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Enablers, levers and benefits of Circular Economy in the Electrical and Electronic Equipment supply chain: a literature review

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A B S T R A C T

Circular Economy in the Electrical and Electronic Equipment (EEE) supply chain has a significant (and still unexploited) potential. This paper aims to systematically review the knowledge emerging from the literature at the intersection between Circular Economy and the EEE supply chain, with a special focus on enablers, levers, and their potential environmental, economic and social benefits. An original framework is developed to categorise Circular Economy enablers, levers and potential benefits. Companies in the EEE industry aiming to implement Circular Economy can exploit several enablers (grouped into digitalization, government intervention, and users' active role) and levers (grouped into circular product design, servitised business models, and supply chain management) to generate economic, environmental and social benefits. Based on the framework, 115 articles were scrutinised. The analysis led to the definition of a research agenda, with policy and industry implications. To advance Circular Economy research in the EEE supply chain, future studies should address: (i) the enabling role of digitalization, particularly within blockchain, 3D Printing, augmented and virtual reality; (ii) design strategies focused on 'reduce'; (iii) servitised business models based on result-oriented offerings; (iv) collaboration in the EEE supply chain; (v) the assessment of social and economic benefits to users. Future research should also investigate the systemic interrelations between enablers, levers and benefits.

1. Introduction

Circular Economy (CE) contributes to sustainable production and consumption by decoupling economic growth from resource use and waste generation (Hofmann, 2019). CE is an 'umbrella concept' (Blomsma and Brennan, 2017) and has its roots in other schools of thought such as industrial ecology, industrial symbiosis, blue economy, product-service systems, cradle-to-cradle, and biomimicry (Geissdoerfer et al., 2017). Within the context of manufacturing companies and supply chains, CE can be implemented to replace the End of Life (EoL) concept with strategies such as reduce, reuse, remanufacture and recycle, by redesigning products, business models and supply chains (Bressanelli et al., 2019).

The application of CE to the Electrical and Electronic Equipment (EEE) supply chain has a significant potential. EEE includes a wide range of products (such as cooling and freezing equipment, screens and monitors, lamps, washing machines, vacuum cleaners, microwaves and information and communication technologies) whose manufacturing and usage is resource-demanding. Furthermore, Waste of Electrical and Electronic Equipment (WEEE) represents a global concern. In 2019, a total of 53.6 million metric tons of WEEE was generated worldwide, and only 17% of this was properly collected and recycled (Forti et al., 2020). With a yearly growth rate of WEEE between 3 and 5%, recycling activities are not keeping pace with the global growth of EEE (Cucchiella et al., 2015). In addition, EEE have a large economic potential: WEEE has the potential to generate 2 billion € in revenue from recycling in Europe alone, although most precious and special metals are still lost in recycling processes (D'Adamo et al., 2016).

Despite the attention devoted to the enabling role of digitalization and the fact that product eco-design and reverse logistics for sustainability have been part of research and development agendas for decades, companies in the EEE supply chain are still struggling with the implementation of CE, lacking a systemic support to understand its potential and to develop implementation roadmaps (Lieder and Rashid, 2016; Rosa et al., 2019). According to the Ellen MacArthur Foundation (2012), the CE paradigms is based on a set

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of building blocks. Manufacturing companies should leverage on circular product design to keep products, components and materials at their highest utility and value; servitised business models – based on the provision of the function instead of the product itself – to retain product ownership by the manufacturer and encourage take-back systems; supply chain management to integrate collaboration and reverse logistics into traditional, linear supply chains. Moreover, some contextual factors may favour the transition, such as digitalization, users' awareness, government intervention and financing. These building blocks have been often recalled in the scientific literature, although in a scattered way. Elia et al. (2020) evaluated the adoption of CE practices in industrial supply chains by investigating companies which have taken some actions in circular product design and production, business models, reverse logistics and collaboration. Govindan and Hasanagic (2018) analysed these building blocks in the context of supply chains through a systematic review, differentiating between drivers (such as policy, health, and environmental protection) and practices (such as product development, cooperation, logistics, etc.). Geissdoerfer et al. (2018) discussed the sustainability performance of business models and supply chain levers in the move towards a sustainable CE. Generally speaking, it is possible to identify two categories of building blocks for CE implementation: levers (i.e., tools and practices on which companies may leverage on to activate the implementation of CE, and enablers (i.e., conditions and contextual factors that facilitate the implementation of such levers). From the scientific point of view, literature reviews on the implementation of CE lack a systemic and holistic perspective in the joint application of such levers and enablers (Merli et al., 2018). This holds true also for literature reviews focused on EEE: for instance, Berssaneti et al. (2019) reviewed the literature to identify the variables related to value creation in the case of remanufactured electronic products, focusing only on the reverse logistics lever; Rosa et al. (2019) reviewed 283 articles to investigate the benefits of servitised business models for EEE, thus addressing only the servitisation lever; Islam and Huda (2018) reviewed 157 papers to define differences of reverse logistics processes for WEEE, thus addressing only supply chain management levers. To the best of the authors' knowledge, no systematic literature review jointly addressed, in a systemic perspective, how CE enablers and levers can be applied to the EEE supply chain, with a clear understanding of the potential benefits.

Thus, this paper aims to systematically review the knowledge emerging from the literature at the intersection between CE and the EEE supply chain, with a particular focus on enablers, levers, and their potential environmental, economic and social benefits. The focus of the analysis has been put on levers, enablers and benefits because they are the most recurrent themes in the EEE literature, thus calling for a systematization. Moreover, they have direct practical implications for EEE companies moving towards CE. In fact, they answer to (i.) what should be done (i.e., redesign of products, business models, and supply chains); (ii.) how to enable the transition (i.e., by exploiting digitalization, government intervention, and users' active role); and (iii.) why (i.e., for gathering economic, environmental and/or social benefits). Other aspects, such as potential side effects and rebounds, are intentionally left out of the scope of this paper.

To better frame the research objective, the following research questions have been formulated:

RQ1. What CE enablers and levers have been pointed out by the literature in the EEE supply chain, and how do they operate?
RQ2. What kind of potential economic, environmental and social benefits have been associated to the adoption of such enablers and levers?

The paper is organised as follows. Section 2 provides the research methodology and the research framework employed for classifying and analysing the articles. The results of the systematic literature review are presented in Section 3. Section 4 provides a critical discussion of the relations between levers, enablers and benefits. It includes a research agenda, key recommendations for managers and policy-makers, and a critical appraisal of the research limitations. Lastly, Section 5 draws concluding remarks.

2. Research methodology

2.1. Literature review process

The scientific literature has been scrutinised in a systematic way to answer the research questions, following the guidelines developed by Seuring and Gold (2012). An initial search was conducted on Scopus, combining two sets of keywords: (i) the research streams underlying the CE umbrella concept; (ii) the key terms focusing on the EEE supply chain (Table 1). Since the combined search of the two main representative terms ('circular economy' and 'Electrical and Electronic Equipment') led to the extraction of only 21 contributions on Scopus, the set of keywords was expanded. Keywords referring to Product-Service Systems, Closed-loop Supply Chain and other streams close to CE has been included in the first set while, for the second set, research terms were expanded to include washing machines, given their relevance for both CE and EEE streams (Bressanelli et al., 2017).

All the combinations between the two sets of keywords have been scanned in Scopus, for a total of 3951 entries (Fig. 1). Only papers written in English have been selected. To further refine the set of documents, and to ensure quality and relevance of the contributions, only articles that appeared in Journals with Impact Factor – according to Clarivate Analytics – have been selected. Thus, 1374 articles were scrutinised by reading the title and the abstract. To be selected, an article must meet three criteria. Only studies addressing (i.) environmental concerns falling into the CE umbrella concept, in the (ii.) EEE industry that (iii.) provides implications for supply chains were included. Based on the application of these three criteria, 106 papers have been selected. The set of articles has been complemented with another 9 articles obtained through cross-referencing. In total, 115 papers (see Supplementary Material) have been selected and further analysed in detail.

2.2. Descriptive analysis

Fig. 2 shows the distribution over time of the 115 articles that lie at the intersection between CE and the EEE supply chain. The first contribution, published in 2000, discussed the idea of moving towards a service economy coupled with the improvements in energy efficiency as a way to stimulate the social changes needed for a sustainable development (Foxon, 2000). The number of publications started to grow after 2005, with most studies (70 out of 115, i.e., more than 60%) published in 2014 or later. This trend confirms the general claim that the number of published articles about CE has grown considerably in the last few years, which can also be observed within the field of the EEE supply chain. The 115 articles are distributed across 43 scientific journals (Fig. 3). Most articles (51%) have been published on 6 journals, i.e., *Journal of Cleaner Production (19%), Resource, Conservation and Recycling (10%), International Journal of Consumer Studies (7%), Energy Efficiency (6%), Sustainability (5%)* and *Journal of Industrial Ecology (4%)*. This shows that research lying at the intersection between CE and EEE is strongly connected to sustainability aspects. Overall, the application of CE to the EEE supply chain is an emergent and rapidly growing topic, tightly connected with sustainability research.

Table 1
Sets of keywords scanned.

Keywords Set 1 – Circular Economy	Keywords Set 2 – EEE
Circular economy; Durability; Eco-eff*; Sustainab*; Closed-loop; Reverse supply chain; Reverse logistics; Reus* OR re-us*; Remanuf* OR re-manuf; Refurbish*; Disassembly; Repair; Eco-design; Shar*; Product-service system	EEE; WEEE; Appliance; Washing Machine

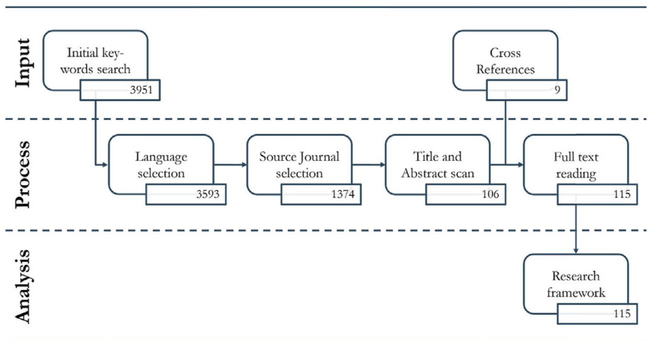

Fig. 1. Systematic Literature Review process.

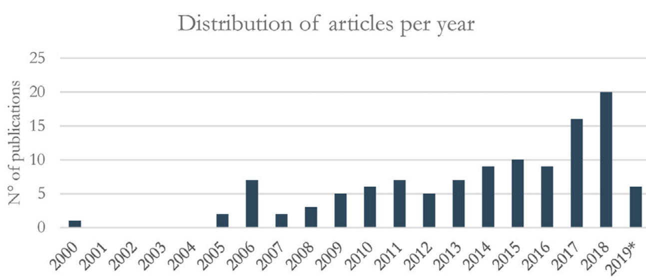

Fig. 2. Evolution of publications per year (last update: May 2019).

2.3. Research framework: enablers, levers, and potential benefits

An original research framework has been developed to answer the research questions and guide the literature analysis. The framework is used as a reference guide to examine the selected articles in a systematic way. First, we identified the three layers of levers, enablers and benefits through a conceptual elaboration on relevant (general and EEE-specific) literature, as described in the Introduction. The coding process that brought to the development of the framework, then, involved two steps: (i.) analysis of the first 65% of the 115 selected articles (i.e., 75 articles) to define options for CE enablers, levers and benefits; (ii.) iterative refinement and validation of each option used for the classification, through the analysis of the remaining set of 40 articles. Consequently, the framework (Fig. 4) has been built on three layers of analysis:

(i) CE enablers, defined as conditions and contextual factors that facilitate the implementation of CE levers; they are characterized by their *exogenous* nature and by their *enabling* role on the CE levers.
(ii) CE levers, defined as tools and practices to support the implementation of CE in companies; they are characterized by their *endogenous* nature, since companies directly invest and primarily act on them in order to implement CE.
(iii) Potential benefits, defined as potential advantages that may be obtained from the adoption of CE enablers and levers,

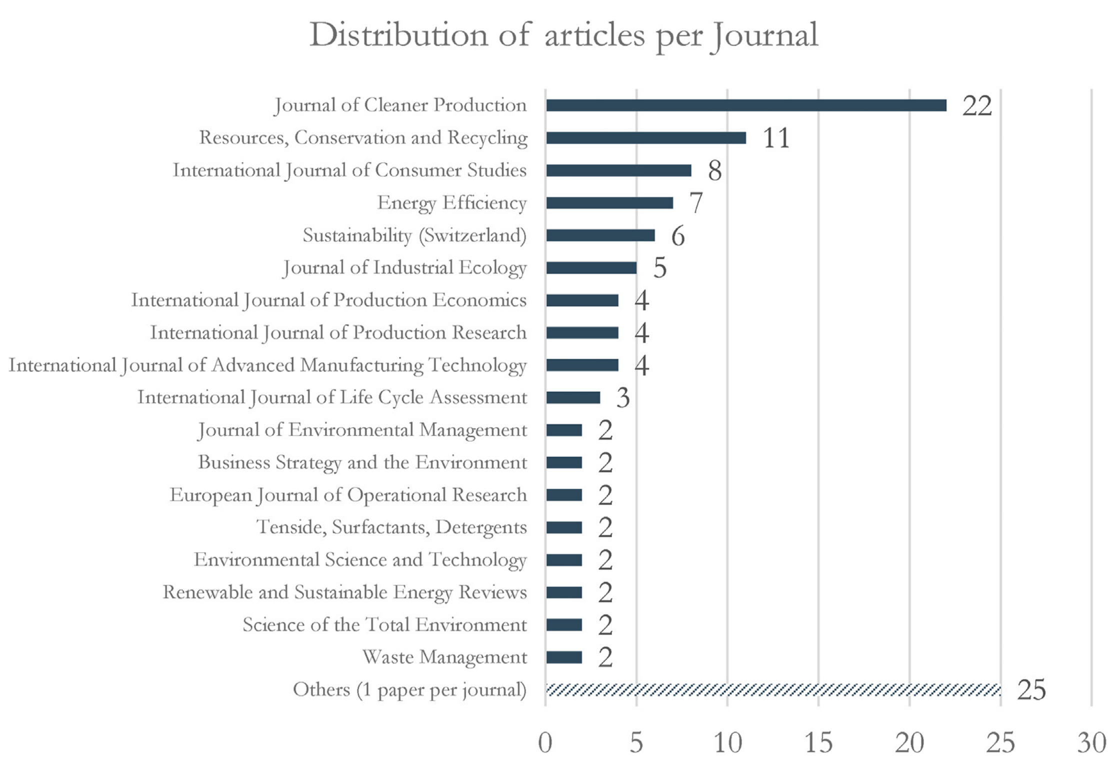

Fig. 3. Distribution of articles per Journal.

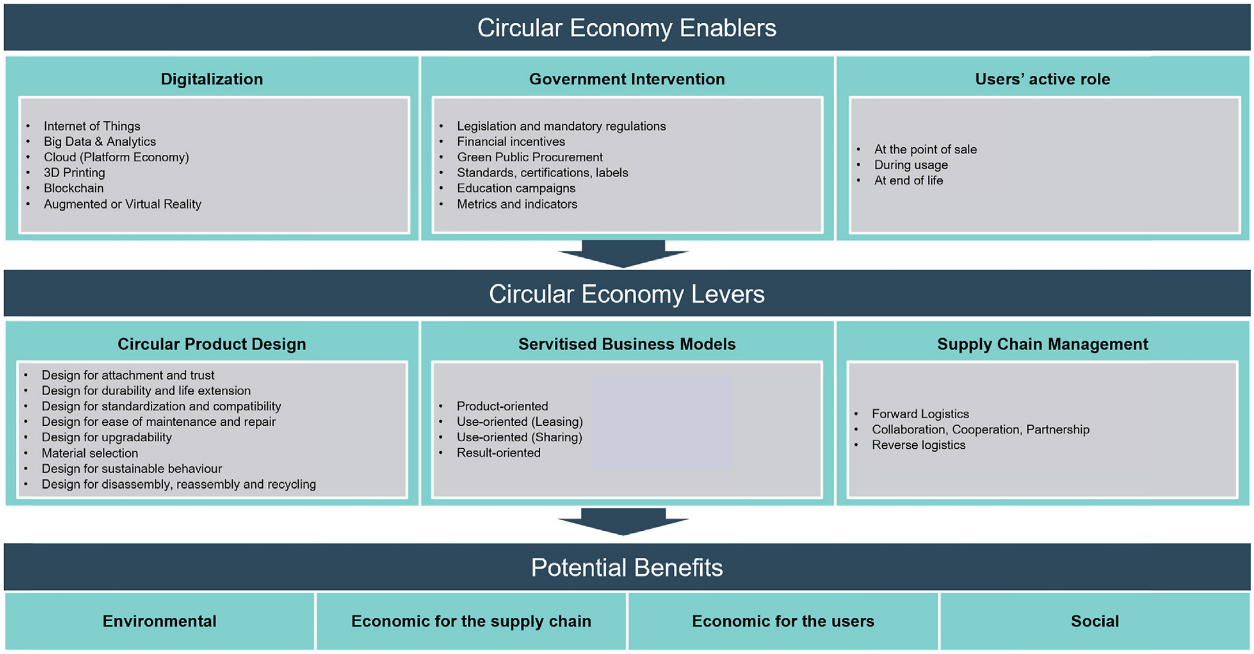

Fig. 4. Research framework.

under the triple bottom line perspective of sustainability (i.e., environmental, economic and social benefits).

The three layers have been divided into categories based on the literature. In turn, we found different options in each category, as shown in Fig. 4. A full definition of each option, including the selection criteria, is available in the Supplementary Material of this paper. The categories are instead introduced hereafter.

First, the three enablers for CE implementation addressed in this paper are: digitalization, government intervention and users' active engagement:

- Digitalization can enable the transition to CE through the introduction of digital technologies connected to Industry 4.0, such as Internet of Things (IoT), Big Data and Analytics, 3D Printing, Cloud, Blockchain, Virtual and Augment Reality (Alcayaga et al., 2019; Saberi et al., 2018). As a CE enabler, digitalization facilitates access to data that supports product management throughout its entire life cycle, lifetime extension and optimization, provision of spare parts, enhanced understanding of user behaviour, technology for service-based business models, decision support for the selection of the most suitable circular strategies at the end of use phases, and so forth. It is important to highlight that digital technologies, by itself, are not the end but rather the means through which enabling a redesign of products, business models and supply chains;
- Government intervention can enable CE by enacting legislation and mandatory regulations; providing financial incentives; promoting green public procurement; promoting the introduction of norms, labels and standards (such as the ISO 14001); promoting education campaigns and advertisement; promoting the adoption of environmental-focused indicators and metrics (Morseletto, 2020; Viani et al., 2016);
- Users' active role and engagement in a CE is the last enabler that companies may exploit. This can happen, for instance, at the point of sale by choosing circular products, during usage by adopting green practices, and at the end of life by properly discarding old items (Lieder and Rashid, 2016).

Second, based on literature, we identify three levers on which companies may act to implement CE: circular product design, servitised business models and supply chain management:

- Circular product design: several circular product design levers can be pursued to keep products, components and materials at their highest utility and value throughout their life cycle. They are: design for attachment and trust; design for durability and life extension; design for standardization and compatibility; design for ease of maintenance and repair; design for upgradability; design for material selection; design for sustainable behaviour; design for disassembly, reassembly and recycling (Bocken et al., 2016; Bovea and Pérez-Belis, 2018);
- Servitised Business Models (SBM): a shift from the sales of products to the provision of services is envisaged to leverage companies in adopting CE (Rondini et al., 2017). Tukker (2015) proposes three SBM types, namely product-oriented (e.g., after sales services, maintenance, repair), use-oriented (e.g., leasing, sharing), and result-oriented (e.g., pay-per-result);
- Supply Chain Management (SCM): to decouple economic growth from environmental losses and resource extraction, companies may leverage on SCM by optimizing forward logistics, by setting-up partnerships and close collaborations in the supply chain and by introducing reverse logistics (De Angelis et al., 2018; Farooque et al., 2019).

Finally, we point out four categories of benefits that can be achieved through the exploitation of CE enablers and the implementation of CE levers: environmental benefits, economic benefits (for the supply chain and for users), and social benefits:

- Environmental benefits arise when CE brings net gains to the environment, by successfully decoupling value creation from resource consumption, which will ultimately lead to a lower consumption of resources and to a higher value capture from waste streams (e.g., through reuse, remanufacturing and recycling);

- Economic benefits for the supply chain are achieved when CE brings net profits to the supply chain, by successfully developing more efficient and effective products/services, which leads to savings in materials purchasing costs, and higher value-added solutions which can enhance the company's competitiveness and market share;
- Economic benefits for the users are achieved when CE brings net savings to users, by successfully providing additional value and access to products that can successfully deliver the intended function, leading to overall life cycle cost savings (e.g., minimized total cost of ownership) or access to high value-added and more efficient products (e.g., sharing models);
- Social benefits arise when CE brings net social gains to the society, by successfully enabling the creation of new market segments connected to extended life and closed-loop strategies, which lead to job creation and enable access to products that can successfully enhance the quality of life.

According to the framework illustrated in Fig. 4, companies in the EEE supply chain may exploit the *enablers* to implement the *levers* for gaining the potential *benefits*.

3. Findings

3.1. Circular Economy enablers

Companies aiming to implement CE should exploit digitalization, government interventions and/or users' active role. In total, 106 articles out of 115 (92%) addressed at least one of those CE enablers. Fig. 5 shows their distribution: 92 articles out of 115 (80%) pointed out the government role in favouring the implementation of CE, 64 articles (56%) addressed the users' active role in enhancing this transition, while only 19 (17%) investigated the role of digitalization in enabling such transformation. Although this enabling character is suggested by the general literature on CE, the role of digitalization in the EEE industry seems to be significantly under-investigated. A relevant set of articles jointly addresses government intervention and users' active role in enabling CE through green purchasing decisions and usage habits (51 papers). Interestingly, only 3 articles address simultaneously the three enablers, indicating a gap in the adoption of a systemic perspective over the CE enablers.

Fig. 6 further details the enabling role of **digitalization**, i.e., what and how many digital technologies have been addressed by the literature. It is remarkable that only three technologies (IoT, Cloud computing and Big Data) have been addressed to date. IoT was the most investigated technology (17 articles). Thanks to both advances in ICT infrastructures and reduction in costs, manufacturers started to provide integrated communication modules for home automation in EEE and appliances such as washing machines and fridges (Nistor et al., 2015). This automation enabled smart appliances, thus creating a two-way link between the virtual and physical worlds (Khan et al., 2015). Few studies addressed cloud computing applications to EEE (8 articles). A cloud platform is an integrated cyber-physical system that provides on-demand digital and physical services by offering a shared pool of resources like software, facilities and capabilities (Wang and Wang, 2017). For EEE, cloud technology could support reuse, remanufacture and recycle of WEEE by setting up a platform where all the data of individual EEE at all life cycle stages can be maintained in an integrated and shared way (Vincent Wang et al., 2015). Only 6 articles addressed Big Data in the EEE industry. While the concept of IoT focuses more on the interconnection of cooperative objects, the concept of Big Data also considers the computational decision-making processes to provide intelligence, responsiveness and adaptation (Leitão et al., 2015). Data mining usually allows extracting valid, previously unknown and comprehensible information from large Big Data databases (Marconi et al., 2019). Overall, digital technologies are rarely investigated together: as depicted in Fig. 6, only two articles out of 115 investigate IoT coupled with Big Data and Cloud technologies. Lastly, none of the articles addressed the CE enabling role of blockchain, 3D Printing, augmented or virtual reality. This is a clear research gap that should be addressed in future research.

Fig. 7 details the enabling role of **government intervention**, i.e., what and how many government interventions have been addressed by literature. Interestingly, the majority of articles (71 out of 115, i.e. 62%) recognizes the enabling role of governments to force the implementation of CE into companies by the means of mandatory regulations (Favot et al., 2018). Other types of government interventions are investigated, but less frequently. Education campaigns and public advertising to better inform users, companies and citizens have been addressed by 25 articles. For instance, the consumers' usage habits can be improved through environmental education to save resources during usage or to avoid behaviours that may compromise the functioning of the product (Alborzi et al., 2017). The promotion of standards, certifications and eco-labels have been suggested by 24 articles, especially through ISO 14001 or energy efficiency labels (Morgan et al., 2018; Scur and Barbosa, 2017). The introduction of financial incentives to directly

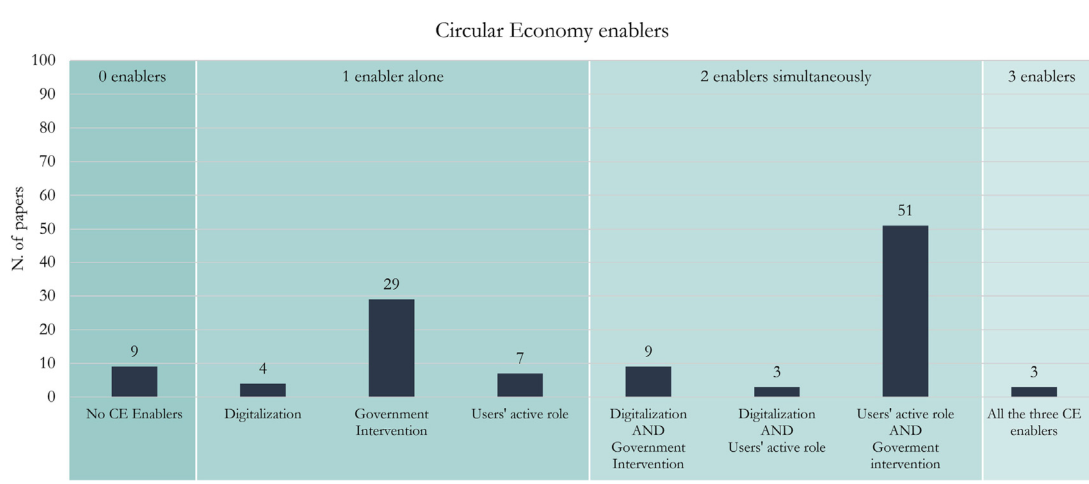

Fig. 5. Number of articles addressing each CE enabler and their combinations.

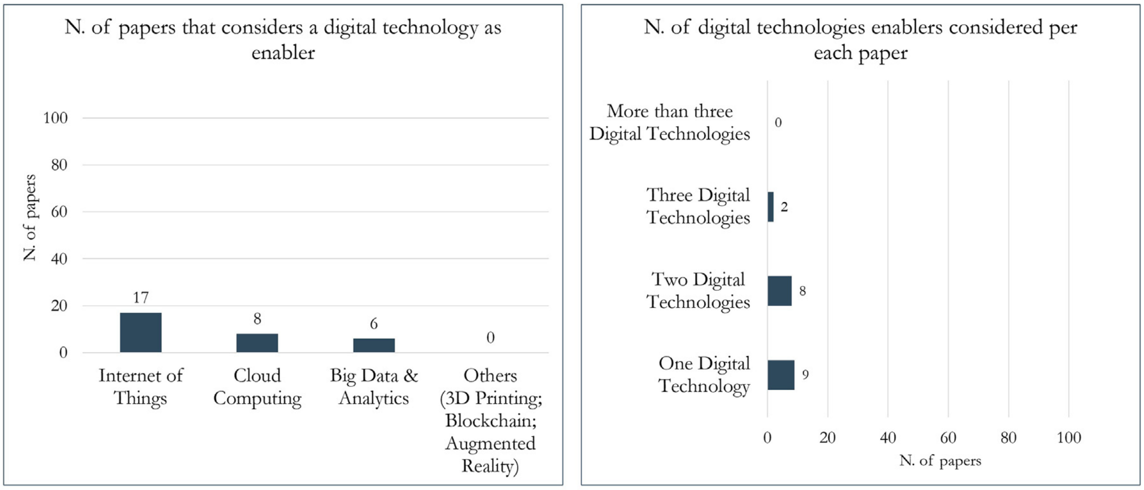

Fig. 6. Digitalization enabling role.

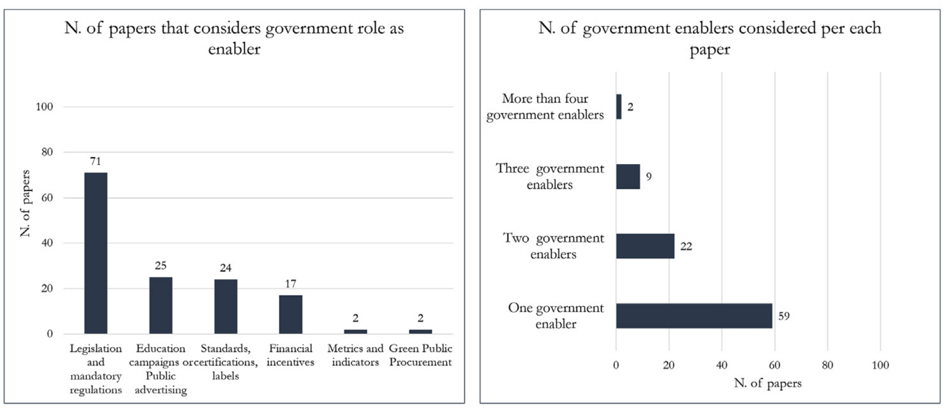

Fig. 7. Government enabling role.

support CE initiatives has been addressed in 17 contributions (e.g. Gnoni et al., 2017; Vendrusculo et al., 2009). Lastly, the introduction of appropriate measures and indicators as well as green public procurement (Singh et al., 2018) have been poorly investigated in the EEE industry, being both addressed by only two publications. Overall, the combination of government measures is very seldom addressed: as depicted by Fig. 7, only two articles investigate more than four government enablers simultaneously.

Fig. 8 details the **users' active role** in enabling CE. Users may have an active role in pushing the transition towards CE during the purchase (22 papers out of 115), the usage (39 papers out of 115) and the EoL of EEE (25 papers out of 115). During purchasing, they can choose greener, more efficient, refurbished or remanufactured models (Abeliotis et al., 2011). During the usage phase, users may be involved by lowering the resource consumption through better usage habits (Conrady et al., 2014) or by properly choosing the best time to replace appliances, counterbalancing the impact of continuing to use old products *versus* the impact of buying new ones, which consume less resources during usage (Ardente and Mathieux, 2014). During EoL, users play a crucial role in how products are discarded, thus improving the supply for recovery processes like reuse, remanufacture or recycling (Parajuly and Wenzel, 2017). Overall, the combination of users' role in different lifecycle phases has been rarely investigated: only two articles investigate simultaneously the users' active role during purchasing, usage and at the EoL.

3.2. Circular Economy levers

82 articles out of 115 (71%) addressed at least one CE lever (Fig. 9). Most articles focused on circular product design or SCM levers alone (respectively 23 and 21 articles). Interestingly, only 9 articles out of 115 addressed simultaneously all the three CE levers.

Fig. 10 illustrates what and how many **circular product design** options have been addressed by literature. Design is the phase where 70% of the cost of a product is set and where commitments to reducing environmental impact are made (Kumar and Putnam, 2008). "Design for disassembly, reassembly and recycling" was the most investigated design option (27 papers). It aims to support designing EEE that can both be easily disassembled into components so to guarantee an efficient recovery of parts and materials within CE models (Mandolini et al., 2018). It mainly depends on factors such as repair rates, product lifetimes, labour costs, collection rates and knowledge about products that reach EoL (Peeters et al., 2017). Modular design, i.e. developing products architectures as a joint union of physically detachable modules, can make disassembly, reassembly and recycling easier, since each module can be assembled and disassembled as a group, and components that can be recycled through the same shredding or separation process (Yang et al., 2011). "Material selection" was addressed by 19 articles, as a design option to promote the use of secondary raw materials such as recycled ones (Gu et al., 2016; Kim et al., 2009), materials with high recyclability rates (Favi et al., 2019) or non-

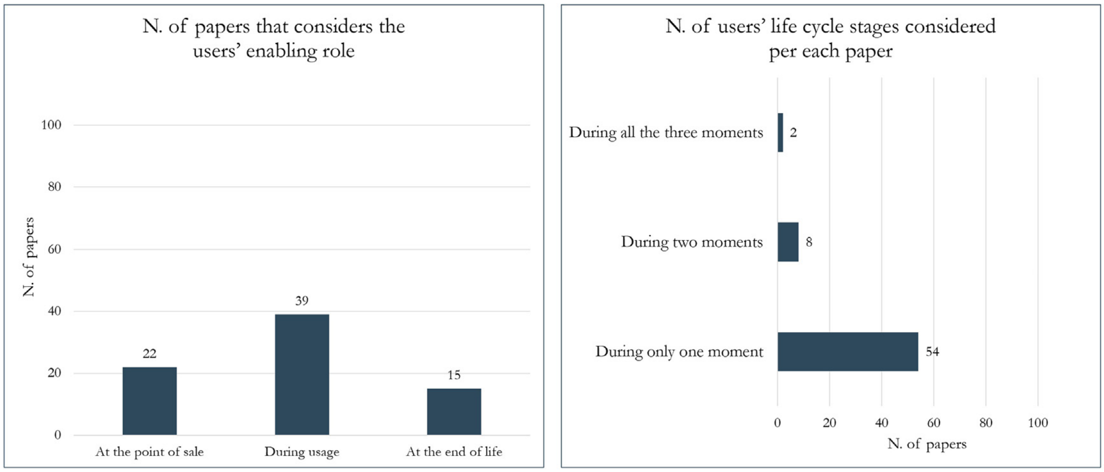

Fig. 8. Users' enabling role.

Fig. 9. Number of articles addressing each Circular Economy lever and their combinations.

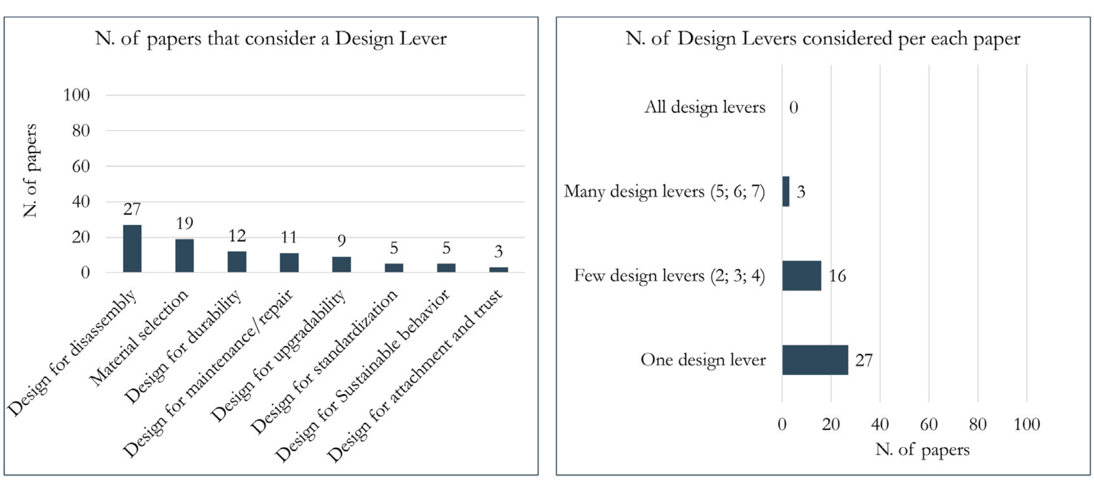

Fig. 10. Circular design levers addressed.

toxic, non-polluting or eco-friendly materials (Gu et al., 2017; Sousa-Zomer et al., 2018). "Design for durability" (Ardente and Mathieux, 2014; Stamminger et al., 2018), "ease of maintenance and repair" (Cooper, 2005; Tecchio et al., 2019) or "upgradability" (Kumar and Putnam, 2008; Sundin and Bras, 2005) have been targeted by only 12, 11 and 9 articles, respectively. Lastly, very few articles addressed the reduction of different non-standard components for eliminating the risk of selecting the wrong part during reassembly (Sundin et al., 2009), design for sustainable behaviour (Amasawa et al., 2018) and design for attachment and trust (Bakker et al., 2014). Overall, circular design strategies are seldom investigated together: only 19 articles investigate more than one design strategy, while none of the analysed articles addressed all the eight circular product design strategies.

Fig. 11 details what and how many **SBM options** have been addressed by literature, following Tukker's typology (Tukker, 2015). Not surprisingly, most articles focused on product-oriented SBM, e.g., after-sales services (24 articles). Maintenance and repair are useful strategies to increase the lifespan of products (Intlekofer et al., 2010). Maintenance is usually grouped into three categories, i.e., reactive, preventive or predictive maintenance (Vincent Wang et al., 2015). In all the three options, the provision of spare parts is crucial (Altekin et al., 2017). Use-oriented SBM have almost the same popularity, with 23 articles (20%). Product leasing helps moving from the current 'replacement system' to the 'optimal usage' of products coupled with an extension of their life spans, since leasing internalizes the life cycle costs to the OEM (Tasaki et al., 2006). Moreover, in use-oriented SBM, product return rates are generally high since OEM retain the ownership of EEE (Krikke, 2011), thus having financial incentives for implementing remanufacturing and design for remanufacturing (Sundin and Bras, 2005). On the other side, sharing models in EEE have been overlooked by literature, addressed by 5 articles only. Lastly, only 10 articles addressed result-oriented SBM, where customers pay for achieving a pre-defined and agreed result, such as a pay-per-wash SBM in the case of washing machines (Bocken et al., 2018). Overall, servitised strategies are seldom investigated together: only two articles out of 115 investigate all the three (product-oriented, use-oriented, and result-oriented) options.

Fig. 12 details what and how many **SCM levers** have been addressed by literature. Several papers (40) focused on reverse logistics to close supply chains (Kara et al., 2007). Reverse logistics includes the processes of planning, implementing and controlling flows of materials, goods and related information from the point of consumption to the original point in an efficient and cost-effective way and for the purpose of recapturing value (Achillas et al., 2012). Usually, used EEE can be supplied from individual users, from collection sites or from retailers (Kissling et al., 2012). How to configure a reverse logistics network is a complex problem, which comprises determining the optimal sites and capacities of collection and inspection centres, remanufacturing facilities and recycling plants (Alumur et al., 2012). Nine articles focused on the optimization of forward logistics too, since integration of forward and reverse logistics is required to build an effective closed-loop supply chain (Islam and Huda, 2018). But more surprisingly, only 18 articles address collaboration among supply chain stages (including partnership, upstream or downstream integration, etc.) and its relevance as a SCM lever (Berssaneti et al., 2019). Overall, the integration of forward logistics, collaboration and reverse logistics has been rarely addressed, since only 5 articles focused on all the three SCM options simultaneously.

3.3. Potential benefits

Fig. 13 illustrates the distribution of the 115 articles analysed across the four types of potential benefits.

All the 115 articles address the potential to generate **environmental benefits** in the EEE industry. This result arises from the criteria adopted for the selection of articles. Many of them highlight three main environmental benefits: (i.) reducing the need of extracting virgin resources from the environment, achieved by using secondary resources taken from the recycling of WEEE, thus avoiding the impacts of new materials production, along with its related energy intensive mining, refining and disposal processes (Van Eygen et al., 2016); (ii.) reducing the amount of waste generated at the EoL, achieved especially through EEE life extension or through recovery options such as reuse and remanufacturing (Stamminger et al., 2018); (iii.) savings on consumables during the usage of EEE, achieved by replacing old appliances with high energy efficient ones, through better and greener usage behaviour or by upgrading EEE (Nakamura, 2016). These three main environmental benefits mitigate greenhouse gas emissions such as CO_2, thus contrasting climate change (Ameli et al., 2016). Other environmental benefits targeted by the articles are the (iv.) prioritization of renewable energy, e.g. through the installation of smart appliances with demand-response mechanism (Khan et al., 2015), or (v.) limiting the release of pollutants such as micro-plastics: for instance, clothes made by synthetic textiles (petroleum-based organic polymers such as polyester) usually release micro-plastics fibres during washing (EEE usage phase), and these effluents can reach the aquatic marine environment via wastewater (Henry et al., 2019; Napper and Thompson, 2016).

A large share of articles (47 out of 115) highlighted how CE can provide **economic benefits to the EEE supply chain**. Overall, the

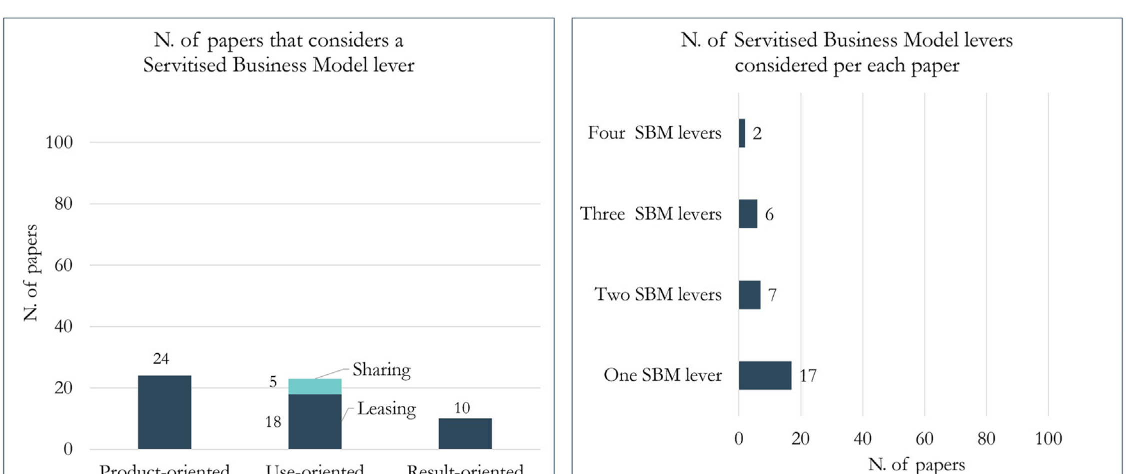

Fig. 11. Servitised Business Models addressed.

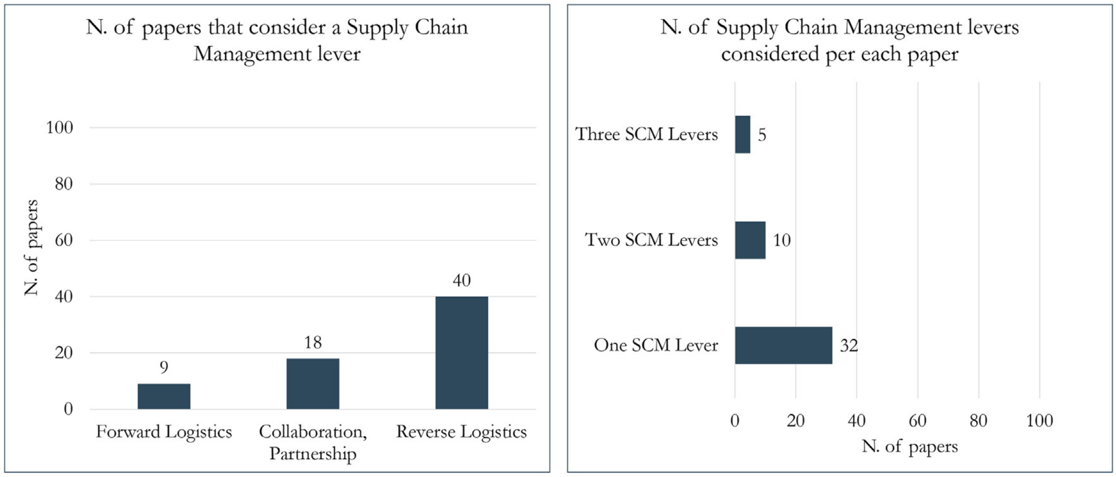

Fig. 12. Supply Chain Management levers addressed.

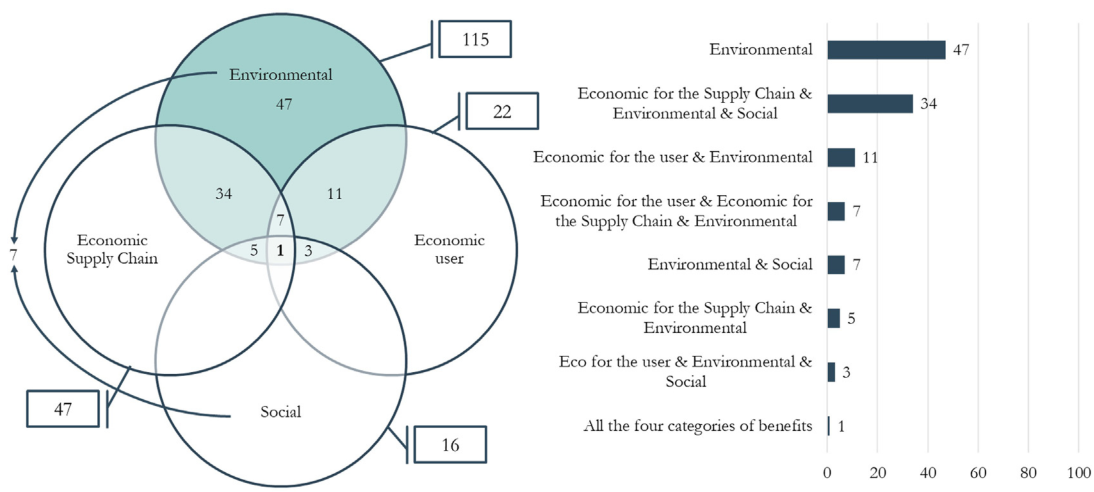

Fig. 13. Number of articles addressing each benefit.

following main economic gains are highlighted: (i.) cost savings achieved by using secondary materials or recovered components into the production of new products (Nelen et al., 2014), e.g. 40–60% lower costs for remanufactured EEE, due to the reuse of most materials and components (Kumar and Putnam, 2008); (ii.) revenue generated from selling recycled materials or recovered components (Wakolbinger et al., 2014); (iii.) revenue generated from selling used or remanufactured products (Quariguasi Frota Neto et al., 2010); (iv.) revenues generated from selling additional services such as maintenance and repair (Lieder et al., 2018; Yang et al., 2009); (v.) the possibility to achieve higher margins, thanks to the offering of high quality and efficient products (Vendrusculo et al., 2009); (vi.) the achievement of a competitive advantage, thanks to a greener image and brand recognition (Kim et al., 2015); (vii.) the minimization of non-compliance risks to regulations (Georgiadis and Besiou, 2010); (viii.) the possibility to further optimize EEE manufacturing and usage due to richer information about product performance (informational value): when EEE are smart, it is possible to evaluate how they have been used throughout their life cycle as well as what should be improved, thus discovering latent design enhancement opportunities (Leitão et al., 2015).

On the other hand, fewer articles (22 out of 115) highlighted how CE can provide **economic benefits for users**. They can be achieved through: (i.) usage savings thanks to the access to high quality and efficient EEE (Deutsch, 2010), such as energy, water and detergent savings from highly efficient washing machines (Saccani et al., 2017); (ii.) usage savings thanks to better users' behaviour during usage (Laitala et al., 2011), e.g. through live feedback mechanisms; (iii.) usage savings generated by smart grids and demand response mechanisms, which can anticipate or delay the usage of the EEE when the electricity prices are low, thus avoiding peaks of energy demand in the system (Nistor et al., 2015); (iv.) lower purchasing price of reused or remanufactured products (Gutowski et al., 2011).

Lastly, only 16 articles out of 115 highlighted how CE can potentially provide **social benefits**, related to: (i.) employment opportunities, since a shift to more skilled design and production methods as well as an increase in repair, maintenance, refurbishment and remanufacturing activities would offset the effect of reduced demand for new products in a CE (M. W. M. O'Connell et al., 2013; Shokohyar and Mansour, 2013); (ii.) an increased access to products or services, since reuse and leasing provides access to good and high quality EEE even for people with low incomes

(Kissling et al., 2012); (iii.) a reduced exposure to toxic materials during EoL (Fiore et al., 2019), by avoiding informal recycling of discarded WEEE that can lead to the contamination of soil, water, air as well as affect human health.

While some areas have been thoroughly investigated – such as environmental benefits and economic benefits for the supply chain – other areas still remain quite unexplored, as in the case of the social benefits and the economic benefits for the users. Only one article simultaneously takes into account all the four benefits, discussing their relations and implications but without quantifying their overall environmental, economic and social impacts (Gnoni et al., 2017). A systemic and holistic perspective in terms of benefits considered has not been observed to date.

4. Discussion

4.1. Relations between levers, enablers and potential benefits

This section assesses and discusses the relations between levers, enablers and benefits. We investigated whether papers addressing a particular enabler also tend to address one specific type of lever (Fig. 14), and the links and mechanisms through which enablers and levers can lead to different types of benefits (Fig. 15).

Digitalization tends to enable especially SBM (11/32 articles, 34%). The joint integration of IoT, cloud platforms, big data and analytics emerged as a strong enabler of SBM based on leasing or pay-per-use (Bressanelli et al., 2018). IoT allows EEE to become smart and connected, enabling their monitoring for billing purposes, thus facilitating the introduction of pay-per-use revenue models. Cloud platforms allow EEE equipped with sensors to be connected for lifecycle data transmission (Yang et al., 2009), facilitating the provision of advanced services such as maintenance and repair. Collecting and analysing big data in the cloud allows companies to learn more about EEE performance during usage, thus improving the service offering (Sundin and Bras, 2005). Digitalization is also related to SCM and circular product design, albeit to a lesser extent (21% and 17%, respectively). IoT installed into EEE can improve EoL activities by providing information about the condition, quality and version of components prior to disassembly (Ilgin and Gupta, 2011). IoT plays a key role in SCM improving the quality and integrity of the information (Garrido-Hidalgo et al., 2020), and promises great advances in the context of reverse logistics to exploit information for a faster and more sustainable collection of WEEE. For instance, RFID (Radio Frequency IDentification) sensors can be used for model recognition, to overcome practical barriers of WEEE identification and sorting, allowing recovery of desired substances such as gold on printed circuit boards or better identification of hazardous materials that must be properly disposed of (M. M.W. O'Connell et al., 2013). IoT and Big Data can finally enable a circular product design, when the information collected throughout the EEE life cycle are used to discover and improve latent design improvement opportunities, e.g. faults on products (Marconi et al., 2019).

Fig. 14 also shows that **government intervention** tends to enable especially circular product design (43/46, 93%). This can be explained by the fact that most papers focused on mandatory regulations, such as the Ecodesign directives in Europe, which force companies to comply with strict requirements about energy efficiency, recyclability and repairability by design (Scur and Barbosa, 2017). On the other side, government intervention enables also SCM and SBM, albeit to a lesser extent (75% and 70%, respectively). Financial incentives for enhancing reverse logistics in the EEE supply chain and the introduction of SBM are often claimed, even though less investigated.

Lastly, we found that **users have an active role** especially in enabling SBM (56%) and circular product design (48%). In fact, literature strongly suggests the consideration of the users' preferences and their changing needs in the design of SBM and circular products (Bocken et al., 2018), also to avoid rebound effects and unintended consequences of circular offerings – e.g., in laundry services, users may start to have their laundry done more often due to an increased convenience, leading to higher resource consumption and costs for the service provider (Kjaer et al., 2019).

EEE literature stressed the need to investigate more deeply the interactions among benefits and CE practices (Rosa et al., 2019). Linking CE levers and enablers to benefits allows better contextualizing how their application can bring environmental, economic and social benefits to the EEE supply chain (Fig. 15). **Digitalization** has been mainly investigated as a means to achieve environmental benefits (19 articles). In fact, many articles highlighted its potential to enable SBM and EEE traceability: both servitisation and traceability promote the collection of EEE at the EoL, reducing waste and the extraction of virgin resources. In addition, digitally enabled SBM are related to the provision of high efficiency EEE, leading to savings on consumables during usage. On the other hand, the links between digitalization and the achievement of economic and social benefits have been much less investigated. **Users** play a critical role in achieving economic benefits for themselves (19 articles

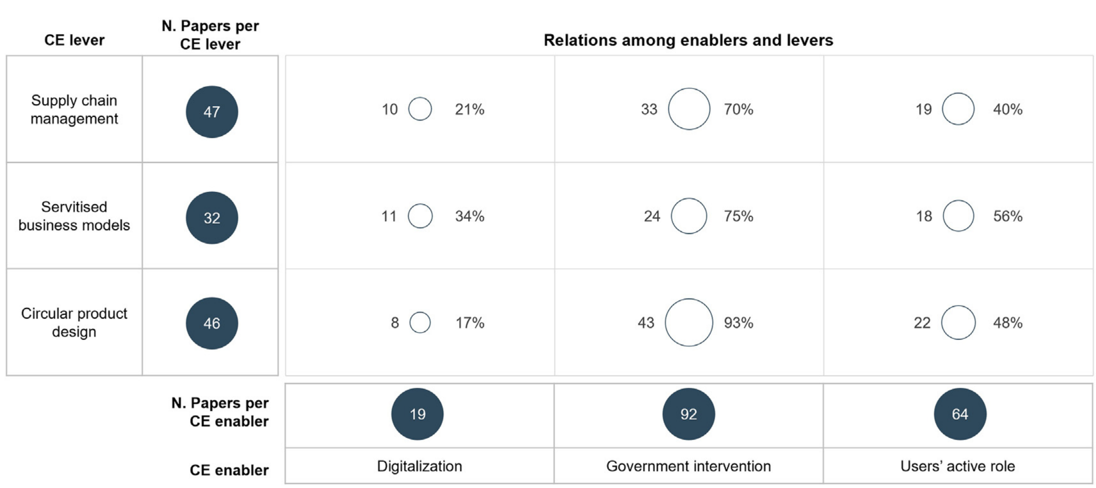

Fig. 14. Relations between CE enablers and levers.

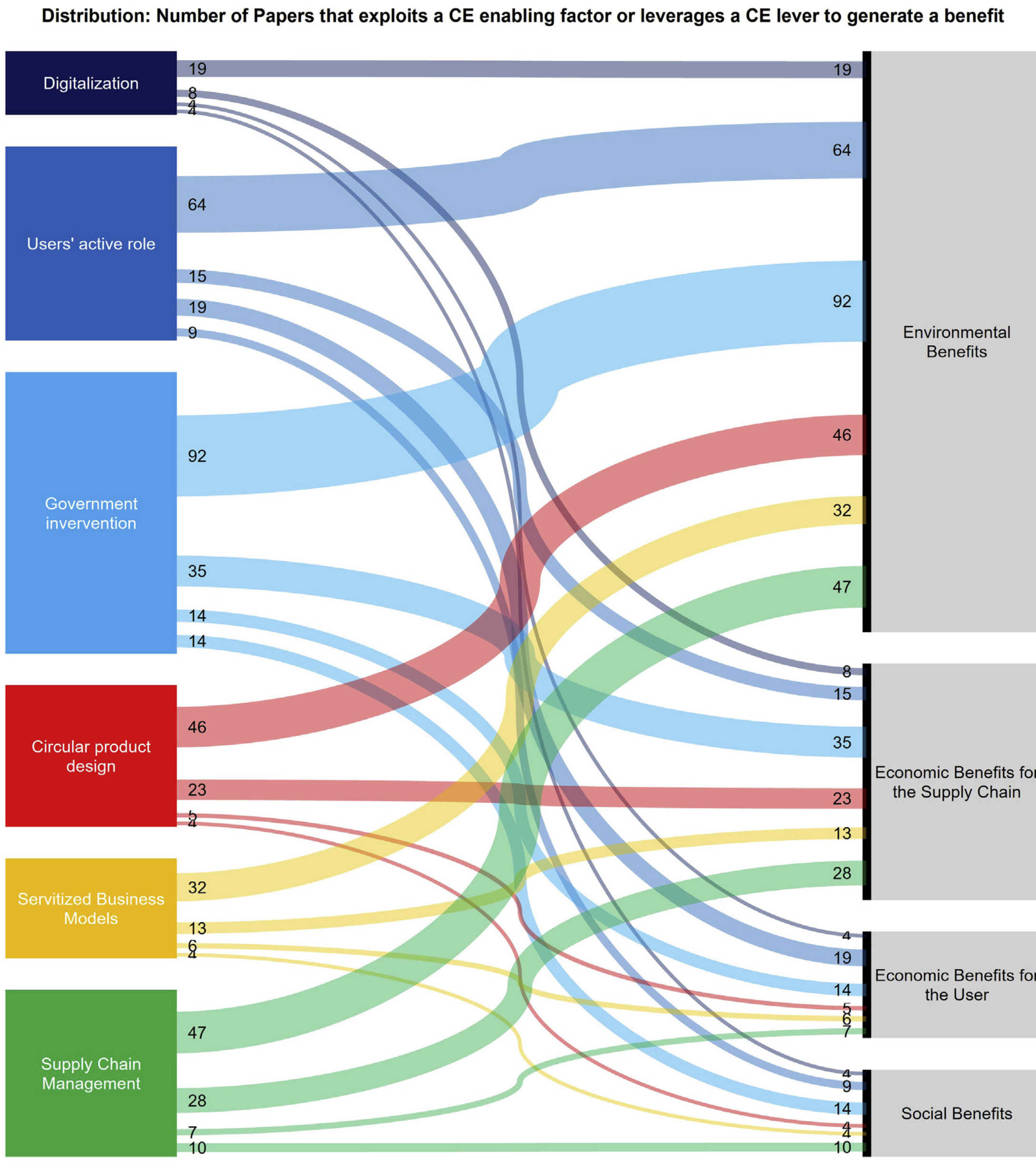

Fig. 15. Relations between CE enablers and levers with benefits.

investigate economic benefits for the users) due to the strong relation between usage behaviour of EEE and their economic impacts. Users who pursue a sustainable behaviour tends to consume less energy and resources, both reducing environmental impact and achieving usage cost savings (e.g., due to a minimized energy consumption). Users who choose to buy a used or remanufactured product may also achieve cost savings through a reduced purchasing price. Not surprisingly, **government intervention** has been often linked to environmental and social benefits (respectively 92 and 14 articles), given the intended purpose of mandatory legislations on EEE, such as the Ecodesign and Extended Producer Responsibility Directives. **Circular product design** levers have been mainly investigated for achieving environmental benefits and economic benefits for the supply chain. In fact, Circular product design reduces the need of extracting virgin resources from the environment (in case of 'reduce' design strategies as durability, upgradability or attachment and trust), and the amount of waste generated (in case of design for disassembly and recycling). Economic benefits, instead, are achieved especially by incorporating secondary (less expensive) materials in the design of EEE. As highlighted before, **SBM** mainly emerged as a lever employed to reduce the stress on the environment, since they entail both the provision of high efficiency EEE and an incentive for their reuse. Lastly, we found that **SCM** have been often linked to environmental and economic benefits for the supply chain, especially due to the role of reverse logistics in both reducing waste and increasing revenues by selling recovered products, components and materials, as in the case of recycling of high-grade waste printed circuit board embedded in EEE (D'Adamo et al., 2019). In summary, all the levers (circular product design, SBM and SCM) have been mainly investigated as a means to achieve environmental benefits or to increase the economic benefits for the supply chain.

4.2. Research agenda

Based on the findings of the literature review and on the discussion about the relations between enablers, levers and benefits, we propose a research agenda for advancing CE research in the EEE supply chain. It consists of eight research directions concerning enabler (2), levers (4) and benefits (2), listed in Table 2.

First, we addressed the role of enablers of CE in the EEE industry (digitalization, government intervention, users' active role). While government interventions and users' role have been investigated in the past, the enabling role of digitalization has been overlooked. In fact, few articles addressed IoT, Big Data and cloud technologies, while no study addressed augmented and virtual reality, blockchain or 3D Printing in the EEE supply chain. This can be partially explained by the emerging role of digitalization in the context of the fourth industrial revolution. Therefore, a first research direction consists in investigating more deeply the role of digitalization in enabling CE in the EEE supply chain, especially regarding the enabling potential of blockchain, 3D Printing, augmented and virtual reality. Moreover, CE enablers have not been investigated in a systemic and holistic perspective so far: digital technologies are rarely investigated together; the combination of government measures is very seldom addressed; and the combined role of users' during purchase, usage and EoL has been rarely analysed. A clear gap emerged from the literature regarding the adoption of a systemic perspective over these enablers. Consequently, a second research direction arises. At a higher level, we recommend the investigation of digitalization, government intervention and users' active role simultaneously, to address their additive and synergistic potential. At a more detailed level, we suggest combining different technologies when researching on digitalization; several regulatory measures when researching on government interventions; all the users' lifecycle stages when researching on users' active role.

Second, companies in the EEE supply chain implement CE by levers that allow redesigning products, business models and supply chains. Research so far has devoted limited attention to the 'reduce' product design strategies (as durability, standardization, upgradability, attachment and trust). In fact, most studies targeted design practices focused on disassembly, reassembly and recycling, while fewer addressed durability, upgradability, standardization, attachment and trust or sustainable behaviours in the product usage. Consequently, the CE hierarchy that advices to prefer Reduce and Reuse (material efficiency through life cycle extension or energy efficiency during usage) over Remanufacture or Recycle strategies is not reflected in literature, based on the popularity of research on the different design levers. Therefore, a third research direction consists in investigating design strategies focused on reduce, such as design for sustainable behaviour, design for durability, standardization, upgradability, attachment and trust. The literature has also devoted limited attention to sharing and result-oriented SBM, even though result-oriented SBM have the greatest CE potential, since product-oriented SBM do not change the incentive to maximize product sales, and use-oriented ones potentially lead to a less careful use thus increasing wear and tear (Kjaer et al., 2019). However, result-oriented are the least investigated SBM in the EEE literature. Thus, a fourth research direction is to carry out more research on result-oriented SBM in the EEE supply chain. In addition - and quite surprisingly - research has devoted limited attention to collaboration as a SCM lever to implement CE in the EEE supply chain. This represents another clear gap in literature, especially considering the important role of collaboration among supply chain actors for implementing CE (Berssaneti et al., 2019). It is very uncommon for a company to be able to get control over all its supply chain to influence also the other actors in transitioning towards CE (Bressanelli et al., 2019). Thus, we recommend, as a fifth research direction, to investigate the potential and the implications of collaboration in the EEE supply chain for the CE. Lastly, CE levers have not been sufficiently investigated in a systemic perspective so far: circular product design, SBM and SCM levers are seldom investigated altogether. For instance, the integration of forward logistics, collaboration and reverse logistics has been rarely addressed as SCM levers. Thus, the sixth research direction suggests to: at a higher level, investigate circular product design, SBM and SCM simultaneously, to leverage

Table 2
Research agenda.

Layer	Findings		Research Agenda
Enablers	Government interventions and users' active role in enabling CE have been well addressed in the past. On the other hand, the enabling role of digitalization has been overlooked: few articles addressed IoT, Big Data and cloud technologies, while no study addressed augmented and virtual reality, blockchain or 3D Printing in the EEE supply chai	1	- Investigate the role of digitalization in enabling CE in the EEE supply chain, especially regarding the enabling potential of blockchain, 3D Printing, augmented and virtual reality
	Lack of a systemic perspective over the CE enablers. Digital technologies are rarely investigated together. The combination of government measures is very seldom addressed. The combined role of users' during purchase, usage and EoL has been rarely investigated	2	- At a higher level: investigate digitalization, government intervention and users' active role simultaneously. At a more detailed level: combine many technologies when researching on digitalization; combine more measures when researching on government intervention; combine all the lifecycle stages when researching on the users' active role
Levers	Research has devoted limited attention to 'reduce' design strategies (durability, standardization, upgradability, attachment and trust)	3	- Investigate design strategies focused on 'reduce' (durability, standardization, upgradability, attachment and trust)
	Research has devoted limited attention to sharing and to result-oriented SBM	4	- Investigate SBM based on result-oriented offering
	Research has devoted limited attention to collaboration among supply chain actors and stakeholders	5	- Investigate the potential and the implications of collaboration in the EEE supply chain for the CE
	CE levers have not been sufficiently investigated in a systemic and holistic perspective: circular design strategies are seldom investigated together; servitised strategies are seldom investigated together; the integration of forward logistics, collaboration and reverse logistics has been rarely addressed	6	- At a higher level, investigate circular product design, SBM and SCM simultaneously. At a more detailed level: combine more design practices if researching on circular design; combine different SBM types if researching on servitisation; combine collaboration, forward and reverse logistics if researching on SCM
Benefits	The application of CE to the EEE supply chain has been mainly focused on environmental impacts and on economic benefits for the supply chain, while few articles covered the social dimension of CE or the economic benefits for the users.	7	- Investigate how CE in general and digitalization in particular can bring social and economic benefits for the users
	Benefits have not been investigated and quantified in a systemic and holistic perspective yet. Whether CE in the EEE industry can (or cannot) contribute to sustainability under a win-win-win strategy still remains an open question	8	- Simultaneously investigate and quantify economic, environmental and social benefits of CE implementation in the EEE supply chain

on their additive potential; at a more detailed level, combine more design practices when researching on circular design, combine different SBM types when researching on servitisation, combine collaboration, forward and reverse logistics when researching on SCM.

Third, research on CE in the EEE supply chain has mainly focused on environmental and economic benefits for the supply chain. Few articles covered the social benefits of CE or the economic benefits for the users. In particular, the link between digitalization and social benefits has been poorly investigated. Literature also neglected how circular product design, SBM and SCM may generate economic benefits to users and social advantages. Considering the intended target of CE to contribute to all the aspects of sustainability, future research is called to fill this gap. Therefore, the seventh research direction is to investigate how CE in general – and digitalization, circular product design, SBM, SCM in particular – can bring social and economic benefits (to users) in the EEE supply chain. Lastly, we found that potential benefits have not been investigated and quantified in a systemic perspective yet, since there is a scarcity of studies that simultaneously assesses economic, environmental and social benefits in the EEE supply chain. This is a relevant gap in the literature, also considering that only by quantifying the impacts it is possible to show the sustainability potential of CE and decide if, for instance, reuse is preferable to recycling for every impact category (Boldoczki et al., 2020). Therefore, whether CE in the EEE industry can (or cannot) contribute to sustainability under a win-win-win strategy still remains an open question. This constitute a clear research gap, which should be addressed in the future. Thus, we recommend to researchers (eighth research direction), to simultaneously investigate and quantify economic, environmental and social benefits of CE implementation in the EEE supply chain.

4.3. Implications for policy-makers and industry

Systematic reviews provide a mean for practitioners to use the evidence of previous research to inform their decisions. The identified benefits represent the starting point for industrials to be involved and act more effectively towards circularity, and can be used also by governments to better plan and act. Through this review, managers and policy-makers can get an overview of CE implementation in the EEE supply chain in terms of enablers, levers and potential benefits. On the basis of these results, we have found several implications for industry and policy-makers.

Policy-makers are advised to focus on governmental interventions such as legislation, financial incentives, eco-labels and especially education campaigns in order to increase the users' acceptance rate of CE solutions, thus leading to environmental and social benefits (as discussed in Section 4.1). To date, governmental interventions tended to enable circular product design by the means of mandatory regulations. From one side, mandatory regulation *pushing* circular product design (e.g., Ecodesign directives) should be aligned with design requirements. From the other side, financial incentives *pulling* the introduction of (i) SBM based on digitalization and (ii) a reverse logistics that prioritises reuse over recycling of EEE should be set. In fact, studies show that WEEE recycling alone is not enough for meeting the yearly demand of most raw materials, even in an ideal scenario in which all the aluminium, iron and copper included in EEE is recycled (Forti et al., 2020). Thus, a combination of levers (circular product design, SBM and SCM) is suggested throughout the EEE supply chain. Given the fact that not all the actors may be willing to voluntarily take part in a CE in the EEE supply chain, regulation should clearly lay out the role and obligations of each stakeholder.

Industry, on the other hand, should reflect on the tendences emerged in Section 4.1 on how CE can be implemented in the EEE supply chain. A first recurrent theme to be exploited is the enabling potential of digitalization – coming from the joint application of IoT, Cloud, Big Data and analytics – to implement SBM. Another key consideration emerged is to follow the users' active role by considering their preferences and changing needs in the design of circular products and business models. Overall, managers in the EEE supply chain are advised to design a roadmap towards CE that consider the combination of all the three levers (circular product design, SBM, SCM), with a prioritization of the different steps. We recognized two recurrent paths. In a *pull* configuration, managers can at first exploit financial incentives focused on digitalization to enable SBM and, when the business model is ready, redesign the product and proceed to configure the supply chain. In a *push* configuration, managers can at first incorporate mandatory regulations and circular design strategies in the design of new products and, when a new circular product is ready, proceed with the redesign of a circular supply chain and the introduction of a SBM. In both configurations, managers are advised to extend the value creation to include also social and economic benefits to users.

4.4. Research limitations

As every piece of research, this study has limitations. Notwithstanding the documentation of the research process to produce a transparent review, the systematization and categorization of the information is affected by researcher bias. To mitigate this issue, the classification criteria described in the Supplementary Material have been adopted. Another limitation is related to the choice to examine only articles published in journals with Impact Factor, which is a way to ensure the quality of the publications analysed, but which exclude other literature that may offer an important contribution to the topic, such as new developments and integrations that are more often found in conference proceedings or in journals without an impact score. Furthermore, it is also important to highlight that there might be a number of rebound effects (i.e., unintended sustainability consequences) connected with the CE implementation in the EEE supply chain – e.g., implementation of digitalization in the EEE industry can lead to enhanced product obsolescence, changes in use patterns and user behaviour, early substitution of devices, etc. These should be investigated in future research, so to ensure a holistic perspective and avoid sub-optimized sustainability performance and backfire effects. Moreover, other enablers and levers, outside the scope of this research and thus not related to digitalization, government intervention, users' role, circular product design, SBM and SCM should be identified and addressed by future research. Finally, future studies should focus on other industries besides the EEE supply chain, to compare the findings, find synergies and potential overlaps.

5. Conclusion

The EEE supply chain has a prominent relevance for the application of CE, but companies are still struggling in understanding and exploiting CE levers and enablers to reach the potential benefits of CE. In order to address the lack of a systemic and holistic perspective in literature, this paper reviewed 115 articles at the intersection of CE and the EEE supply chain to point out CE enablers, levers, and their potential environmental, economic and social benefits.

This article contributes to the accumulation of scientific knowledge on how the application of CE enablers and levers can bring environmental, economic and social benefits to the EEE supply chain. An original research framework has been developed as one of the first attempts to systematize how CE can be introduced in practice. The framework can be seen as a practical tool for contextualizing the transition to a CE. Finally, the paper highlights the main research gaps about enablers, levers and potential benefits in the EEE supply chain. In addition to systematizing CE enablers and levers (RQ1), we drafted a comprehensive list of how the application of CE enablers and levers to the EEE supply chain can bring benefits to the environment, to the supply chain economics, to users and to the society (RQ2). In this domain, the literature has mainly investigated environmental and economic benefits for the supply chain, and there is a need to further investigate how CE in general and digitalization in particular can bring social and economic benefits. We pointed out also the systemic need to investigate and quantify economic, environmental and social benefits simultaneously.

Following those findings, a research agenda with eight research directions has been proposed in Section 4.2, especially regarding: the role of digitalization in enabling CE; design strategies focused on 'reduce'; SBM based on result-oriented offerings; supply chain collaboration in CE endeavours; the social and economic benefits (for users) related to CE in EEE. The research agenda also highlights the need to simultaneously investigate the categories within each layer (i.e., the different types of enablers, levers and benefits) adopting a systemic perspective, to understand their interplay and combined effect.

According to our review, policy-makers are advised to advance mandatory regulations to *push* circular product design (such as Ecodesign directives) and to clearly lay out role and obligations of each stakeholder in the EEE supply chain. They are also advised to design financial incentives to *pull* the introduction of both SBM based on digitalization and a reverse logistics that prioritises reuse over recycling. Managers in the EEE supply chain are advised to design a roadmap towards CE that considers the combination of all the three levers of circular product design, SBM and SCM, following *pull* and *push* configurations to prioritize actions. In both cases, managers are advised to undertake CE approaches leading to social and economic benefits to users.

CRediT authorship contribution statement

Gianmarco Bressanelli: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Daniela C.A. Pigosso:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Nicola Saccani:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Marco Perona:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.126819.

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