Journal of Manufacturing Systems 60 (2021) 429–448

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

journal homepage: www.elsevier.com/locate/jmansys

Review

Supporting disassembly processes through simulation tools: A systematic literature review with a focus on printed circuit boards

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A R T I C L E I N F O

Keywords:
Circular Economy
Simulation
Disassembly
Industry 4.0
Systematic literature review

A B S T R A C T

Several strategies have been detected in the extant literature to understand how Circular Economy (CE) can be pursued. Considering all the End-of-Life (EoL) management practices detected, disassembly processes have been identified as strategic. However, only scattered attempts have explored how digital technologies (specifically, simulation) can support the CE adoption, by focusing on disassembly processes. This research detects, through a systematic literature review, how so far simulation approaches have been proposed and applied in the extant literature to foster the disassembly process with a focus on Printed Circuit Boards (PCBs). At this purpose, the main roles played by simulation to ease the disassembly process, also through the support of Industry 4.0 (I4.0) technologies, have been detected. Based on the results obtained, two roles of simulation to support the disassembly process (Sequence planning and process optimization and Training) seem the most interesting from the twofold CE/I4.0 perspective, combining up to date technologies with traditional simulation approaches. Discussed in a deeper and sector-independent way, results provide directions about the lifecycle phases to be explored through simulations, the technologies to be involved, and both the final purpose and the type of simulation approach to be adopted. Finally, the gaps needing for further contributions, raised from the adoption of a Digitized Disassembly, are listed, and the main technologies so far employed to cope with them, through a Virtual/Augmented Disassembly-oriented Simulation perspective, have also been detected and provided as a guide for those who want to approach the hybrid simulation/disassembly research context.

1. Introduction

Circular Economy (CE) has become even more important during the last decade. Manufacturing companies are investing big capitals to make both more sustainable products and more circular processes. To this aim, several strategies (e.g. reuse, remanufacturing, recycling) have been detected in the extant literature [1–4] and specific business models have also been suggested [5] to support a practical adoption of CE and get real benefits from it [6]. In this context, the importance of slowing, narrowing and closing product lifecycles has been raised [7]. However, very few works assessed how different design alternatives can influence End-of-Life (EoL) management practices, specifically disassembly processes (considered by the experts as the most important stage for the adoption of specific EoL actions) [8,9]. So far, only scattered attempts have been done, by exploiting simulation as reference approach to solve EoL issues [10–12]. However, they focused on either i) recovery/recycling [10], reuse [11] or remanufacturing [12], without considering the link with design decisions. Considering all these elements, this

Abbreviations: AB, Agent-Based; AM, Additive Manufacturing; AR, Augmented Reality; AVS, Augmented Vision System; A/D, Assembly and Disassembly; BIM, Building Information System; BDA, Bid Data and Analytics; CAD, Computer Aided Design; CAM, Computer Aided Manufacturing; CE, Circular Economy; CPS, Cyber-Physical Systems; CHAS, Collaborative Haptic Assembly Simulator; COTS, Commercial-Off-The-Shelf; DES, Discrete Event Simulation; EoL, End of Life; EW-MFA, Economy-Wide Material Flow Analysis; GA, Genetic Algorithm; HMD, Head Mounted Display; HS, Hybrid simulation; HSG, Haptic-path Sequence-Guidance; IC, Integrated Circuits; IoT, Internet of Things; IS, Industrial Symbiosis; ISN, Industrial Symbiosis Network; I4.0, Industry 4.0; KM, Knowledge Management; KPI, Key Performance Indicator; MAS, Multi-Agent System; MES, Manufacturing Execution System; MISO, Material Inputs, Stocks and Outputs; MTBO, Mean Time Before Overhaul; MTTR, Mean Time To Recovery; ODE, Open Dynamics Engine; OO, Object Oriented; PCB, Printed Circuit Board; RI, Recycling Index; RFID, Radio Frequency Identification; RPM, Recycling Product Model; SD, System Dynamics; SFT, Stress Free Temperature; V/A, Virtual/Augmented; VE, Virtual Environment; VH, Virtual Human; VR, Virtual Reality; VTK, Visualization Toolkit; WEEE, Waste from Electrical and Electronic Equipment.

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https://doi.org/10.1016/j.jmsy.2021.07.009
Received 15 October 2020; Received in revised form 6 July 2021; Accepted 6 July 2021
Available online 11 July 2021

research wants to investigate how simulation has been exploited to both support disassembly processes and enable a real transition towards CE with a focus on the Printed Circuit Board (PCB) domain. It has to be said that a focus has been dedicated to PCBs since they represent the most valuable component embedded in the Waste from Electrical and Electronic Equipment (WEEE) sector, one of the most important sources of waste globally [13]. To this aim, a systematic literature review has been conducted. Firstly, a state-of-the-art analysis was performed to identify how simulation can be seen as an enabler of CE, with a specific focus on PCB disassembly processes. Secondly, an in-depth analysis of contributions allowed to understand the main characteristics and address the main issues, discussing them in a deeper and sector-independent way. Indeed, the paper is structured as follows. Section 2 provides the research context. Section 3 shows the adopted research methodology to perform the systematic literature review. Section 4 presents results coming from the literature analysis and Section 5 is dedicated to their discussion. Finally, Section 6 draws conclusions and proposes future research areas.

2. Research context

2.1. Circular economy

Trying to mix some of the most common definitions proposed by Refs. [14,15], CE can be defined as a global economic model to minimize the consumption of finite resources, by focusing on intelligent design of materials, products, and systems, in order to overcome the traditional (linear) economy model (e.g., take, make, and dispose) developed with no built-in tendency to recycle. Only in the last few years the relevance of CE has been amplified worldwide [16]. Progressively, new (closed loop) patterns completely focused on balancing economic, environmental, and societal impacts are trying to substitute old industrial practices.

2.2. Industry 4.0

Contrarily to what evidenced before about CE, I4.0 does not have neither a common definition nor a standard classification of technologies pertaining to this paradigm. Trying to cope with the absence of a technological classification, the present work considers the nine pillars described by Ref. [17] as a reference set of I4.0 technologies. Another work [18] already started from these pillars to implement a structured literature analysis focused on the identification of existing relations between CE and I4.0. Results of this study assessed as only five of these nine pillars (e.g. Cyber-Physical Systems (CPSs), Internet of Things (IoT), Big Data and Analytics (BDA), Additive Manufacturing (AM) and simulation) can be considered potential technologies supporting the transition towards CE practices. CPSs are an integration of computational and physical processes, where computers and networks monitor and control physical processes through feedback loops and physical processes affect computations [19]. IoT are technologies allowing the interaction and cooperation among people, devices and things through modern wireless connections (e.g. radio frequency identification (RFID), sensors, tags, actuators, and mobile phones [20]). BDA is the adoption of advanced data analysis techniques for managing big datasets [21]. AM is a set of technologies allowing the production of goods via the layering or 3D printing of materials [22]. Finally, simulation considers a wide range of mathematical programming techniques exploited to implement decision-making tools.

2.3. Simulation

Simulation can be defined as a way for managing change, reproducing or projecting the behaviour of a modelled system in order to bring clarity to the reasons for change [23]. In its main meaning, simulation is an experimental computer-based approach [24], where a set of rules (e.g. equations, flowcharts, state machines) defines how the system being modelled will change in the future, given its present state [25]. Generally, system behaviours are coupled with an experimental design [26] for testing more alternatives. Depending on their functionality, several types of simulation approaches and tools are available in the scientific literature. Most of them are focusing on R&D, conceptual and detailed engineering and operations [27].

Simulation models can be classified along four distinct dimensions [23]: i) system of interest (e.g. physical, managerial or meta-model), ii) visibility (e.g. transparent or black-box), iii) probability (e.g. probabilistic or deterministic) and iv) dynamics (e.g. steady-state or dynamic). The system of interest determines the kind of information generated. Visibility determines if the scope of the model is offering an answer to a problem or the way a result was obtained. Probability determines the range of behaviours that can be realized with the model. Dynamics determines the ability of a model to show the change of important business metrics over time or across space.

The major approaches (paradigms) in simulation modelling are System Dynamics (SD), Discrete Event Simulation (DES) and Agent-Based (AB). Technically, SD deals mostly with continuous processes whereas DES and AB work mostly in discrete time [25]. DES is the most popular simulation technique and is appropriate for tactical and operational decision-making. DES focus on the concept of entities, resources and block charts describing entity flow and resource sharing. SD follows DES in popularity and is appropriate for strategic decision-making and analysis, high-level perspective and qualitative analysis (e.g. knowledge management). SD focus on modelling the behaviour of the whole system, rather than modelling the behaviours of actors within the system [26]. Hybrid simulation (HS) follows SD in popularity. It exploits two or more simulation techniques (commonly DES and SD) to solve a problem and is applied in several contexts depending on the reference models constituting it. AB simulation follows HS in popularity and is applied in strategical behaviours definitions and organizational development. AB simulation focus on modelling the behaviours of adaptive actors who make up a social system and who influence one another through their interactions. The behaviour of the system is an emergent property of the interaction of the agents [26]. Intelligent simulation is the integration of simulation and artificial intelligence techniques (e.g. artificial neural networks and genetic algorithms) into a meta-model (or response surface) in order to approximate the unknown input-output function implied by the underlying simulation to provide fast and robust decision support aids to improve the overall decision-making process [28]. Other techniques are Monte Carlo simulation, traffic simulation, simulation gaming, Petri-nets and virtual simulation (modelling and simulating a system in a three-dimensional, immersive environment) [29].

Looking at the I4.0 paradigm, simulation is adopted to study real world functioning in virtual settings. Doing so, physical and virtual environments exist together and made synchronized in real-time [19]. However, data models of different scenarios to be represented are needed [30–32], leading to the concept of Digital Twin (DT). DT acquires in real time from the field data needed to represent physical objects reproducing their behaviour [33,34]. Through DTs, both static analyses (prognostic assessment at design stage) and dynamic ones (real-time synchronization and optimization of the virtual object) are enabled [12]. However, even if easily applicable to CE paradigm, few papers use DT in this research domain [35]. For example, Ref. [12] proposed the adoption of a DT in different CE practices. They proposed the virtualization of either the optimization disassembly process, through the monitoring of materials and energy consumptions, or of the remanufacturing and recycling process, leveraging on the storing of the knowledge concerning the components and the materials embedded into products. Instead Ref. [36], used the combined concepts of Augmented Reality (AR) and Virtual Reality (VR) as a strategic key for empowering disassembly and remanufacturing processes. Finally, Ref. [37], raising that technologies as IoT and CPS have still not been adopted together with AR/VR and DT simulation tools and robots, presented a real demonstration of the benefits coming from the application of I4.0 technologies to CE (e.g., optimizing forward and reverse material flows).

3. Materials and methods

To identify relevant studies describing the relation between simulation and CE (specifically focusing on disassembly process of PCBs), a literature analysis has been conducted. A systematic literature review was conducted according to the method proposed by Ref. [38] to investigate the relation between simulation and disassembly with a focus on the PCB domain. Contributions were classified and discussed based on an innovative framework of analysis.

This section shows how the data were collected and analysed, starting from the identification of the search criteria for selecting the papers. Then, other information sources were also checked, to expand the initial sample, and were classified with the papers, to consider their consistency to the aim of the analysis. Finally, the documents resulting from the selection process were analysed meticulously in terms of year of publication, type of research, industry, and role of simulation in supporting CE (specifically focusing on disassembly process).

A multiple layered analysis (from macro to micro perspective), to be able to investigate all the possible extant contributions to the research specific purpose, has been performed.

The definition of the keywords and related queries has been based on the results of a previous systematic literature review [18] about the relationship between I4.0 and CE domains, that introduces two hybrid I4.0/CE domains named Circular I4.0 and Digitized CE. This analysis found that there is a strict relation between simulation and disassembly (especially in the PCBs/WEEEs domain, as stated, among others, also by Ref. [11]). This relation unveils that simulation not only supports CE in multiple ways (e.g. product lifecycle management, remanufacturing, natural resources exploitation, supply chain management [39,40]) but is also considered among the main I4.0 technologies supporting remanufacturing (a process strictly requiring the disassembly operations).

Even considering the specificity of this study, i.e. simulation of disassembly process with a focus on the PCB domain, a contextualization is needed. Indeed, simulation and disassembly are subsets of I4.0 and CE, respectively. In turn, as shown in the paper, simulation can be of different types (physics-based, VR and AR (these last two directly involving DT). Finally, WEEE and PCB are a sector suitable for the particular domain addressed in this work, bringing to an idiographic study but also allowing to lead to a generalizable discussion of the results. Therefore, all the set of queries conducted in the literature analysis were performed to avoid to neglect any contribution that could be contributing in some way to the specific aim of this paper.

In particular, the review process has been carried out in three steps (collection, evaluation and analysis). During collection, a structured keyword search was conducted in Scopus™, one of the most used scientific database for industrial engineering [41]. As shown in Table 1, a generic perspective was taken with the first round of queries, carried out to detect those documents explicitly aimed at empowering the touching points between Circular Economy and simulation. Keywords as “Simulation”, “Industry 4.0” (I4.0), “Virtual Reality” (VR), “Digital Twin” (DT) have been combined with “Circular Economy”. Here, a higher attention has been dedicated to the application of I4.0 technologies in the context of CE, considering those technologies (VR and DT) more suitable to support the simulation of disassembly processes.

Then, in round 2, to unveil the tacit knowledge linking disassembly processes with Industry 4.0 technologies, further queries have been performed. Keywords as “Virtual Reality”, “Digital Twin”, “WEEE”, “PCB”, “Circular Economy”, combined with “disassembly”. They have been combined to try to grasp the knowledge related to the adoption of VR and DT technologies (based on simulation theories) in the disassembly process. Indeed, first round 2.1 was conducted to assess the link between disassembly and simulation, then round 2.2 concentrated the attention exactly on the field of investigation of the paper, shrinking the analysis of this last relation to the PCB/WEEE domain.

Table 1
Searches by keywords and documents selection.

Focus of the rounds of queries	Searches by keywords	Results on Scopus
1. Link between CE and Simulation	“Circular Economy” AND “Simulation”	111
	“Circular Economy” AND “Industry 4.0”	30
	“Circular Economy” AND “Digital Twin”	1
	“Circular Economy” AND “Virtual Reality”	3
2.1 Link between Disassembly and Simulation (DT, VR)	“Disassembly” AND “Digital Twin”	2
	“Disassembly” AND “Virtual Reality”	213
2.2 Link between Disassembly and Simulation (DT, VR) of PCBs/WEEEs	“Disassembly” AND “WEEE”	111
	“Disassembly” AND “Virtual Reality” AND “WEEE”	0
	“Disassembly” AND “PCB”	66
	“Disassembly” AND “Virtual Reality” AND “PCB”	0
	“Disassembly” AND “Circular Economy” AND “WEEE”	3
3. Applied research in the CE-simulation domain	“Circular Economy” AND “Simulation” AND (“application” OR “industrial” OR “laboratory”)	33
Total		**573**
Total from 2000 to 2019		**573−14 = 559**
Total discarding redundancies among searches		**559−184 = 375**
Total after title-abstract-keywords analysis		**375−189 = 186**
Total after manuscript analysis		**186−123 = 63**

A final query (round 3 in Table 1) was carried out to give evidence to those contributions presenting either industrial or laboratory applications to the combined context of CE and simulation.

During evaluation, all the queries were performed looking at titles, abstracts and keywords. In addition, queries were performed without considering constraints on the publication year and evaluating only journal or conference papers written in English. Table 1 reports the twelve strings used to carry out the searches in Scopus™, leading to 573 results, refined to 389 after redundancies removal. Subsequently, only documents from 2000 onward were considered (given the role of technologies in this research context). This way, 14 contributions were discarded, leading to a final amount of 375 papers. By assessing just titles, abstracts and keywords, the set of documents considered was reduced to 186 documents. Subsequently, a full reading of these manuscripts allowed to consider a final set of 63 documents assessing the role of both digital technologies and simulation tools in supporting CE practices, specifically disassembly processes. The assessment was focused on two aspects: i) the role of digital technologies and simulation tools in supporting current CE-driven disassembly practices and ii) the presence of similar application cases matching I4.0 with CE, especially for WEEE disassembly processes monitoring and control.

Fig. 1 shows the research strategy used in the systematic literature review [42–44]. Three documents were considered through cross-referencing processes and two through hand search. Furthermore, two documents were suggested by experts to be added to the list. Applying the three criteria, the number of initial documents was reduced to a final set of 63 articles. The entire process of documents selection and examination was conducted by two authors, carrying it out autonomously to avoid bias of analysis along the review. Finally, their results were compared and made consistent to each other. The selection was based on the relevance of documents, by considering only those contributions proposing simulation to support disassembly processes

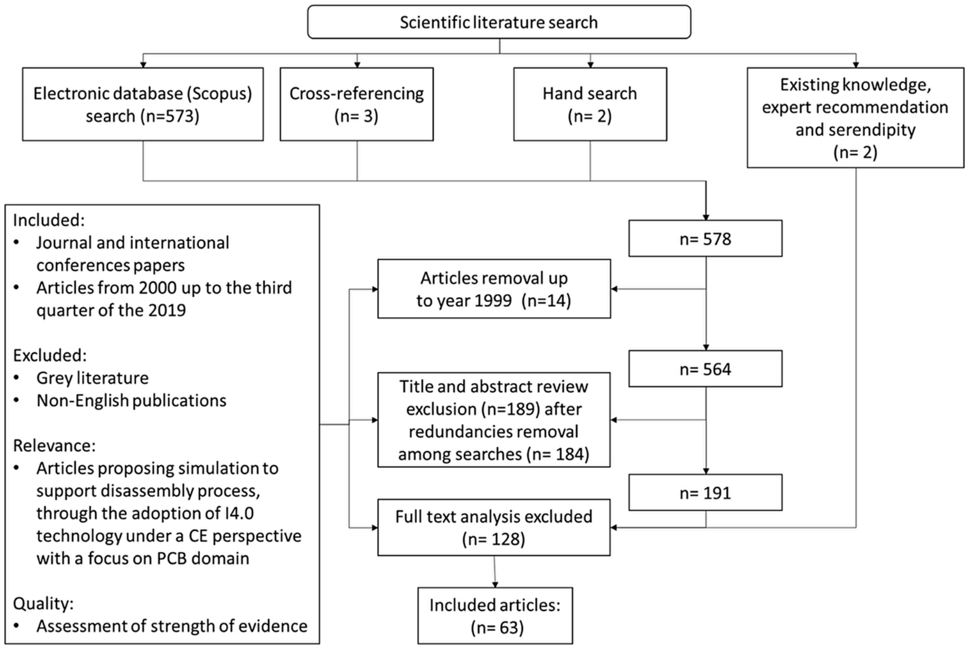

Fig. 1. Research strategy (adapted by Smart et al. [42]).

under a CE perspective.

4. Literature review

Trends along the years of the selected 63 articles (Fig. 2) illustrate a quite steady and weak interest on simulation methods and tools to foster disassembly process, recording an increasing average value in number of contributions in the last decade (81,1 % of the contributions are from 2010 onward). This can be justified by the growth of interest in digital technologies from both research and industry [17,45], and to the advent of the I4.0 paradigm, also with the aim to practically support CE [37].

Concerning the type of contributions, 33 were articles published in scientific journals, 29 papers in international conference proceedings and 1 book chapter. Publications are quite scattered in 28 journals. Two journals can be considered more relevant ("The International Journal of Advanced Manufacturing Technology" and "Resources, Conservation and Recycling") compared to others, even if they have only 3 publications each. This behaviour can be explained by the fact that different topics are linked to this context, from manufacturing and sustainability, through digitization and automation, to nanoscience, building engineering, metallurgy and advanced materials.

In view of the nationality of authors, European countries provided most of the selected contributions (49,2 %), followed by Southeast Asian/Chinese countries (38,1 %) and North American ones (12,7 %).

Assessing the literature, most of the papers gave relevance to the applicative side, contributing to the improvement of the actual state of both knowledge and practice (Fig. 3). Indeed, applicative research, declined in action research (the most popular with 47,6 %), followed by case studies and analytical assessments (20,63 % per each of them), and combined case study and survey (3,2 %), constitute 92,1 % of

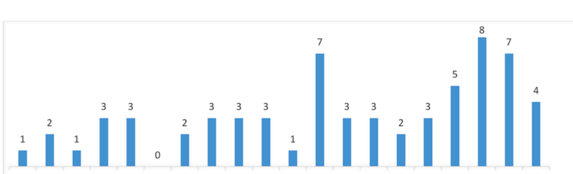

Fig. 2. Historical publication trend by year.

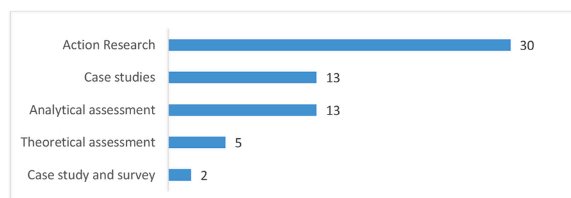

Fig. 3. Type of research.

contributions. While theoretical assessment represented only 7,9 %.

To strengthen these numbers, it can be noticed that 52 out of 63 contributions included in their researches applicative cases in specific industries with the aim to validate and demonstrate results (Fig. 4). The two most relevant industries found were manufacturing and assembly/disassembly (A/D) plants (i.e. shop floor fabrication, assembly planning for product completion, disassembly planning for product end-life management, turbocharger, pneumatic actuator of a butterfly-type valve assembly system, fixture, robot) and WEEE (washing machine, lamps, PCBs, laptop computers, telephone, small household appliance, torch light, coffee machine, printing machines).

Also automotive (e.g. automobile engine, mechanics and camshaft housing of an internal combustion engine), refinery and process production (system of coal power and cement, coal resource utilization system, coalmine equipment, refinery bump system, marble residuals

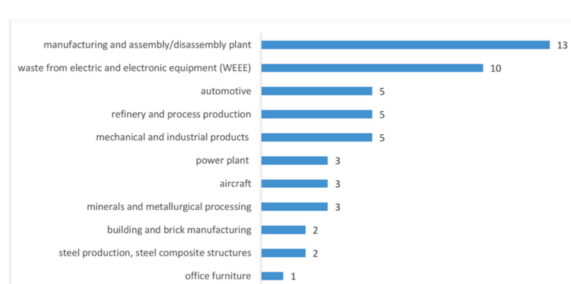

Fig. 4. Industries.

used in concrete production, alcohol slops used in fertilizer production), mechanical and industrial products (industrial product parts, disassembly of manufacturing products, 3D objects and complex environments) resulted quite relevant. Finally, power plants (power components, centrifugal pump system, thermal power plant), minerals and metallurgical processing (copper processing; metallurgical IoT), aircraft (electrical box for an airplane engine), steel production and building industry were the less involved.

4.1. Extant state of the art on the role of simulation supporting disassembly through digital technologies with a focus on PCBs

The set of 63 documents selected have been analysed. All the articles were focused on exploring the roles of simulation to support disassembly under a CE perspective with a focus on PCBs. Eight main groups have been detected (Table 2): a) design alternatives selection, b) decision-support tools, c) sequence planning and process improvement, d) Industrial Symbiosis (IS) monitoring online platforms, e) recycling performance and Key Performance Indicators (KPIs), f) material and technological properties, g) benefits and business impacts and h) training. 25 contributions were focused on the definition of the disassembly sequence plan and the improvement and optimization of related processes. 10 contributions exploited simulation to train operators and improve their skills and knowledge in the disassembly process. 8 contributions were oriented at supporting the selection of different design alternatives. 5 contributions were aimed at strengthening and highlighting the benefits and business impact deriving from the adoption of the CE paradigm. 5 contributions were focused on supporting the decision-making process while adopting CE paradigm. 4 contributions described simulation as a tool providing recycling performances and KPIs metrics and evaluations. 4 documents identified simulation to provide online platforms and monitoring for the adoption of CE at all IS levels. The last 3 articles were focused on the evaluation of material and technological properties. Table 2 reports some details about the final set of 63 papers.

All the detected roles played by simulation supporting disassembly under a CE perspective (see Fig. 5 below), have been analysed in terms of:

- mean proposed/used (method, tool, algorithm, rules, virtual environment, system architecture, etc.) to support simulation in addressing circularity through I4.0 technologies,
- Lifecycle phase improved through simulation,
- technologies involved,
- type of simulation (physics-based modelling, virtual reality, augmented reality),
- improved human-machine interaction,
- variables optimized using simulation,
- specific issue addressed through simulation along systems lifecycle.

4.1.1. Design alternatives selection

To support the selection of both design alternatives and EoL options [10], developed a simulation-optimization enterprise input-output model providing a cost–benefit analysis of IS, integrated to an AB model, to support design alternatives selection. The proposed model is also useful for manufacturers to evaluate EoL performances of their products and for policymakers to foresee the reaction of producers to a defined set of CE strategies. Ref. [46] built a methodological framework supporting the flexible design of remanufacturing systems. Through a case study based on remanufacturing of laptop computers for the Cambodian market, they demonstrated as Monte Carlo simulation can be adopted to gauge the efficacy of different flexible design strategies in managing uncertainties. Ref. [47] integrated a method in a VR disassembly environment based on Python programming language. It evaluated the ergonomics of disassembly operations based on three new criteria (visibility, neck and bending scores) presented through dimensionless coefficients. To support the adoption of this method and provide improvements to the product development process, they used a mixed visualization toolkit (VTK) and open dynamics engine libraries (ODE). Similarly Ref. [48], used the same tools to support the evaluation of the complexity of disassembly sequences in a VE. They developed a method based on five criteria (visibility of a part, disassembly angles, number of tools' changes, path orientation changing, and sub-assembly stability) paired with a mixed VR disassembly environment. Ref. [49] developed a set of rules for manipulating strings representing parts and handlers in binary A/D operations. These rules support a method for translating high-level instructions from product designers into low-level A/D instructions. The entire system, integrated into a CAD/CAM environment, is aimed at evaluating products in their design phase, calculating the cost for assembling and disassembling parts in virtual manufacturing. As well, Ref. [50] used VR simulation, proposing a framework for using it at design stage. They used it from design till EoL stages, in order to improve training, virtual user manual, virtual repair maintenance, and disassembly before recycling. Ref. [51] proposed an object-oriented modelling method, a software tool and a system architecture enabling enterprises to analyse and design all critical aspects of their de-manufacturing processes over the web, to manage their disassembly lines and provide electronic support systems for operators. In this context, the methodology heeds on the process parameters through the interaction with the networked database. Ref. [52] developed an immersive VE for constraint-based assembly and maintenance task simulation and analysis of large-scale mechanical products. In this research, maintenance operations simulation allows to early address maintenance in the design stages, reducing both the lifetime operating costs and unforeseen problems (saving both time and money while enhancing product quality).

Table 3 shows that, within the category "design alternatives selection", researchers focus their attention on design/development phase (5) to improve either the entire lifecycle (1) or single specific phases (A/D (5), remanufacturing (1), EoL, specific post manufacturing tasks (as training, virtual user manual, virtual repair maintenance, and disassembly before recycle)). To support the conduction of such simulations, VTK and ODE libraries are adopted, sometimes supported by web-based libraries and CAD/CAM environments. The variables to be optimized with the simulation are quite heterogeneous. They go from design errors to EoL products performance, from ergonomics of disassembly operations to cost for A/D parts, from lifetime operating costs to the complexity degree of disassembly sequence in a VE. Few cases evidence the attempt to improve the machine-human interaction.

4.1.2. Decision-support tools

Decision-support tools were proposed to support the entire lifecycle, from the design phase up to production and disassembly. Ref. [53]

Table 2
The eight roles of simulation supporting disassembly through digital technologies.

	Simulation roles in supporting disassembly							
	Design alternatives selection	Decision-support tools	Sequence planning and process improvement	Online platforms and monitoring for IS	Recycling performance and KPIs	Material and technological properties	Benefits and business impact	Training
Total	8	5	25	4	4	3	5	9

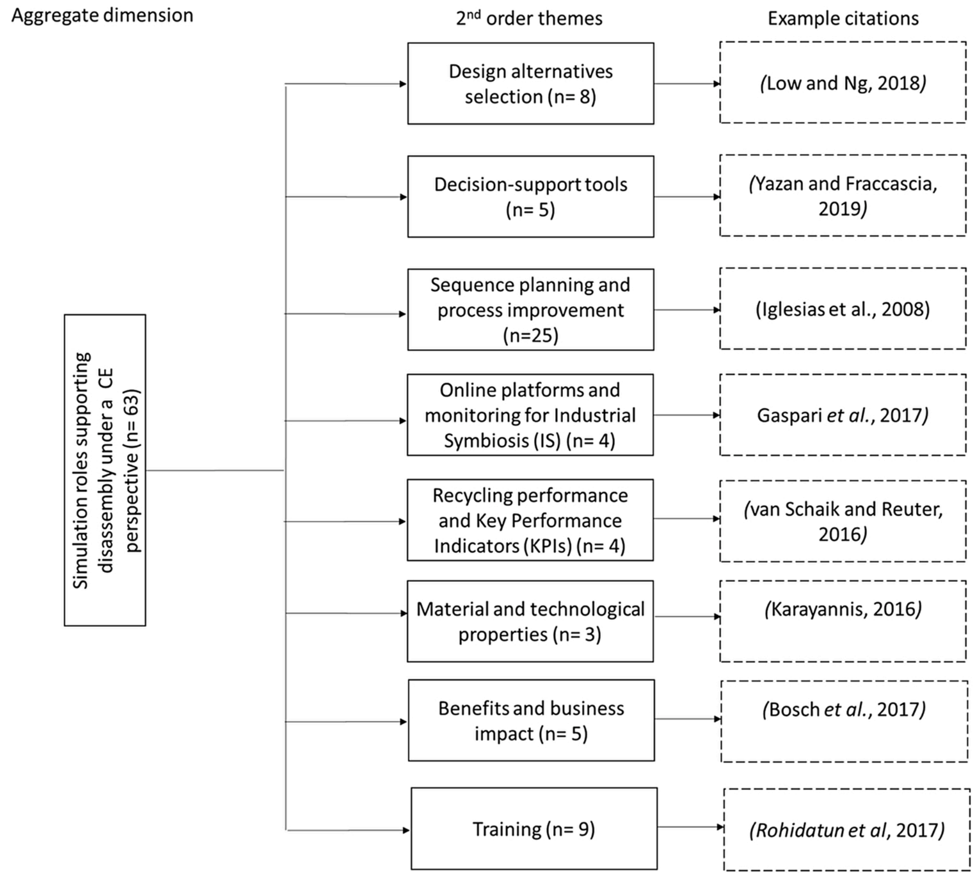

Fig. 5. Scheme of simulation roles supporting disassembly under a CE perspective through the use of digital technologies (adapted by Ref. [43]).

developed a systematic method to quantify design effort for different circular design options through a multi-method simulation approach. The method provides a decision support at the intersection of multiple lifecycle design and business models in the CE context to identify effects on cost and CO_2 emissions. The simulation model combines an AB product architecture and a DES closed-loop supply chain model. Ref. [54] paired a macroeconomic simulation model and a substance flow model to define both sectoral copper demand and the availability of secondary copper. They modelled and simulated several scenarios aiming at diminishing primary copper demand and rising the supply of secondary copper. Shifting the focus on the production phase [55], quantified the electric energy consumption and environmental impact of unconventional electric steelmaking scenarios, by concurrently monitoring the steel composition. Through the proposed Decision Support System (DSS) they highlighted as the scrap quality strongly affects the monitored energy and environmental KPIs [56]. Moreover, the developed simulations highlighted the slag reduction and the yield improvement, conserving the steel quality and marginally improving the electric energy consumption. Looking at the disassembly phase, Ref. [57] developed a web-based virtual electronic product disassembly system supporting the decision-making process of teams of engineers and technicians. Indeed, they can virtually assess and visualize the disassembly problem, identifying critical parts of the product and creating a disassembly process plan. Finally, they can evaluate various disassembly process sequences to maximize value of recovered materials with minimum effort and expense. Ref. [58] proposed an automated approach to support the decision about the best way to disassemble electronic components in PCBs, in a non-destructive and selective mode. They developed a prototype of an automated dismantling station to assess the technical and economic feasibility of the process at industrial scale. Through simulation, the best method to extract parts in an automatic way can be decided (dealing with the geometry of the components, their location within the PCB, the soldering method of components on the PCB surface, etc).

Table 4 illustrates that, within the category “decision-support tools”, researchers adopted traditional simulation approaches to enhance product design/development and production, and involved VR only for disassembly decisions, without attempting to improve machine-human interaction. To assist simulation and enable a web-based system, an Object Oriented (OO) modelling and engineering multimedia for knowledge management and communication was implemented. In addition, an automatic handling device was used to support decisions during the disassembly process (e.g. costs and CO_2 emissions deriving from specific design options, scrap quality, macroeconomic material flows, value of recovered materials with minimum effort and expense in disassembly sequences, parts extraction method in an automatic way).

4.1.3. *Sequence planning and process improvement*

Sequence planning and process improvement is a multi-objective problem [56,59]. Few contributions exclusively used traditional simulation approaches for this purpose. Ref. [60] developed an optimum assembly algorithm with ant colony model to support the maintenance assembly process for 3D objects and complex environments and find both optimal sequence and 3D path planning. They considered A/D sequence, number of gripper changes and the path used in an A/D process to apply VR in the assembly context. Ref. [61] developed an approach to automatize the disassembly processes of electronic equipment. They developed a flexible semi-automated disassembly cell for PCBs. Ref. [62] developed a robotized, semi-automated, flexible disassembly cell for minidisks, PCBs and mobile phones for industrial applications. The disassembly cell was based on the concept of “disassembly families”, integrating mobile robots and multi-agent

Table 3
Design alternatives selection category.

Authors	What is proposed	Lifecycle phase improved through simulation	Technologies/tools involved	Type of simulation			Improved human machine interaction	Variables optimized
				Physics-based	VR	AR		
[10]	Enterprise input-output model providing a cost–benefit analysis of IS, integrated to an AB model, to support design alternatives selection	- Product Design - EoL	–	AB	–	–	–	- EoL products performance - Companies sharing of the total economic benefits stemming from IS
[46]	Methodological framework for flexible design of remanufacturing systems	Remanufacturing	–	Monte Carlo	–	–	–	Economic performance in the face of uncertainties
[47]	Method for ergonomic evaluation of disassembly operations based on three criteria (visibility, neck and bending scores)	Product development	- Mixed Visualization Toolkit (VTK) - Open Dynamics Engine (ODE) libraries	x	x	–	–	Ergonomics of disassembly operations
[48]	Method for the evaluation of disassembly operations in a mixed virtual reality environment	- Product development, - Disassembly	- VTK - ODE libraries - Python programming language	–	x	–	–	Complexity of disassembly sequences in a VE
[49]	Set of rules for manipulating parts and handlers' strings in binary A/D operations, supporting a method for translating high-level instructions from product designers into low-level A/D instructions	- Product Design, - Assembly, - Disassembly	CAD/CAM environment	–	x	–	–	Cost for assembling and disassembling parts
[50]	Framework for building VR simulation for designed products	Entire lifecycle	–	–	x	–	–	Design errors
[51]	Modelling methods, software tools and system architecture to analyse/design critical aspects of de-manufacturing processes over the web, manage disassembly lines and provide electronic support systems for operators	- Manufacturing, - Assembly, - Disassembly	Networked (web) databases	–	x	–	x	A/D Process parameters
[52]	VE for constraint-based assembly and maintenance task simulation and analysis of large-scale mechanical products	- Product design, - Assembly, - Maintenance	–	–	x	–	x	Lifetime operating costs
TOTAL				3	5	0	2	

systems (MAS).

Some researches added VR to traditional simulation approaches. Ref. [63] presented a method to discover task precedence and find all physically admissible subassemblies in which a set of rigid objects can be disassembled. They also discovered the potential benefits of physics-based modelling for automatic learning of assembly tasks and for intelligent disassembly planning in desktop VR. Ref. [64] introduced a global interactive scheme including fast motion planning and real time guiding force for 3D CAD part A/D tasks. It starts with a preliminary workspace discretization and then finds, through simulation, a collision free path supported in real time by a haptic assistance compelling the user on the path.

Other contributions focused their experimentations on VR simulations and their related VE. Ref. [65] proposed an optimal assembly path planning algorithm for aircraft part maintenance. They used Genetic Algorithm (GA) to obtain optimal sequence of parts for A/D process in a VE. Ref. [66] presented an intelligent virtual assembly system supported by an optimal assembly algorithm allowing haptic interactions during virtual assembly operations. Simulation was conducted using a virtual assembly system for measuring the performance of the assembly system suggesting the haptic-path sequence-guidance (HSG) mode as the one providing the best performance improvement. Ref. [67] proposed a methodology for the simulation and optimization in a VE of a manual assembly process. Layout, devices, tools and movement sequences were considered modification vectors to optimize the assembly process through simulation. Ref. [68] developed an automated information management platform to assist managers to manage life cycle information related to open-building projects (implementing an integrated "radio frequency identification with building information model" (RFID-BIM)). As result, they obtained a 3D time factor-integrated figure able to generate a 4D VR model for construction progress simulation in the planning and design phase. Indeed, users can use the 4D installation process simulation model to optimize the building disassembly effort (whose steps can be inferred from information stored on the RFID tags and integrated in the platform). Due to the presence in manufacturing environments of islands of automation and to the uncertainty bonded to the actual presence of resources in real manufacturing environments, Ref. [69] presented a dynamic tasks planning system. It provides both a 3D visualization and user intensive interaction through a manufacturing VE and a tool for the data update and access timely using internet technology.

In developing VE, some contributions also focused on the machine-human interaction. Ref. [70] developed a user-friendly and cooperative human-robotic exoskeleton for manual handling work and validated it in digital and VE on car disassembly and automotive suppliers. Ref. [71] conducted a real-time simulation test bed to assess the usefulness of haptic technology for A/D planning, conducting several experiments to focus on the characterization of the perception of weight in the VE. Ref. [72] built a VR maintenance system performing rapid maintenance of mechanical coalmine equipment through the virtual disassembly. It can also estimate the maintenance time and cost, define the component disassembly sequence and the space that maintenance work needs. Some researches dealt with VR particularly heeding on collaborative systems. Ref. [73] developed an assembly simulation application on a collaborative haptic VE, where several users interact with virtual models to perform assembly operations within the same

Table 4
Decision-support tools category.

Authors	What is proposed	Lifecycle phase improved through simulation	Technologies/tools involved	Type of simulation			Improved human machine interaction	Variables optimized
				Physics-based	VR	AR		
[53]	Multi-method simulation approach to quantify design effort for different circular design options combining an AB product architecture and a DES closed-loop supply chain model	Product design	–	AB + DE	–	–	–	Costs and emissions on CO_2
[54]	Methodology for analysing material flows of copper in relation to the wider economic system, coupling a macroeconomic simulation model and a substance flow model to determine both sectoral copper demand and the availability of secondary copper	Product development	–	x	–	–	–	Reduction of primary copper demand or increasing of secondary copper supply
[55]	Decision Support Tool to quantify electric energy consumption and environmental impact of unconventional electric steelmaking scenarios, also monitoring steel composition	Production	–	x	–	–	–	Scrap quality (affecting production resource and energy consumption)
[57]	Web-based virtual electronic product disassembly system to assess and visualize the scope of the disassembly problem, identify products' critical parts, create a disassembly process plan. Teams can share disassembly and product identification solutions to identify hazardous components and proprietary components, information and data	Disassembly	- Object oriented (OO) modelling and engineering multimedia for knowledge management and communication - Robust analytical methods	x	x	–	–	Value of recovered materials with minimum effort and expense in disassembly sequences
[58]	- Automated approach to support the decision about the best way to disassemble electronic components in PCBs in a non-destructive and selective mode, - Automated dismantling station developed as a prototype to assess the technical and economic feasibility of the process at an industrial scale	Disassembly	Automatic handling device	x	x	–	–	Best method to extract parts in an automatic way (considering geometry of the components, their location in the PCB, the method used for their soldering to the PCB surface, etc.)
TOTAL				5	2	0	0	

virtual scene. In a subsequent work, Ref. [74] developed a peer-to-peer collaborative haptic assembly simulator (CHAS) whereby two users can simultaneously carry out assembly tasks using haptic devices, addressing virtual scene synchronization (consistency) and provision of a reliable and effective haptic feedback. Starting from the concept of Design for A/D [75] (traditionally furthering assemblability, disassemblability, part accessibility, and part layout), Ref. [76] introduced Motive3D, a collaborative virtual A/D system [77]. Thanks to the use of the high bandwidth network and VR technologies, it can support system development and the product design cycle, also reducing A/D process bottlenecks. Some works strongly contributed not only to collaboration among humans, but also to the human-machine interaction enhancement. Ref. [78] proposed a multi-layer approach of interactive path planning for assisted manipulation in VR. Using geometrical, topological and semantic information of the environment, simulation guides the user through a haptic device suggesting a better suited path. In another research, Ref. [79] developed a hybrid method of rule-based reasoning and fuzzy comprehensive judgment. It recognizes both the hint of the user's in performing operations and geometric properties and shapes (supporting the design of interactive modular fixture assembly in a VE).

Given that virtual human (VH) plays an important role in virtual assembly and maintenance simulations, Ref. [80] defined the function requirements for VH. Then, they developed two models and a modelling method:

- a real-time driving model (with a dynamic constraint applied to support personalized human model driving),
- a driving error model (for quantitatively analyse VH's driving error coming from the motion capture system),
- an interactive operation model for VH (where VH directly manipulates product, tools, and product using tools).

In another research, Ref. [81] focused on the model using real-time driving VH with motion capture to simulate the A/D for complex products. Given that the driving accuracy is influenced by size difference between real human and VH, they developed a noise compensation model based on grey system theory (based on body joints' limit angles and the ranges of the joints angles between following frames) to realize online compensation for filterable missing information.

Some contributions paired the use of AR to VR. Ref. [82] presented in real space robot A/D processes and the movement of the robot work in animation. Ref. [83] presented a new concept for a maintenance system which provides a synchronous shared visual workspace even when only limited bandwidth. To support the human operators interaction with a robotized production unit, Ref. [84] developed a numerical control unit and its ergonomic human-machine interface. Human A/D objects' time was enhanced through the introduction of an augmented vision system (AVS) aiding the operator to detect and correct errors in the system. Ref. [85] built an AR-guided product disassembly framework with an automatic content generation module to improve the efficiency of the disassembly process performed by human operator without expert intervention. A disassembly sequence table and an automatic content generation domain are able to adapt the generated sequence to the visual cues' virtual information. Ref. [86] developed an AR adaptive guiding scene display method to show the 3D virtual guiding scene on suitable screen region from a comfortable viewpoint. The optimal viewpoint selection algorithm took the projection area, visible proportion, information entropy, and difference in depth of all visible vertexes of CAD feature's bounding box in 3D virtual guiding scene into account.

Table 5 shows that, within the category "sequence planning and process improvement", contributions were characterized by a strong presence of VR (19) (sometimes paired with traditional simulation approaches (5) and AR (5)) and focusing on machine-human interaction empowerment (18). Most of them were aimed at supporting the core process of A/D (23). Some of them were also focused on phases that are directly related to A/D process, like maintenance (6), design (4), production (2), remanufacturing (1) and installation (1). To support the conduction of such simulations (often in a VE) haptic devices were adopted, as HSG (6), robotized units (5), high-bandwidth networks and telecommunication equipment (3), data-glover and motion capture/tracker systems (2), CAD, RFID-BIM and VR-based modular fixture assembly design systems. Here, the main objective was optimizing the sequence and path (also for haptic guidance) of the A/D/maintenance process (10). In addition, other objectives have been identified in literature (e.g. process time/quality [87], assembly time to market, number of gripper changes, computational time - 8). Ergonomics, in terms of manipulations and working conditions, has also been considered several times (8), involving robots' capability of manipulating objects, the possibility of perceiving objects' weight in VR and the proficiency of capturing user's operation intent and recognizing geometric constraints. Moreover, other variables were considered:

- features linked to the VE (the projection area with the visible proportion and information entropy deriving by CAD systems utilization, the virtual scene synchronization (among more users concurrently working), the VH driving errors and the process driving noise and accuracy) (4),
- process cost (3),
- degree of process automation (2),
- use of manufacturing resources in the process, the physically admissible sub-assemblies and the effective storage and retrieval of critical information needed by managers at different project phases.

4.1.4. Online platforms and monitoring for Industrial Symbiosis (IS)

Ref. [88] designed an AB model to simulate the emergence and operations of self-organized Industrial Symbiosis Networks (ISN). Three scenarios (no information-sharing platform, platform to provide information about geographical location and wastes and platform to provide sensitive information about IS operating costs) were simulated in two IS businesses (marble residuals in concrete production and alcohol slops in fertilizer production). The simulations were useful to demonstrate that online platforms improve the economic and environmental performance of IS networks. Ref. [89] proposed a remanufacturing systems simulation model based on a modular framework enabling users in managing process settings and production control policies (e.g. token-based policies). It aided the logistics performance evaluation, by enabling the selection of optimal production policies in specific businesses. Ref. [90] developed a virtual platform including features needed to design and implement a prototype of a flexible automated disassembly system.

Table 6 concerns the category "online platforms and monitoring for Industrial Symbiosis (IS)". It shows a joint use of traditional simulation with VR when the focus is monitoring for IS (to improve remanufacturing aspects) while either traditional simulation approaches or VR are used when platforms are provided to act at a strategic level or on the design phase. In this category, information sharing has a very important value.

4.1.5. Recycling performance and Key Performance Indicators (KPIs)

Ref. [91] developed a Recycling Index (RI) (comprising a new material-RI), based on minerals and metallurgical processing simulation models, aimed at measuring the recycling performance of a product and its embedded materials. Ref. [92] extended the Economy-Wide Material Flow Analysis (EW-MFA) framework jointly addressing material flows, in-use stocks of manufactured capital and waste. Using a fully consistent dynamic model of Material Inputs, Stocks and Outputs (MISO) model, they enabled a dynamic and complete appraisal of resource use, stocks and all wastes in the socio-economic metabolism. Ref. [93] simulated solvent extraction process to determine the mass and energy balance of the whole recycling treatment of spent lamps. The process consists in the recovery of rare earth elements from sulfuric leaching solutions achieved by the dissolution of fluorescent powders of lamps. Ref. [94] used a DES model to analyse the effect of CE strategies on power plant availability and maintenance time. They demonstrated results through a case study on a thermal power plant, by finding that components upon failure replacement and maintenance time have the highest impact on system availability.

Table 7 concerns the category "recycling performance and Key Performance Indicators (KPIs)". No specific technologies and tools are involved to support this kind of contributions and human-machine interface is neglected. Only traditional simulation approaches are adopted to support the measurement of either the entire lifecycle or the specific phases (maintenance or recycling). Recycling variables are considered (i.e. mass and energy balance of the treatment, recycling performance of a product and of the individual materials, materials recovery from EoL products, environmental footprint), but also maintenance (Mean Time Before Overhaul (MTBO) and Mean Time To Recovery (MTTR)) and more general aspects along the entire lifecycle (annual flows of material and energy) are measured in some cases.

4.1.6. Material and technological properties

Ref. [95] analysed the effect of stress relaxation before and during disassembly using simulation to measure variables as interfacial delamination of reused Integrated Circuits (IC), viscoelasticity of moulding compound, Stress Free Temperature (SFT) of the plastic integrated circuit package. Ref. [96] studied the development of building bricks through a pilot-plant simulation of industrial processes for red brick manufacturing. They found that extruded and fired bricks developed with up to 15 wt% (percentage by weight) recycled steel industry by-product is feasible without compromising their technological properties. Ref. [97] performed 15 large scale push-out tests, two large scale composite beam tests and several finite element simulations for demountable flooring and beam systems. These applications were useful to determine the suitability for dis-/re-assembly and of some inner material characteristics.

Table 8 describes the "material and technological properties" category. Only traditional simulation approaches have been used so far to gauge with a CE lens the material properties of product and by-products, looking at the A/D, reassembly, recycling and manufacturing phases.

4.1.7. Benefits and business impacts

Ref. [98] used a dynamic business model simulation to estimate CE business impacts. Ref. [99] conducted a simulation, based on SD modelling, whose results stated that manufacturing transition towards CE can foster coal power and cement companies to decrease waste emission and improve economic profits. Ref. [100] focused on the metallurgical industry. Given that: i) all metals have strong intrinsic recycling potentials and ii) a digital integration of metallurgical reactor technologies and systems can support dynamic feedback control loops,

Table 5
Sequence planning and process improvement category.

Authors	What is proposed	Lifecycle phase improved through simulation	Technologies/tools involved	Type of simulation			Improved human machine interaction	Variables optimized
				Physics-based	VR	AR		
[60]	Optimum assembly algorithm with ant colony algorithm to solve the maintenance assembly process for 3D objects and complex environments and to find both optimal sequence and 3D path planning	- Production - Maintenance - Assembly - Disassembly	–	x	–	–	x	- A/D sequence and path, - N of gripper changes
[61]	- Approach to automate disassembling processes of electr(on)ic equipment with disassembly cells - Flexible semi-automatic disassembly cell for PCB	Disassembly	Robot system	x	–	–	–	- Disassembly automation - Working condition
[62]	- Robotized, semi-automatized, flexible disassembly cells (for minidisks, PCBs, …) in industrial use, - New concept for modular disassembly cells based on “disassembly families”, mobile robots and MAS	Disassembly	Robot system	x	–	–	–	- Disassembly automation - Working condition
[63]	Method to discover task precedence and to reason about task similarities coupled with a motion planning technique developed to generate non-destructive disassembly paths	- Assembly, - Disassembly	Data-glove and motion tracker	x	x	–	Realistic physical animation of manipulation tasks from user demonstrations used for learning sequential constraints	- physically admissible subassemblies. - computational time. - disassembly times
[64]	Interactive scheme including fast motion planning and real time guiding force for 3D CAD part A/D tasks.	- Assembly, - Disassembly	Haptic device	x	x	–	x	A/D path
[65]	Optimal assembly path planning algorithm for aircraft part maintenance	- Maintenance - Assembly, - Disassembly	–	–	x	–	–	Process precedence
[66]	Intelligent virtual assembly system with an optimal assembly algorithm allowing haptic interactions during virtual assembly operations	- Assembly, - Disassembly	Haptic-path sequence-guidance (HSG)	–	x	–	–	- paths for haptic guidance - assembly sequence
[67]	Methodology for the simulation and optimization in a VE of a manual assembly process	Assembly	–	–	x	–	–	Assembly process (layout, devices, tools, movement sequences)
[68]	3D time factor-integrated figure able to generate a 4D VR model for construction progress simulation in the planning and design phase	- Assembly, - Disassembly, - Planning and (detailed) design, - Installation	RFID with building information model (BIM)	–	x	–	–	Effective storage and retrieval of critical information needed at different project phases
[69]	Dynamic tasks planning enabled by a manufacturing VE	- Manufacturing, - Assembly, - Disassembly	Internet technologies	–	x	–	–	Use of manufacturing resources
[70]	A user-friendly and cooperative human-robotic exoskeleton for manual handling work	- Production, - Assembly, - Disassembly	Exoskeleton for manual handling work	–	x	–	x	Ergonomic workplace
[71]	Real-time simulation test bed to assess the usefulness of haptic technology for A/D planning	- Design, - Assembly, - Disassembly	Haptic technology	–	x	–	x	Perception of objects’ weight in VR
[72]	VR maintenance system to perform rapid maintenance of mechanical equipment by the virtual disassembly and to measure the maintenance time and cost	- Maintenance, - Disassembly	–	–	x	–	x	- disassembly sequence - maintenance workspace, time, cost
[73]	Assembly simulation application on a collaborative haptic VE, where users interact with virtual models to do assembly operations within the same virtual scene	- Assembly, - Disassembly	Haptic devices	–	x	–	x	Process sequence. task performance (lowered costs)
[74]	Force-smoothing algorithm and collaborative haptic assembly simulator (CHAS), where users can simultaneously do	Assembly	Haptic devices	–	x	–	x	Virtual scene synchronization (consistency)

(continued on next page)

Table 5 (*continued*)

Authors	What is proposed	Lifecycle phase improved through simulation	Technologies/tools involved	Type of simulation			Improved human machine interaction	Variables optimized
				Physics-based	VR	AR		
	assembly tasks using haptic devices							
[76]	Collaborative virtual A/D framework and system (Motive3D)	- Design, - Assembly, - Disassembly	High bandwidth network	–	x	–	x	Assembly costs, quality, time to market
[78]	A multi-layer approach of interactive path planning for assisted manipulation in VR	- Assembly, - Disassembly, - Maintenance	Haptic device	–	x	–	Operator's simulation assisted by path planning techniques (robotic field)	- path plan. - manipulation ergonomics
[79]	Geometric constraint-based approach (hybrid method of rule-based reasoning and fuzzy comprehensive judgment) for interactive modular fixture assembly design in a VE	- Design - Assembly	VR-based modular fixture assembly design system	–	x	–	x	User's operation intent capturing and geometric constraint recognition
[80]	- function requirements for VH, - real-time driving model with a dynamic constraint applied to support personalized human model driving - driving error model for quantitatively analyse VH's driving error coming from the motion capture system, - interactive operation modelling method for VH (where VH manipulates product, tools and product using tools)	- Assembly, - Disassembly	Motion capture system	–	x	–	x	VH driving error
[81]	A noise compensation model based on grey system theory to realize online compensation for filterable missing information in A/D processes	- Assembly, - Disassembly	–	–	x	–	x	A/D process driving noise and accuracy
[82]	Robot disassembly and assembly processes in real space and movement of the robot work in animation	- Assembly, - Disassembly	Robot	–	x	x	x	Robots' object manipulation
[83]	Maintenance system providing a synchronous shared visual workspace even with limited bandwidth	- Maintenance, - Disassembly	Telecommunication equipment, tablet	–	x	x	x	Sequence planning
[84]	Numerical control unit and related ergonomic human-machine interface for a robotized production unit	- Assembly, - Disassembly	Robotized production unit	–	–	x	x	A/D time
[85]	AR-guided product disassembly (ARDIS) framework with an automatic content generation module	- Maintenance, - Remanufacturing	–	–	–	x	x	Disassembly process efficiency done by the operator without expert intervention
[86]	An AR adaptive guiding scene display method using automatically extracted CAD feature's bounding box model of part as input data so they could be implemented for online planning	- Assembly - Disassembly	CAD	–	–	x	x	- projection area, visible proportion and information entropy, - difference in depth of all visible vertexes of CAD feature's bounding box in 3D virtual guiding scene
TOTAL				5	19	5	18	

they used modelling, simulation, and optimization to perform real-time measurement of ore and scrap properties in intelligent plant structures, by enabling CE-oriented big data analysis and process control of industrial metallurgical systems. Results were used to elaborate in an easy way the resource efficiency of the CE system. Ref. [101] proposed a similar SD model, but applied on coal resource utilization systems with a full lifecycle perspective. Thirteen development projects divided in two types of scenarios were run on the model. Simulation results were analysed through the efficacy coefficient method to determine the best project of coal resource utilization system and demonstrate the benefits coming from CE adoption. Ref. [102] used SD methods to enlighten the benefits deriving from CE in countries without resource shortage issues. The simulation demonstrated that, despite the investment costs, countries can obtain economic benefits through a lower raw material cost in a long run.

Table 9 describes the "benefits and business impacts" category. Only SD simulation method is used to support either strategic analysis about raw material costs and sale volume or specific product lifecycle phases (from product design, through manufacturing up to disassembly), attempting to optimize waste emission, economic profits, resource utilization or the materials recovery process.

Table 6
Online platforms and monitoring for Industrial Symbiosis (IS).

Authors	What is proposed	Lifecycle phase improved through simulation	Technologies/ tools involved	Type of simulation			Improved human machine interaction	Variables optimized
				Physics-based	VR	AR		
[88]	AB model to simulate the emergence and operations of self-organized ISNs in three scenarios: (1) no information-sharing platform. (2) a platform where companies provide information about their geographical location and the type and quantity of produced and required wastes. (3) a platform where companies provide sensitive information about the costs of operating IS	Strategic level	Platform	AB	–	–	–	Information sharing
[89]	Simulation environment for predicting the relevant remanufacturing systems performance as a function of the applied production control policy within a VE, before its implementation in a real system	Remanufacturing	–	DE	x	–	–	- Remanufacturing system performance, - Logistics performance, - Production control policies selection in specific businesses
[90]	a virtual platform including the features needed to design and implement a prototype of a flexible automated disassembly system.	- Design, - Disassembly	Platform	–	x	–	–	Product features
TOTAL				2	2	0	0	

Table 7
Recycling performance and Key Performance Indicators (KPIs) category.

Authors	What is proposed	Lifecycle phase improved through simulation	Technologies/ tools involved	Type of simulation			Improved human machine interaction	Variables optimized
				Physics-based	VR	AR		
[91]	Recycling Index (RI) based on simulation models of minerals and metallurgical processing	Recycling	–	x	–	–	–	- recycling performance of a product and of the individual materials, - materials recovery from EoL products, - environmental footprint
[92]	Dynamic model of Material Inputs, Stocks and Outputs (MISO-model) as an expansion of EW-MFA framework, jointly addressing material flows, in-use stocks of manufactured capital and waste	Entire lifecycle	–	x	–	–	–	Annual flows of material and energy
[93]	Recycling process simulation using a specific software in order to define the mass and energy balance of the entire recycling treatment of spent lamps	Recycling	–	x	–	–	–	Mass and energy balance of the treatment
[94]	- DES model to analyse the effect of remanufacturing and maintenance on power plant availability and maintenance time, - framework applying a simulation modelling approach for evaluating the effects of remanufacturing and maintenance strategies on plant availability	Maintenance	–	DES	–	–	–	- mean time before Overhaul (MTBO), - mean time to recovery (MTTR)
TOTAL				4	0	0	0	

4.1.8. Training

A couple of contributions employed both traditional approaches and VR in this simulation scope domain.

Trying to enhance training in the development and engineering phases, Ref. [103] developed in a CAD 3D environment a method of ecological-oriented product assessment during the design process to empower designers' skills and knowledge about products' environmental features. Immersive VR technologies, based on the recycling product model (RPM) and agent technology, improve the effectiveness of the training of designers. Indeed, the VE can be used by designers for educational and exercise purposes. Merging Petri Nets and VE, Ref. [104] introduced an engineering method to develop a desktop-based interactive virtual maintenance training system able to dynamically configure scenarios. The maintenance knowledge and procedures of A/D in VE are presented by using high level Petri Net (PN), useful also to configure scenarios dynamically.

Shifting the attention to pure VR, Ref. [105] introduced the use of haptics-enabled virtual tools in a native CAD environment (CATIA V5™) to enable to perform interactive A/D simulations for training applications. Ref. [106] developed a 3D modelling VR-based training system for the printing-machine for the new product development, product maintenance and operation phases. Some contributions were aimed at enhancing maintenance and thus also A/D processes. Ref. [107] developed a desktop VR prototype for industrial training applications and to improve context rendering and response to user manipulations. It provides the data interface to import both the VE models and specific domain knowledge. Feature-based modelling and assembly function created by external CAD tools contribute to develop a visibility culling

Table 8
Material and technological properties category.

Authors	What is proposed	Lifecycle phase improved through simulation	Technologies/ tools involved	Type of simulation			Improved human machine interaction	Variables optimized
				Physics-based	VR	AR		
[95]	Analysis of the effect of stress relaxation before and during the disassembly	- Disassembly, - Recycle	–	x	–	–	–	- interfacial delamination of reused IC, - viscoelasticity of moulding compound - SFT of the plastic IC package
[96]	Pilot-plant simulation of industrial processes for red brick manufacturing	Manufacturing	–	x	–	–	–	- effect of the by-product content (%) and of the firing temperature on brick shrinkage, bulk density, water absorption capability, mechanical strength and thermal conductivity
[97]	Basic modular and standardized structural load bearing elements which can be adapted in the building or assembled, properly disassembled and partly or entirely be reused again in a subsequent building	- Assembly, - Disassembly, - Reassembly	–	Finite element simulations	–	–	–	- strength, - stiffness, - slip capacity, - ductility
TOTAL				2	0	0	0	

Table 9
Benefits and business impacts category.

Authors	What is proposed	Lifecycle phase improved through simulation	Technologies/ tools involved	Type of simulation			Improved human machine interaction	Variables optimized
				Physics-based	VR	AR		
[98]	- Dynamic business model simulation using the SD methodology, - CE design framework to support circular product design development	Product design	–	SD	–	–	–	CE Business model
[99]	SD modelling to infer that the transformation of manufacturing towards a CE system can prominently help coal power and cement enterprises reduce waste emission and increase economic profits	Manufacturing	–	SD	–	–	–	- waste emission, - increase economic profits
[101]	Coal resource utilization SD model based on full life cycle	Manufacturing	–	SD	–	–	–	Coal resource utilization
[100]	Integration of metallurgical reactor technology and systems digitally, not only on one site but linking different sites globally via hardware, for describing CE systems as dynamic feedback control loops, i.e., the metallurgical IoT	Disassembly	Connection via digital technologies	SD	–	–	–	Recovery of all minor and technology elements in the refining metallurgical infrastructure of the global carrier
[102]	Economic benefits of a CE in countries without resource scarcity problem. SD method was used to overcome the data limitation problem	Strategic level	–	SD	–	–	–	- raw material costs, - raw material sale volumes
TOTAL				5	0	0	0	

approach for fast rendering and user interaction. Ref. [108] created a low-cost object-oriented VR application for maintenance training (V-REALISM). Integrating a novel disassembly sequence planning technique and evolutionary algorithms with VR using the object-oriented methodology, they showed the effectiveness of desktop VR to reduce costs in maintenance training.

Finally, some contributions proposed combined VR and AR solutions. Ref. [109] designed and developed a VR and AR system for learning and training platform. Interactive learning methods resulted in better knowledge with less assembly error while learning and training in AR and VR system ensured better users' skill performance. Ref. [110] conducted a research for operators training through the adoption of an immersive mixed reality system. They proposed a system through which users can see their own real hands, through a 3D camera placed on the head-mounted display (HMD), use them to grapple and move the machine pieces, and perform the training operations.

Ref. [111] developed an AR application for training system in automotive industry and evaluated its effectiveness. The VR application is conducted to evaluate the effectiveness of VR adoption for engine assembly, disassembly and performance to enhance learning method in tertiary education.

Table 10 shows results about the "training" category. A strong presence of VR (9) and AR (3) to improve human machine interaction (8) is glaring, with a marginal role of traditional simulation approaches. Training is aimed at improving operators' skills mainly in A/D process (9) and maintenance (5), not neglecting product development/design (2) and operations (1). A strategic role is played by CAD and authoring systems (either 3D or external or native systems) (4) but also other supporting devices (e.g. haptic devices, immersive mixed reality system, 3D camera, HMD, Unity 3D and Vuforia installed in Samsung Galaxy A Tablet, commercial-off-the-shelf (COTS) systems, cyberforce™/cybergrasp™) (6).

Table 10
Training category.

Authors	What is proposed	Lifecycle phase improved through simulation	Technologies/tools involved	Type of simulation			Variables optimized
				Physics-based	VR	AR	
[103]	Method for ecological-oriented product assessment during the design process implemented in CAD 3D environment in order to improve the skills and knowledge of future designers about products' environmental aspects	- Design, - Disassembly	- CAD 3D systems. - RpM (data needed for a comprehensive product recyclability evaluation already at the design stage)	AB	x	–	Skills and knowledge of future designers about environmental aspects of the designed product
[104]	Engineering method to develop a desktop-based interactive virtual maintenance training system, to dynamically configure scenarios. The maintenance knowledge and procedures of A/D in VE are presented using Petri net	- Engineering, - Assembly, - Disassembly	–	Petri net	x	–	Interactive representation of task and action scenarios in the virtual maintenance training system.
[105]	Haptics-enabled virtual tools integrated in a native CAD environment to provide the capability to perform interactive A/D simulations using tools such as allen and box-end wrenches with force feedback (using a cyberforce™ and cybergrasp™)	Assembly	- haptic tools - native CAD environment - commercial-off-the-shelf (COTS) systems - cyberforce™/cybergrasp™	–	x	–	- training effectiveness - native CAD assembly data accuracy with the VE - manipulation with virtual hand in A/D training
[106]	VR-based training system for the printing-machine in new product development, A/D, maintenance and operation training	- Assembly, - Disassembly, - Development, - Maintenance, - Operation training	Solidworks	–	x	–	Training effectiveness
[107]	Desktop VR prototype for industrial training applications	- Assembly, - Disassembly, - Maintenance	- external CAD tools, - hierarchical structure	–	x	–	Training effectiveness
[108]	Low-cost VR application for maintenance training (V-REALISM) integrating disassembly sequence planning technique and evolutionary algorithms with VR using the object-oriented methodology	- Assembly, - Disassembly, - Maintenance	–	–	x	–	Training effectiveness
[109]	VR and AR system for learning and training platform in A/D and maintenance operations	- Assembly, - Disassembly, - Maintenance	–	–	x	x	- training and working times, - training costs, - influence of interactive learning method (with AR), - user skill performance
[110]	System to train people in A/D and maintenance operations (the user can see his own real hands, by means of a 3D camera placed on the HMD, and use them to grab and move the machine pieces in order to perform the training task)	- Assembly, - Disassembly, - Maintenance	- immersive Mixed Reality system, - 3D camera, - HMD	–	x	x	- user's training and working times, - training costs, - user skill performance
[111]	AR application for training system in automotive industry, also evaluating its effectiveness	- Assembly, - Disassembly	Unity 3D and Vuforia, installed in Samsung Galaxy A Tablet	–	x	x	Training effectiveness
TOTAL				2	9	3	

Object of the analysis are:

- training effectiveness, in terms of time and cost (10),
- user skill performance and knowledge of future designers about environmental aspects of the designed product (3),
- accuracy of data of native CAD assembly with the VE (2),
- accuracy of manipulation tasks with virtual hand in A/D training,
- effectiveness of interactive learning method (with AR).

5. Discussion

Considering all the results coming from the previous sections, it is worth mentioning the type of simulation approaches adopted by either scholars or professionals in each of the categories identified in literature. Generally, simulation is adopted in terms of virtually assessing/anticipating real issues without the need to either implement any physical test or take any decision. From the design alternatives selection view (see Table 3), the decision-support tool view (see Table 4) and the online platform and monitoring for the Industrial Symbiosis view (see Table 6), the prominent approaches are VR and physics-based. From the sequence planning and process improvement view (see Table 5), VR and improved human/machine interaction represent the most suitable options. From the recycling performance and KPIs view (see Table 7), materials and technological properties view (see Table 8) and benefits and business impacts view (see Table 9), physics-based is the only tool adopted. Finally, from the training view (see Table 10), VR, AR and physics-based are the three options emerging from the literature. Trying to summarize all these contributions (considering also their limited amounts), it's not possible to do a precise distinction among simulation tools for different categories identified, apart from improved human/machine interaction and AR. The first one seems to be directly related with the improvement of sequence planning and processes. The second one is, evidently, related with just training activities.

In addition to the results presented in the previous section, it is worth assessing also the twofold domain of simulation and disassembly in terms of their tangled relationship in a deeper (sector-independent) way. As shown in Fig. 6, simulation and disassembly are subsets of I4.0 and CE, respectively. This discussion is based (and triggered) on results from a previous systematic literature review about the relationship between I4.0 and CE domains, who introduced two hybrid domains named *Circular I4.0* and *Digitized CE* [18]. The objective of this work, instead, is to pursue a further step in this direction, by analysing the intersection

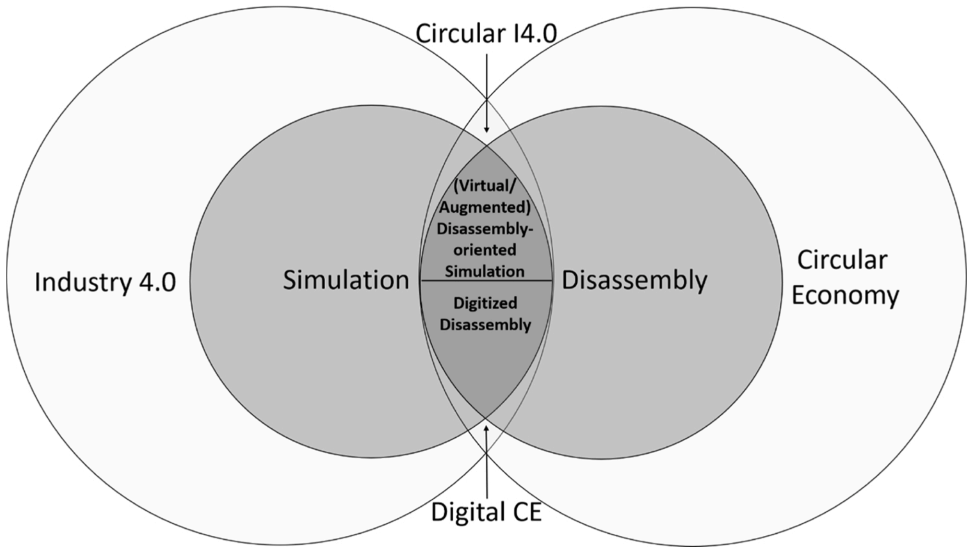

Fig. 6. The hybrid categories of Simulation and Disassembly.

between specific subsets of simulation and disassembly, represented by AR/VR/DT-based simulation tools and PCB/WEEE disassembly processes, respectively. Indeed, this work provides a further characteristic of this connection in terms of the main issues related to disassembly processes potentially addressable by simulation. From one side, simulation can unveil the issues occurring to both researchers and practitioners approaching a digitized disassembly. From the other side, virtual/augmented disassembly-oriented simulation tools are indicated and suggested (as a sort of guide) to those academics and industrials facing these issues. As evidenced by the literature, scholars already analysed the connection between simulation and disassembly looking at two points:

1 The influence of disassembly (with an EoL/CE-based perspective) on the way simulation is conducted/adopted, named *digitized disassembly*
2 The potential support of simulation in improving disassembly processes, named *virtual/augmented (V/A) disassembly-oriented simulation*.

These hybrid categories of simulation and disassembly are shown in Fig. 6.

To further explore and understand this connection, the main issues occurring throughout the adoption of a *digitized disassembly* have been detected. They represent the basic points raised by researchers needing a particular heed when approaching the fuzzy simulation/disassembly research context. Furthermore (assuming a *V/A disassembly-oriented simulation* perspective), the following list reports how each of these issues can be addressed:

1 Problems prediction through alternative scheme suggestion in a VE. The high accuracy in a VE can improve the efficacy of virtual simulation and foster problems prediction, also suggesting alternative A/D settings, paths and routes.
2 Product lifecycle data/information/knowledge management (KM) and sharing. KM and sharing, from a low level (data) up to a higher level (knowledge), can strongly support CE adoption [112], also through virtual A/D systems under a micro, meso and macro perspective [113]. Moreover, A/D plants have been characterized by automation islands causing high uncertainty. This brought to several issues in the process, also disregarding resources in real manufacturing environments. A higher level of automation connected to a more effective exploitation of simulation and VE can limit these effects.
3 Workplace safety and security. Simulation supports A/D operation evaluation, from both a workplace and system ergonomic side.
4 Avoidance of destructive A/D paths and collisions. Using VR/AR, collisions and destructive A/D paths are prevented and avoided in practice.
5 Accurate VE reducing human's difficulty to perform precise tasks. Often, inaccuracy of VE can cause human difficulty in conducting precise tasks (e.g. positioning) in A/D processes. Several researches improved the accuracy of such VE and reduced this risk.
6 Bandwidth for remote operations enabling concurrent tasks on collaborative VR. Concurrent tasks are enabled in different lifecycle phases, from design and development up to A/D and EoL. Online VE avoids design errors, but also supports control and KPI evaluation along the entire lifecycle.

Table 11 shows how frequently these issues can occur in relation to the role adopted by simulation.

Table 11 shows as the most important issues raised by the literature are: i) destructive A/D paths and collisions [114], ii) lack of product lifecycle data/information/knowledge and iii) inaccuracy of VE. Some endeavours have been done to provide VE with a bandwidth enabling online concurrent tasks, predicting errors in A/D processes and improving ergonomics and workplace safety. 71 % (44 out of 62) of issues have been improved when simulation had the role of sequence planning, process improvement and training. Here, the higher use of VR/AR improved the human-machine interaction. In addition, these technologies have been summarized in five groups and proposed as starting points to both researchers and practitioners willing to approach this research domain:

1 Visualization tools. Tablet (with Unity 3D and Vuforia installed), VTK, HMD, commercial-off-the-shelf (COTS) simulation packages
2 Motion trackers/capture systems and robots. Haptic technology and HSG, data-glove (with cyberforce™/cybergrasp™), motion tracker, RFID, motion capture system, exoskeleton for manual handling work, robot system and automatic handling device, 3D camera
3 Engineering environments. CAD/CAM environment, VR-based modular fixture assembly design system, ODE libraries and Python programming language
4 KM systems and tools. OO modelling and engineering multimedia for KM and communication, robust analytical methods, BIM

Table 11
Issues occurring in digitized disassembly that can be addressed from disassembly-oriented simulation.

Simulation role	Authors	Issues addressed					
		Problems prediction through alternative scheme suggestion in the VE	Product Lifecycle data/information/ KM and sharing	Workplace safety and security	Avoidance of destructive A/D paths and collisions	Accurate VE reducing human's difficulty to perform precise tasks	Bandwidth for remote operations enabling concurrent tasks on collaborative VR
Design alternatives selection	[10]	–	–	–	–	–	–
	[50]	–	x	–	–	–	–
	[46]	–	–	–	–	–	–
	[47]	–	–	x	–	–	x
	[49]	–	–	–	–	–	–
	[52]	x	–	–	–	x	–
	[51]	–	x	–	x	–	x
	[48]	–	–	–	x	–	–
Total per *Design alternatives selection* category		1	2	2	2	1	2
Decision-support tools	[53]	–	–	–	–	–	–
	[55]	–	–	–	–	–	–
	[54]	–	–	–	–	–	–
	[57]	–	x	–	x	–	x
	[58]	–	–	–	–	–	–
Total per *Decision-support tools* category		0	1	0	1	0	1
Sequence planning and process improvement	[63]	–	–	–	x	–	–
	[78]	–	–	x	–	x	–
	[85]	x	x	–	–	–	–
	[86]	–	–	–	–	–	–
	[68]	–	x	–	–	–	–
	[66]	x	–	–	–	–	–
	[65].	–	x	–	x	–	–
	[69]	–	x	–	–	–	–
	[70]	–	–	x	–	–	–
	[71]	–	–	–	–	–	–
	[79]	–	–	–	–	x	–
	[67]	–	–	–	–	–	–
	[60]	–	–	–	x	–	–
	[72]	–	–	–	–	–	–
	[74]	–	–	–	x	–	–
	[73]	–	–	–	x	x	–
	[82]	–	–	–	x	x	–
	[83]	–	–	–	–	x	x
	[61]	–	–	–	–	–	–
	[62]	–	–	–	–	–	–
	[64]	–	–	–	x	x	–
	[76]	–	–	–	x	–	x
	[84]	x	–	x	–	–	–
	[80]	–	–	–	x	x	x
	[81]	–	–	–	x	x	x
Total per *Sequence planning and process improvement* category		3	4	3	10	8	4
Online platforms and monitoring for IS	[88]	–	x	–	–	–	–
	[89]	–	x	–	–	–	–
	[90]	–	x	–	x	–	–
Total per *Online platforms and monitoring for IS* category		0	3	0	1	0	0
Recycling performance and KPIs	[93]	–	–	–	–	–	–
	[91]	–	–	–	–	–	–
	[94]	–	–	–	–	–	–
	[92]	–	–	–	–	–	–
Total per *Recycling performance and KPIs* category		0	0	0	0	0	0
Material and technological properties	[96]	–	–	–	–	–	–
	[95]	–	–	–	–	–	–
	[97]	–	–	–	–	–	–
Total per *Material and technological properties* category		0	0	0	0	0	0
Benefits and business	[98]	–	–	–	–	–	–
	[99]	–	x	–	–	–	–
	[101]	–	–	–	–	–	–
	[100]	–	–	–	–	–	–
	[102]	–	–	–	–	–	–
Total per *Benefits and business* category		0	1	0	0	0	0
Training	[111]	–	–	–	–	–	–
	[106]	–	–	–	–	–	–

(*continued on next page*)

Table 11 (*continued*)

Simulation role	Authors	Issues addressed					
		Problems prediction through alternative scheme suggestion in the VE	Product Lifecycle data/information/ KM and sharing	Workplace safety and security	Avoidance of destructive A/D paths and collisions	Accurate VE reducing human's difficulty to perform precise tasks	Bandwidth for remote operations enabling concurrent tasks on collaborative VR
	[103]	x	x	–	–	–	–
	[107]	–	x	–	–	x	–
	[105]	–	x	–	–	x	–
	[108]	–	–	–	x	x	–
	[109]	–	–	–	x	–	–
	[110]	–	–	–	x	x	–
	[104]	–	–	–	–	–	–
Total per *Training* category		1	3	0	3	4	0
TOTAL		5	14	5	17	13	7

5 Platforms. Networked (web) databases, high bandwidth network and internet connection via digital technologies, telecommunication equipment.

Fig. 7 shows how simulation can support disassembly processes, by enabling circular strategies (i.e. the 6R – repair, refurbish, remanufacture, repurpose/redesign, recycle, recover) in manufacturing [115]. Specifically (assuming the *V/A disassembly-oriented simulation* perspective), the main technologies occurring in the conduction of a *digitized disassembly* are proposed to effectively use simulation-based technologies in the CE domain.

5.1. A simulation-based PCB disassembly process through a lab-scale application case

Since the extant literature evidences a lack of empirical cases enacting in the PCB disassembly domain, the two hybrid categories (V/A disassembly simulation and digitized disassembly – Fig. 6) are proposed through a lab-scaled application case in this sub-section. Indeed, the practical evidence of this exercise is suitable to validate the inner characteristics of the two categories presented before (Fig. 7).

The application case was conducted in the Industry 4.0 Lab of Politecnico di Milano [37], one of the few pilot plants in Italy fully focused on proving benefits coming from the introduction of I4.0 technologies in manufacturing. Connected to the research activities funded by the H2020 FENIX project, it demonstrated how I4.0-based technologies (as CPSs, IoT, AR/VR, DT, and robots) can support CE practices by virtually testing, through a set of dedicated simulation tools, a WEEE disassembly plant configuration. In addition, it gives an empirical evidence of results obtained in this work, by highlighting how service-oriented, event-driven processing and information models can support the integration of smart and digital solutions in current CE practices at factory level. To this aim, two configuration tools have been implemented:

- a VR-based configuration tool supporting disassembly processes reconfigurability and implementation, enhancing the ability to handle a higher product variety for disassembly and to reach better materials recovery. Through a VE, the disassembly process was simulated and optimized (following five steps: disassembly line modelling; disassembly process design; robotic disassembly program coding; disassembly work plan creation within the MES software and process simulation; disassembly configuration uploading on the real system) to be, then, replicated in the real world.
- a DT-based configuration tool for a real-time disassembly process monitoring and control, providing a graphical representation of the disassembly line. In addition, it also enabled to control each station in terms of number of pieces worked and those waiting to be worked. The DT also permits the exploitation of a database for data post-processing supporting decision making based on the computed KPIs.

Through the use of digital technologies, a set of results have been achieved under a CE vision. First of all, virtually designing, simulating, and optimizing the system and converting it on the real world, it was possible to reconfigure the line (originally set up to execute assembly processes) to enable also disassembly processes. System reconfigurability was enabled through a change of both specific hardware (i.e., change of robot tools for disassembly activities), and software resources (i.e., robot program coding). Second, the DT of the line was created to simulate the behavior of the system and evaluate in real-time the energetic performance of the line through data acquisition and analysis from the field. Thus, DT allowed to fully exploit the IoT potentialities and digitalize the CE practices thanks to the implementation of smart disassembly process and dynamic feedback control loops. Third, an energy-based KPI (e-OEE) has been introduced in the DT to evaluate the

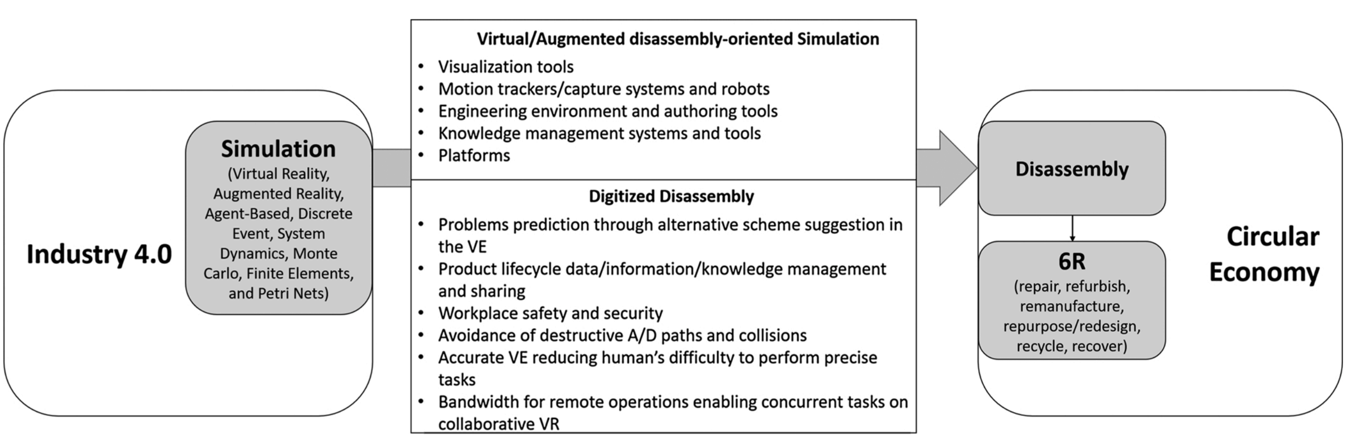

Fig. 7. Simulation supporting Disassembly to enable 6R.

energetic performance of the system. DT can extract all the values for real-time energy consumption using an accumulator function and gives back useful information for energy management. Here, CPS and BDA on energy consumption have been used to improve disassembly process performances. Fourth, the Manufacturing Execution System (MES) and the DT have been integrated using a communication protocol able to give instructions to the MES from external sources. Indeed, the DT not only had a monitoring function but also a bi-lateral communication management one. Finally, the DT can also be useful to implement a real validation of application models reacting to disassembly work order's lack of conformity, aborting the non-compliant orders and re-scheduling them to avoid scraps.

This lab-scale application case gives the opportunity to explore only some of all the potential CE-driven functionalities and enhancements that can be brought using digital technologies in the design and operation of disassembly systems. Indeed, the introduction of CPS and I4.0 technologies bring to a higher level of automation and flexibility of disassembly systems and to the digitalization of CE practices thanks to the creation of powerful simulation models and resource monitoring tools. It has also to be highlighted that DT can be applied both to assembly and disassembly processes, without the need of heavy changes on the systems. This way, the DT allows the evaluation of the behavior of real systems in real-time, enabling the data gathering to be used for decision-making processes. Their adoption leads to a better use of resources in disassembly processes, increasing the capacity to recover valuable components, to improve materials restoration and enhance the production cycles' sustainability.

6. Conclusions

This research consisted in a systematic literature review with the aim of investigating how disassembly process simulation tools have been exploited to foster the adoption of CE in the PCB domain. Here, a specific focus on the EoL stage has been adopted but keeping a whole lifecycle perspective. The final aim was to raise the attention of both researchers and practitioners about the importance of disassembly process simulation tools in supporting i) the disposal of both products and plants, ii) the definition of stronger links between design and EoL stages, iii) the transition towards CE and iv) the improvement of knowledge and skills of both manufacturers and researchers about the role of I4.0 technologies in empowering CE performances. The adoption of simulation in CE contexts have been detected and listed in eight categories, with sequence planning, process improvement and training as the most explored ones. Indeed, they present the higher use of VR and AR to improve human-machine interaction through different types of digital technologies and tools [116]. The literature analysis confirmed that simulation can address all the issues pertaining to a combined circular-digital research context, only mutually involving traditional approaches (e.g. AB, DES, SD, Monte Carlo, Finite Elements simulation, and Petri Nets) and supporting the adoption of digital technologies and tools (e.g. VR and AR). Focusing on disassembly, simulation can allow a better prediction of operational problems, a higher data/information sharing with other EoL actors involved in the same value chain, a better safety/security/ergonomic level of workplaces and the introduction of concurrent/remote operations [117]. Starting mainly from the PCB domain, the results can provide a full and systematic categorization of how simulation can be used to enhance disassembly processes in a deeper and sector-independent way. From a research point of view, the main findings show which research areas have been investigated and detect those gaps still waiting for contributions (raised from the adoption of a *digitized disassembly* and addressable through a *V/A disassembly-oriented simulation*). From a practical point of view, designers can look on available simulation approaches and how to exploit them in different lifecycle stages. Moreover, also triangulating the results obtained in this literature review with those coming from a recent laboratory pilot application case, managers can better comprehend which are the product/process circularity issues they can solve through simulation, by taking more effective and efficient decisions also thanks to the adoption of a defined set of supporting technologies. Finally, this paper opens the way to further researches, suggesting and promoting simulation as a key enabling technology for the adoption of different CE strategies.

Declaration of Competing Interest

The authors report no declarations of interest.

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