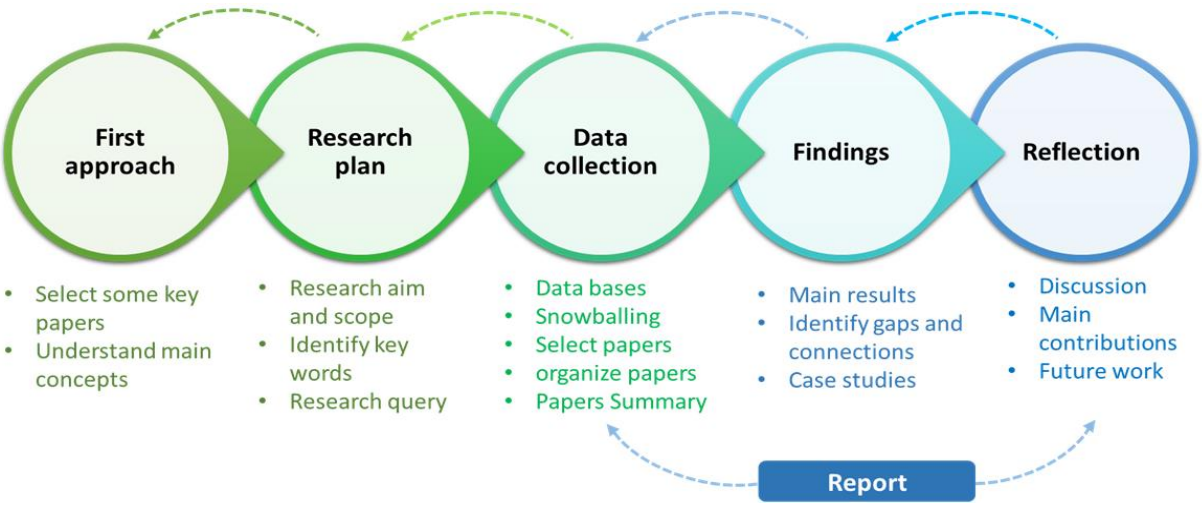

Figure 1. Systematic literature review methodology

Table 1. Total of papers by publication year and main analysis aspects

Published year	Total of papers	CE	PLM	ICT	Study case	BoL	MoL	EoL	All LC stages	System perspective	Stakeholder role
2000-2005	1	0	1	1	0	0	0	1	0	1	0
2006-2010	4	0	2	4	1	3	1	1	1	3	1
2011-2015	8	1	4	7	1	3	5	4	3	4	4
2016-2019	35	23	11	31	13	10	14	16	6	19	15
Total	**48**	**24**	**18**	**43**	**15**	**16**	**20**	**22**	**10**	**27**	**20**

3. Review results: Product lifecycle management and CE - ICT focus

To understand how ICT enables CE in PLM, the product life cycle phases are grouped in three stages: 1) Beginning of life (BoL), 2) Medium of life (MoL), and 3) End of life (EoL). In this section, each phase will be explained. Examples and key finding from the literature present an overview of how ICT enables CE in PLM. These findings are further developed in the discussion section 4.

3.1. Beginning of Life (BoL)

The Beginning of Life (BoL) includes "design" and "production" phases. Those phases require data and technical support that is provided by ICT, to design products linked to CE, avoiding losses in the process and being more efficient in terms of resources (Reuter, 2016). User-product data is collected to trigger the design innovation along life cycle, to improve the product design for disassembly, remanufacturing, reusing and future recycling (Li et al., 2015). Zheng et al. (2019) considers mass customization and personalization to involve users along the product life cycle, proposing a smart connected open architecture product (SCOAP). Where IoT enables the configuration of smart products by communicating with physical products and based on users' needs and preferences, to provide design flexibility in early stages of product development and replace or upgrade the existing product in later stages. Van Schalkwyk et al. (2018) used simulations to compare different industry scenarios using LCA to improve energy efficiency and material recovery, providing useful data for the decision-making process in BoL. Bertoni et al. (2018) used simulations and machine learning to guide the decision-making stage by combining criteria such as: volume reduction, fuel consumption, besides other variables with sustainability compliance indicators to assess the complete product life cycle and identify the best scenarios from a sustainability perspective. Mourtzis (2018) presents a framework with three tools: 1) an augmented reality product configuration tool to utilize customers' opinions in the design phase, 2) a decision support tool for manufacturers using a multi-criteria search algorithm to find the optimum supplier network based on the customers' preferences, and 3) a PLM tool to connect and support the communication between the other tools.

3.2. Middle of Life (MoL)

Middle of Life (MoL) of a product covers the product use phase, maintenance, repair and distribution. In MoL, ICT is useful to gather data of the customers' behavior and preferences, product failures and distribution logistics. Processing this information makes the difference between conventional life cycle management and ICT based PLM, i.e., manufacturers can actively manage different stages and implement changes according to the continuous user's feedback, opening the possibility to develop multiple life cycle products. Elliot and Binney (2008) analyzed how with IoT, big data and analytics, it is possible to track the product and service functioning, highlighting that real-time data improves the sustainability performance of their products, prolonging the product life, and incrementing energy and resource efficiency. Främling et al. (2013) used machine learning and data analysis to implement sustainability in smart homes, where intelligent products can be connected while they are in use, reducing energy consumption, controlling the product functioning and tracking device issues. David et al. (2016) linked collaborative systems and shared economy supported by ICT to be more sustainable.

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3.3. End of Life (EoL)

In the End of Life (EoL), ICT can provide very useful information to close the loops by tracking the products or material for reuse, remanufacturing, recycling or energy recovery. Some companies have used the data to improve the design of products for remanufacturing or recycling, collaborate with stakeholders, track the recovery material quality (Álvarez and Ruiz-Puente, 2017), among other possibilities. Kalverkamp et al. (2017) identified several factors related to cascades methodology, such as: stakeholders, complexity, technical and marketing life cycle perspective, EoL scenarios, changes in raw material acquisition, value of EoL material changes, legislation - policies, material quality and acquisition. Where a high variety of scenarios makes the system more resilient. Gåvertsson et al. (2018) analyzed eco-labeling use in ICT products to inform and encourage users to return valuable products that can be reused, remanufactured or recycled. Álvarez and Ruiz-Puente (2017) analyzed the SymbioSyS tool, which is a software to link different companies, by planning the management, networking and collaboration between industries and storing information about valuable disposal material that can be used in other manufacturing processes.

4. Discussion

In this section, different aspects to link ICT with CE and PLM are discussed, such as: ICT as enabler of CE transition, the opportunities and challenges, active and passive PLM, system perspective, sustainability and the stakeholder's role.

4.1. ICT is an enabler of the CE transition

With the review, it was possible to determine that PLM and ICT are a crucial support for companies that plan to move towards CE transition. In the past, it was hard to get users product feedback, in contrast, nowadays ICT helps to provide data in the complete product life-cycle (Zheng et al., 2019). Bressanelli et al. (2018) defined eight digital technologies functionalities to achieve CE: "improving product design, attracting target customers, monitoring and tracking product activity, providing technical support, providing preventive and predictive maintenance, optimizing the product usage, upgrading the product, enhancing renovation and end-of-life activities". A Product Service Systems (PSS) solution is easier to manage using ICT devices, e.g. in the bike sharing system it is possible to identify by GPS where is the nearest available bike. Comparing PSS solutions with traditional rental services, there are management, and networking improvements. This transition is beneficial in three main areas: 1) Design: ICT is used for supporting the decision-making process (Li et al., 2015), for the creation of future scenarios to evaluate which is the best alternative, e.g. to simulate the system and adapt it according to the collected data during the complete product life cycle (Bertoni et al., 2018). 2) Business Model: ICT allows the creation of new business models with a different value proposition, such as sharing, i.e., where the value is focus on the function instead of the physical object (Zhang et al., 2017), e.g. PLM with ICT support, helps the management of the offered services (Li et al., 2015). 3) Process - operation: ICT is useful to improve the logistics and stakeholder's collaboration, allowing the management of the complete value chain and closing the loops (Li et al., 2015), e.g. the active use of ICT allows to track PSS, improve the system in real time, connect with stakeholders and expand the system logistics (Oliveira and Soares, 2017).

4.2. Opportunities and challenges

This study allowed to identify opportunities and challenges of linking CE and PLM with ICT focus. They have been clustered following the product life-cycle stages: BoL, MoL, EoL. A fourth category collects all life cycle stages, see Table 2. It was possible to identify opportunities for specific categories, e.g. in the EoL: track the product materials for resources recovery support (Asif et al., 2018). With opportunities such as: increment of profit, energy efficiency, service track, get reliable data, real time data, track the complete product lifecycle, decision-making information (Zhang et al., 2017), it is possible to determine that ICT enables the transition to CE linked to PLM.

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Table 2. Opportunities of linking CE and PLM with ICT focus

PLM	Opportunities	References
BoL	Collaborative design	(Shamsuzzoha et al., 2016)
	Integrate customers in design phase	(Mourtzis, 2018)
	Economic benefits: Profit Increment, predict product demand and reduce production cost.	(Antikainen et al., 2018; Li et al., 2015; Oliveira and Soares, 2017; Zhang et al., 2017)
	Track suppliers for future business agreements	(Mourtzis, 2018)
	Decision-making information: simulation of different scenarios at early stage of design	(Bertoni et al., 2018; Elliot and Binney, 2008; Li et al., 2015; Oliveira and Soares, 2017; Reuter, 2017; van Schalkwyk et al. 2018; Sousa-Zomer et al., 2017; Toche et al., 2010; Zhang et al., 2017)
MoL	Close the information gap after product sale	(Oliveira and Soares, 2017)
	Service track e.g. repair and maintenance	(Elliot and Binney, 2008; Li et al., 2015; Monostori et al., 2016; Sousa-Zomer et al., 2017; Zhang et al., 2017)
	Track product performance during use and prolong product life	(Antikainen et al., 2018; Asif et al., 2018; Bressanelli et al., 2018; Elliot and Binney, 2008; Främling et al., 2012; Zhang et al., 2017)
	Customized product service	(Li et al., 2015; Sousa-Zomer et al., 2017)
	ICT can facilitate the development of PSS	(Belvedere et al., 2013; Li et al., 2015)
EoL	Material knowledge to facilitate recycling e.g. content, supplier, performance, etc.	(Kiritsis et al., 2015; Sousa-Zomer et al., 2017)
	Optimize resource stock: reducing material waste and transport costs.	(Kiritsis et al., 2015)
	Product life extension	(Elliot and Binney, 2008; Watanabe et al., 2019)
	Resources recovery support i.e. track material flow.	(Alvarez and Ruiz-Puente, 2017; Asif et al., 2018; Elliot and Binney, 2008; Gåvertsson et al., 2018; Hannan et al., 2015; Pagoropoulos et al., 2017; van Schalkwyk et al., 2018; Watanabe et al., 2019)
	Reduce waste	(Alvarez and Ruiz-Puente, 2017; Antikainen et al., 2018; Gåvertsson et al., 2018; Li et al., 2015)
All LC	Energy and resources efficiency	(Elliot and Binney, 2008)(Li et al., 2015; Neligan, 2018; Reuter, 2017; van Schalkwyk et al., 2018; Zhang et al., 2017)
	Sustainability benefits, e.g. reduce carbon	(Bertoni et al., 2018; Elliot and Binney, 2008; Zhang et al., 2017)
	Track the complete product life-cycle	(Elliot and Binney, 2008; Li et al., 2015; Oliveira and Soares, 2017; Zhang et al., 2017)
	Reliable data: accuracy and quality	(Antikainen et al., 2018; Elliot and Binney, 2008; Li et al., 2015; Zhang et al., 2017)
	Real time data	(Bertoni et al., 2018; Elliot and Binney, 2008; Li et al., 2015; Monostori et al., 2016; Reuter, 2017; Zhang et al., 2017)
	In advance, identify problems in the system	(Antikainen et al., 2018, Asif et al., 2018)
	Useful information for other life-cycle stages	(Jun et al., 2009; Oliveira and Soares, 2017; Zhang et al., 2017)
	Close the loop transition	(Asif et al., 2018; Elliot and Binney, 2008; Pagoropoulos et al., 2017; Rashid et al., 2013)
	Networking: internal and external stakeholders´ collaboration	(Alvarez and Ruiz-Puente, 2017; Antikainen et al., 2018; David et al., 2016; Elliot and Binney, 2008; Gåvertsson et al., 2018; Lunghi et al. 2016; Oliveira and Soares, 2017; Rajala et al., 2018; Rashid et al., 2013; van Schalkwyk et al., 2018)
	Stakeholder tracking	(Alvarez and Ruiz-Puente, 2017; Antikainen et al., 2018; Elliot and Binney, 2008; Kalverkamp et al., 2017; Li et al., 2015)
	Support new business model adaptation	(Elliot and Binney, 2008; Jun et al., 2009; Lieder et al., 2016; Neligan, 2018)
	Management support - IT integration / industry 4.0.	(Antikainen et al., 2018; Främling et al., 2012; Li et al., 2015; Monostori et al., 2016; Oliveira and Soares, 2017; Reuter, 2017; van Schalkwyk et al., 2018; Watanabe et al., 2019)
	Multiple life-cycles support	(Oliveira and Soares, 2017; Pagoropoulos et al., 2017; Rashid et al., 2013)
	Deal with complexity	(Kalverkamp et al., 2017; Oliveira and Soares, 2017)

The challenges of linking CE and PLM with ICT focus are shown in Table 3. One of the challenges is the big and diverse kind of data (van Schalkwyk et al., 2018), requiring resources for its organization, analysis and application, e.g. the needed knowledge to apply the information in the different LC stages (Zhang et al., 2017). ICT can be an enabler of CE, but it is necessary to solve these challenges to reach sustainability in the complete life cycle, and avoid that ICT solutions generate more negative impacts, e.g. increment of e-waste (Elliot and Binney, 2008). Some challenges are linked to unsustainable aspects, needing further investigation, e.g., the rebound effect, which results in product overuse.

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Table 3. Challenges of linking CE and PLM with ICT focus

PLM	Challenges	References
BoL	Use of conflict minerals in ICT devices manufacturing	(Amnesty International, 2016)
	Use of critical material in ICT devices manufacturing (e.g. resource scarcity)	(Evans et al., 2010; Wäger et al, 2015)
MoL	Rebound effect (e.g. over use of a product), Boomerang effect	(Korhonen et al., 2018)
	Knowledge gaps in information of the service-based business model	(Xu, 2015)
EoL	Mainly focused on EoL stage	(Alvarez and Ruiz-Puente, 2017; Gåvertsson et al., 2018; Kalverkamp et al., 2017)
	Increment of e-waste	(Elliot and Binney, 2008; Forti et al., 2018; Gåvertsson et al., 2018)
All LC	Difficult to measure sustainability performance	(Främling et al., 2012)
	Lack of stakeholder integration - collaboration to link CE and ICT	(Antikainen et al., 2018)
	User perspective, e.g. low quality of remanufactured product	(Gåvertsson et al., 2018; Korhonen et al., 2018)
	Data process - required resources: time, knowledge	(Li et al., 2015; van Schalkwyk et al., 2018)
	Limited knowledge of the use of new technologies ICT and PLM	(Antikainen et al., 2018; Li et al., 2015; Zhang et al., 2017)
	Additional use of IT technologies and infrastructure	(Asif et al., 2018; Oliveira and Soares, 2017)
	Data security	(Li et al., 2015)
	Quick changing data / storage and transfer data	(Li et al., 2015)
	Big and diverse kind of data.	(Li et al., 2015; Reuter, 2017; Zhang et al., 2017)
	Get data on time	(Zhang et al., 2017)
	Thermodynamics and Entropy e.g. any activity requires to use extra resources	(Korhonen et al., 2018; Schalkwyk et al., 2018)
	Systems complexity	(Korhonen et al., 2018; Monostori et al., 2016; Neligan, 2018; Reuter, 2017)
	deficient management and stakeholder collaboration	(Jun et al., 2009; Korhonen et al., 2018)
	Path dependency (e.g. track and recover products for remanufacturing)	(Korhonen et al., 2018)

4.3. Active and passive product life cycle management

Enabling CE by ICT can be seen from a passive or active PLM perspective. In the passive perspective the information is collected and later it is applied, i.e., the current user will not have benefits from the changes. As opposite, in the active perspective, ICT can be used to track manufactured products to improve their performance, offer better services, increment product life and continuously change the product features based on customer needs, i.e., the current user can experience those changes. ICT provides an opportunity for manufacturers to gather real-time data, e.g. tracking products to get customer's preferences and usage patterns data, to make proper decisions aimed at redesigning the processes where necessary, providing better service and producing multiple life cycle products, all in compliance with CE goals (Belvedere et al., 2013). Active PLM helps manufacturers to manage the product life cycles with the provided information and promotes companies to move toward service-oriented businesses, an example is Product Service Systems (PSS), it replaces the ownership by combining services and products, which requires redesigning the products to last longer and be more efficient, by changing the relation between profit, value creation and volume of products (Bocken et al., 2014). PSS might help to conserve resources, reduce the environmental impacts, and generate more value through the product life cycle by selling services and ensuring better relationship with customers (Belvedere et al., 2013). ICT can play an important role to facilitate this collaboration.

4.4. System perspective by linking CE and PLM

There are advantages to link CE and PLM such as: circularity, closed loops, multi-lifecycles, profit increment, efficiency and sustainability (Kalverkamp et al., 2017). ICT is an enabler for the CE transition, but it requires a holistic perspective (Pagoropoulos et al., 2017), i.e., to understand the complete system and propose circularity in the complete cycle, by using data to support all the LC

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stages (Jun et al. 2009). Asif et al. (2018) presented an ICT framework to change business models and adopt circularity in industry, identifying a high variety of data that can be useful to understand the complete system. Jun et al. (2009) proposed to implement Radio Frequency Identification RFID in products in all the stages of the product life cycle, where the data is useful in the complete cycle, e.g. product use data (MoL) is useful to improve the design (BoL) and know about product conditions for the remanufacture (EoL). Li et al. (2015) explained how Big data is necessary for each LC stage: BoL, MoL, EoL, considering the "5Vs theory": volume, variety, velocity, variety and value. Zhang et al. (2017) suggested a framework to manage the complete life-cycle of the product, providing reliable data, real time data, track the complete product life-cycle for an optimal management. Rashid et al. (2013) proposed the model Resource Conservative Manufacturing, ResCoM for Multiple life cycle products, to facilitate disassembly, provide flexibility for technology adaptation, value management and product upgrading at the end of each life cycle. ICT systems require high infrastructure and logistics (Asif et al., 2018), for that reason, it is necessary a deeper understanding of the ICT (van Schalkwyk et al., 2018). For the CE transition, it is essential to have a solid plan in terms of design, manufacturing, supply chain and management with a system perspective (Rashid et al., 2013).

4.5. Sustainability

The ICT devices used for tracking and collecting data in different stages of the product life cycle can be beneficial from a sustainability perspective, e.g. improving energy and resources efficiency, decreasing emissions and changing consumer behavior (Zhang et al., 2017). Although, it is crucial to reflect on the ICT devices purpose and the negative environmental impacts generated for their production, use and disposal. Circularity does not ensure sustainability, Korhonen et al. (2018) mentioned some CE barriers, such as all the activities to close the loops require resources and produce emissions in the process. The ICT devices manufacture requires a high use of critical metals (Evans et al., 2010), which are related to resource scarcity, monopoly, and other factors, risking the manufacturing processes. Hallstedt and Isaksson (2017) proposed a material criticality assessment at the early stages of the product development process to avoid some of these challenges. Furthermore, ICT devices fabrication need some conflict minerals, such as cobalt (Amnesty International, 2016), tantalum, tungsten, and gold (Young, 2018), conflict minerals are extracted or produced in zones with activities related to war, conflicts or human rights violations, e.g. child labor in the raw materials extraction for batteries manufacturing (Amnesty International, 2016). ICT enables CE transition, demanding more devices and infrastructure, which might increment the e-waste, e.g. in China the number of phones has increased from 400 million in 2006 to 800 million in 2011 (Forti et al., 2018). The worldwide e-waste has increased from 33.8 million metric tons (Mt) in 2010 to 49.8 Mt in 2018 (Statista, 2018), in "Europe the e-waste is 12.3 Mt, with 16.6 kg on average per inhabitant… 35% is collected to be recycled" (Baldé et al., 2017). Due to the different EoL management and legislation of each country, still a high percentage of e-waste is dumped to other countries, e.g. Ghana (Gnanasagaran, 2018). None of the reviewed papers have focused directly on social sustainability, according to Mesquita et al. (2016) there is a gap in the implementation of social sustainability in companies, e.g. they are tackling mostly company workers, leaving behind other stakeholders, such as the affected communities by raw material extraction. The negative environmental impacts of ICT devices can overpass the sustainability benefits (Främling et al., 2013). For that reason, it is crucial to define clear sustainability purpose to reduce the negative environmental impacts generated in the whole product life cycle. (Li et al., 2015).

4.6. Stakeholders role

For CE and PLM with ICT focus, the role of the stakeholders in the complete process is crucial (Jun et al., 2009), e.g. predicting future collaboration with supplier by the analysis of big data (Li et al., 2015). According to Antikainen et al. (2018) co-creation, collaboration and networking are key elements to fill up the gap between ICT and CE, e.g. ICT enhance collaboration between companies, recovering the wasted material from other companies, this space promotes: communication, "trust and reciprocity" (Álvarez and Ruiz-Puente, 2017). Shamsuzzoha et al. (2016) proposed an ICT-based platform to achieve a collaborative approach in design and manufacturing of products, by capturing customers' requirements, searching for appropriate partners and monitoring the process. In some

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cases, there is a negative consumer perception about reuse and remanufacturing products, which can be changed by implementing PLM strategies focused on stakeholder's collaboration (Antikainen et al., 2018). Jun et al. (2009) mapped the stakeholders in each specific LC phase to understand their interaction with the system and for a further application in ICT implementation.

Arup circular building is an example of how ICT can enable circularity by facilitating stakeholders' collaboration and implementing active lifecycle management with a holistic perspective, from design to end of life management strategies. The company uses the Building Information Modelling (BIM) tool to enable information exchange among stakeholders through the whole lifecycle phases of the building, leveraging Big Data and IoT to maximize material and component use on a building construction (Nobre and Tavares, 2017). It allows contractors to minimize the on-site waste by delivering products just-in-time rather than stocking on-site. Moreover, it can act as a material bank to introduce opportunities for reusing, remanufacturing or recycling of components. In the BoL phase, BIM aids to optimize the design process while it can also support the maintenance during the MoL.

5. Conclusions

Many manufacturing companies are adopting CE to implement sustainability, i.e., CE is used to solve negative environmental impacts and resource scarcity by turning waste into valuable materials, increase efficiency, develop new business models, close the loops, increase awareness and legislation. In this study, it is concluded that ICT is an enabler of the transition to CE based on PLM, i.e., it makes it possible to consider multiple product life cycles and fill the information gap, establishing a knowledge base network to achieve a sustainable development in a collaborative and cooperative way. ICT provides valuable data to transform and disseminate the knowledge in the whole life cycle, e.g. to improve the current production process, redesigning the product to facilitate reusing and remanufacturing, providing better services, implementing sustainability and improving the business model. This review provides a better understanding of the CE transition and its connection to PLM with an ICT focus, where some opportunities were found, which can motivate the development of sustainable innovations for the complete product life cycle. These were: get reliable data for system improvement, promote networking and obtain quick feedback. Moreover, the study identified some challenges that need to be tackled to reach CE transition, such as: increased E-waste, social sustainability gap, unclear ICT purpose. The link between CE and PLM with ICT focus is a new field, perhaps in the future new challenges are identified, needing further research in this topic. Furthermore, the parallel between active and passive PLM, helped to understand the relevance of the active perspective, which supports the adaptation of the system as early as possible. In addition, the study also concluded that an analysis of sustainability aspects with a holistic perspective with the active participation of the stakeholders can support an understanding of positive and negative implications in the whole product life cycle and determine the real contribution of ICT in the CE transition.

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