How de-manufacturing supports circular economy linking design and EoL - a literature review

Original
How de-manufacturing supports circular economy linking design and EoL - a literature review / Cappelletti, Federica; Rossi, Marta; Germani, Michele. - In: JOURNAL OF MANUFACTURING SYSTEMS. - ISSN 0278-6125. - ELETTRONICO. - 63:(2022), pp. 118-133. [10.1016/j.jmsy.2022.03.007]

Published
DOI:10.1016/j.jmsy.2022.03.007

How de-manufacturing supports Circular Economy linking Design and EoL - a literature review

De-manufacturing is at the basis of the Industry of the Future that competitively and sustainably will manage natural resources. This review retrieved 106 papers investigating the main obstacles that prevent Circular Economy from being a reality and the possible actions to overcome them. The analysis of the literature outlined a great discussion regarding the key topics of CE, de-manufacturing, disassembly and re-manufacturing. The CREDIT analysis proposed by the authors clusters all the risen barriers in 6 factors (Culture, Resources, Economy, Design, Information, Technology) and 18 sub-factors. The CREDIT analysis highlights among the two most critical barriers, the costs of the activities that occur at the EoL stage and the urgency to train designers to approach design thinking to the whole Product Lifecycle; here an innovative focus of research can be more incisive to overcome the actual barriers. Future research needs to focus the attention on the potentialities hidden behind a strong cooperation between academies and enterprises in order to find a balance among the several existing DfX or unveil and tackle their single limitations. Cooperation (industrial symbiosis, academy, etc) and innovative technological solutions of industry 4.0 can help tackle the obstacles.

Keywords: Design for X; Design for de-manufacturing; De-manufacturing; Circular Economy; Industry 4.0

List of Acronyms

ACO	Ant Colony Optimization	GAIA	Geometrical Analysis for Interactive Aid
AHP	Analytical Hierarchy Process	G.EN.ESI	Green ENgineering dESIgn
AM	Additive Manufactruing	GFDA	Green Fuzzy Design Analysis
APP	Assembly Path Planning	HALG	Hierarchical Attributed Liaison Graph
AR	Augmented Reality	I4.0	Industry 4.0
ARDET	Augmented Reality Disassembly Evaluation Tool	IP	Intellectual Property
ARTODTO	Advanced- Re-manufacturing-To-Order-Disassembly-To-Order system	KET	Key Enabling Technologies
BM	Business Model	KPI	Key Performance Indicator
BoL	Beginning of Life	LCA	Life Cycle Assessment
BoM	Bill of Material	LCC	Life Cycle Costing
C2C	Customer to Customer	LCED	Lifecycle Engineering Design
CAD	Computer Aided Design	LCP	Product Life Cycle Planning
CBM	Circular Business Model	MAAP	Method to assess the adaptability of products
CE	Circular Economy	MCDM	Multi-Criteria Decision-Making
CREDIT	Culture Resources Economic Design Information Technology	MICMAC	Matrix of Cross-Impact Multiplications Applied to a Classification
CRR	Composite Rate of Return	MLC	Multiple Life Cycle
DAPP	Disassembly Assembly Path Planning	OEM	Original Equipment Manufacturer
DASP	DisAssembly Sequence Planning	PBM	Population Balance Model
DEI	Disassembly Effort Index	PDC	Product Disassembly Complexity
DfN	Design for Nature	PLC	Product Life Cycle
DfX	Design for X	PPBM	Product-Process- Business Model
DOG	Disassembly Order Graph	PSS	Product Service System
DSS	Design Support System	QFD	Quality Function Deployment
DSSG	Disassembly Sequence Structure Graphs	RDMF	Re-manufacturing Decision Making Framework
ECMPRO	Environmentally Conscious Manufacturing and Product Recovery	REE	Rare Earth Elements
ECPD	Environmentally Conscious Product Design	RIFF	Re-manufacturing Information Feedback Framework
EDIT	Environmental design industrial template	RL	Reverse Logistics
EDST	Environmental design support tool	RoR	Rate of Return
ELSEM	EoL Scenario Evaluation Method	SDSP	Selective Disassembly Sequence Planning
ELVs	End of Life Vehicles	SMA	Shape Memory Alloy
EoL	End of Life	SMP	Shape Memory Polymer
ERP	Enterprise Resource Planning	TCE	Transaction Cost Economics
EU	European Union	TISM	Total Interpretive Structural Modelling
FDM	Fuzzy Delphi Method	TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
FMEA	Failure Mode and Effect Analysis	WEEE	Waste Electric and Electronic Equipment

1 Introduction

The transition from Linear to CE is decisive to state whether the human being will be able to rationalize the exploitation of natural resources. The main challenge is to join forces from multiple players, since the circularity of a product goes beyond the product itself: involves stakeholders, customers and administrative bodies [1]. Frameworks [2] and circular industrial cases (such as Audi, Nokia, Ikea, etc.) have been proposed to successfully act the transition, as guidance for other companies seeking to tackle climate change [3].

The concept of CE is receiving increasing attention worldwide as a way to overcome the issues of the current production and consumption model [4]; it requires companies to rethink their supply chains and BM [5] since today they do not feel any responsibility for EoL of products. The RL tries to account for EoL products in the most environmental-friendly manner possible [6]. This can be achieved through the implementation of long-lasting design, maintenance, repair, reuse, re-manufacturing, refurbishing, and recycling operations and processes. The main goal is to launch a product in a MLC loop [7] [8], where recycling concerns a minimum percentage of the product and is more efficient [9] since goods are designed for this purpose [10][11].

De-manufacturing represents the sustainable approach that encompasses all the EoL strategies; it requires reasonable design decisions from the very early stage to optimize the product and components' circularity.

In some cases, industries may feel environmental restrictions as obstacles to innovation in product design [12]. On the contrary, research has been very active in proposing methods and tools to face product circularity. The following, also presented in Table 1, are the main clusters of more recently published research papers:

- Disassembly strategies, e.g. papers dealing with evaluation of product accessibility, disassemblability, balancing disassembly line, disassembly strategies oriented to material or components recovery;

- Design approaches, e.g. papers focusing on the designers' role and in particular on their influence over strategic and managerial issues, defining fundamental their role to establish CBMs. In this group, there are also papers that propose Design for X approaches or others that reflect on the need for new DfX methods and tools to satisfy quite heterogeneous issues of the design process;

- Sustainability dimension, e.g. all the papers investigating how all the pillars (economic, environmental and social) are faced and applied in CE industrial cases.

Table 1. Main limits identified

Cluster	Theme	References	Main limits identified by research
Disassembly strategies	Product accessibility	[13] [14]	Although important, active disassembly cannot be coupled with idle/automatized/manual disassembly; limited application.
	disassemblability	[15] [16] [17] [18] [19] [20] [21] [22] [23]	
Design approaches/Design for X	Definition and application of r-strategies	[24] [25] [30] [32] [33] [34]	Support in prioritizing environmental issues over time and costs drivers.
Sustainability dimension	Integration level of sustainability pillars	[27] [28] [29]	Integration of sustainability (economic, environmental, and social) at the strategic planning level is not reflected at the operational level (production planning and controlling), where decision-making is mostly driven by single sustainable dimensions (environmental and economic).

Concerning recently review papers on the matter of CE and de-manufacturing, some can be identified:

- Sassanelli et al. [26] explore how design can contribute towards a CE transition through the adoption of DfX approaches. The challenge is to determine when to apply each strategy in addressing prevention, reuse, and recycling. The authors identify 5 DfX approaches to foster CE adoption. However, this work retrieved a short number of papers focusing on the link between DfX and CE; this is instead narrowed to provide a complete framework;

- Schöggl et al. [28] affirm that the CE body of literature can be divided into management and technically oriented studies, and these have either a BoL or an EoL focus. The authors sketch thematic maps, carry out quantitative analyses that highlight that only a limited number of environmental aspects (such as waste, resource use and CO_2 emissions) are centrally addressed, while other environmental and social aspects form the periphery of CE research. Schöggl et al. suggest focus research in the context of CE but did not identify which would be more useful to overcome the CE implementation barriers;

- De Kwant et al. [31] conduct a review article upon the CE literature foundation, including definitions, challenges, and business model frameworks needed to better understand the role of product design; however, they only paid attention to electric vehicles and white goods. Focusing on certain product categories leads to identify distinctive barriers of a certain sector and may prevent the identification of common challenges that may provide hints for innovative solutions;

- Okorie et al. [35] investigate the relationship between re-manufacturing and cannibalization, whose blurred connection often prevents re-manufacturing activities to be scaled. In this work many hints are provided (taxonomies, risk of cannibalization, guidelines, etc.), but none of them provides a clear picture of the state of the art and why the practice too infrequently follows the expectation.

Starting from these limits, the current work reviews how the literature is approaching the shift from Linear to CE by proposing strategies to enable it from the design phase. The need for this review stands in the awareness that several propositions for DfX are available in the literature, nevertheless, designers still struggle to manage and assess the product lifecycle thinking. The existing literature deepens in specific aspects or product category and identifies their lacks or obstacles; nevertheless, it is hard to be aware of the main barriers that prevent CE and de-manufacturing systems to become real. The novel contribution of this work consists in:

- Providing a clear and complete overview of barriers and difficulties in implementing CE and de-manufacturing systems, in the industrial context including managerial and cultural aspects;

- Including in the analysis all the EoL strategies, which can support the transition from linear to CE.

The review is focused on mechanical and mechatronics products (i.e. textile, construction sectors were discarded) but does not narrow down on a specific product category.
The research deeply investigated 106 papers in the context of CE to clarify the role of de-manufacturing and aims at answering the following research questions (RQs):

RQ1: Which are the main obstacles to de-manufacturing implementation at industrial scale and the related hidden reasons?

RQ2: Which are possible actions to overcome these obstacles, both in the industrial and academic sectors, raising the level of actual results?

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2 Material & methods

Fig. 1 shows the method followed in retrieving the papers. The first step consisted in the selection of articles in electronic scientific databases. The keywords “de-manufacturing”, “tools”, “methods” and “Circular Economy” were chosen and combined for the research. Unfortunately, the results were extremely various or scarce when there was the word de-manufacturing. This was the first sign of the variety and the absence of standard definition. The word de-manufacturing was then substituted with *manufacturing, in order to collect paper related to re-manufacturing, de-manufacturing, remanufacturing and de-manufacturing. All papers not related to the industrial engineering sector (i.e., building sector, biomedical, etc.) were discarded, as well as grey literature and works produced in different languages than English. The electronic database research provided a collection of 767 papers. Those were reduced to 164 by removing duplicates and sorting the articles by reading their title, abstract and conclusions. By fully reading the remaining papers, 78 papers were maintained. The last part of the literature research was the cross-referencing that allowed to discover 40 additional interesting works, but only 28 of them were fully analyzed.

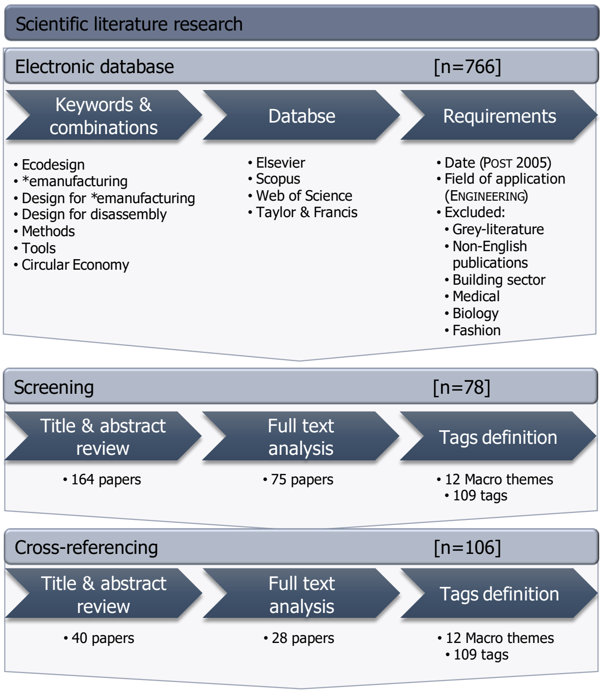

Fig. 1 Research methodology, adapted from [26]

The debate about design for de-manufacturing is wide and concerns simultaneously many different aspects. This explains why the authors dealt with papers published by 60 different journals; Fig. 2 shows the 20 most common.

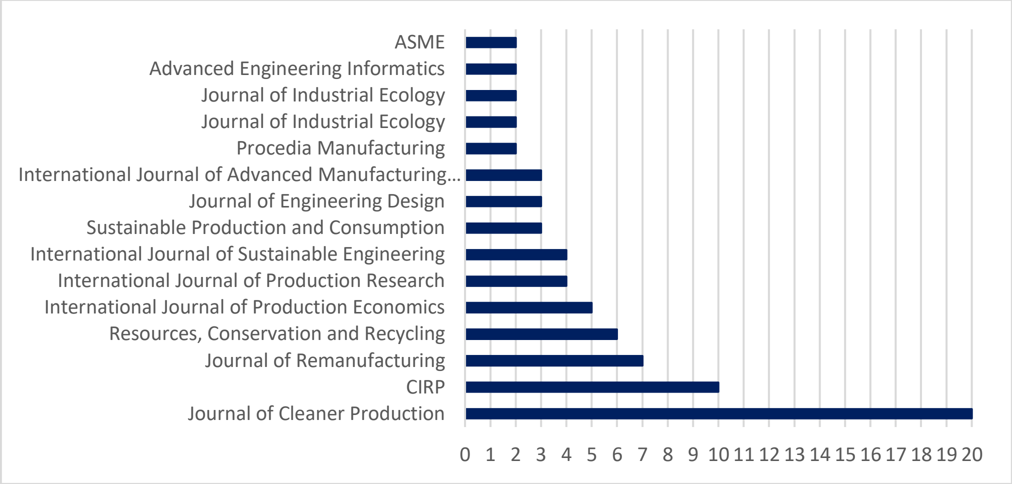

Fig. 2 Most common journals.

The analysis focused on industrial engineering. Fig. 3 sums up the products analyzed in the retrieved papers. The green group is electronics and encompasses both small household appliances (such as hairdryers, microwaves, toasters, etc), big household appliances (under the label "white goods", such as coffee machines, hoods, etc) and electronic devices and components (phone, laptop, pc battery, etc). All components and/or full products related to the transport sector belong to the second group; the third concerns mechatronics product (such as robots, robotic cells, lifts) and the last one groups all products that does not belong to the previous categories.

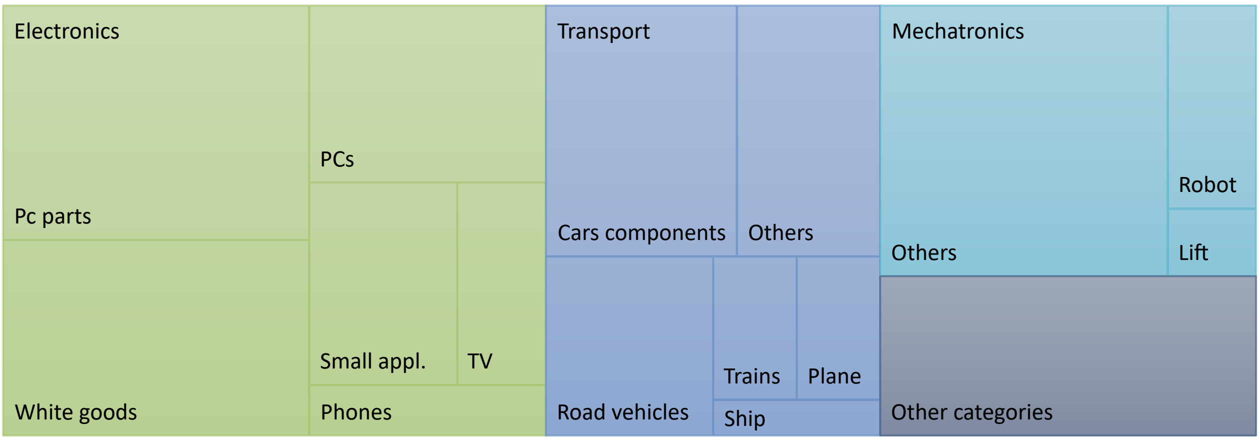

Fig. 3 Products presented by retrieved papers.

As deeply explained later in this section and detailed in the additional material, tags were addressed to each work, so it was possible to cluster papers and evaluate which topics were most exploited in literature. 109 tags were identified and gathered in 12 clusters.

Tags were attributed to achieve greater interaction with papers. Tags are like keywords: they were attributed by the reviewed while retrieving the papers; they are not limited in number per paper, and they can refer not only to the subject of the paper but also to structure or reviewer considerations. The tags were not pre-defined prior to reading the papers. They were chosen along the way and whenever a new tag was identified, papers already analyzed were retrieved and the tag attribute (if needed). Tags were combined with product life cycle stages and grade of industrial implementation. The horizontal axis in Fig. 4 contains the product lifecycle stages, while the vertical one distinguishes the grade of implementation of that specific tag; the size of the balloons is proportional to the times the tag is used. Besides the main research topics: disassembly time, disassembly sequence, modularization, disassembly cost and target components are the most recurrent tags (20 or more articles). The literature has been very active in proposing methods and tools to ease the product disassembly and thus allow the valorization of materials and parts (15 or more articles). Many suggestions are linked to the concept of embedded disassembly (i.e. fasteners) or product modularization. The theme of governance often recurs and even more the concept of transforming the product into services to sell the value of their function, instead of the object. For greater readability the matrix contains only the tags whose numerosity is higher than one; to match the tag and the related document please consult the additional material. One sheet of the file contains a numbered list of the retrieved papers and their title, the second one contains a table where is shown which tag (rows) is attributed to which paper (columns).

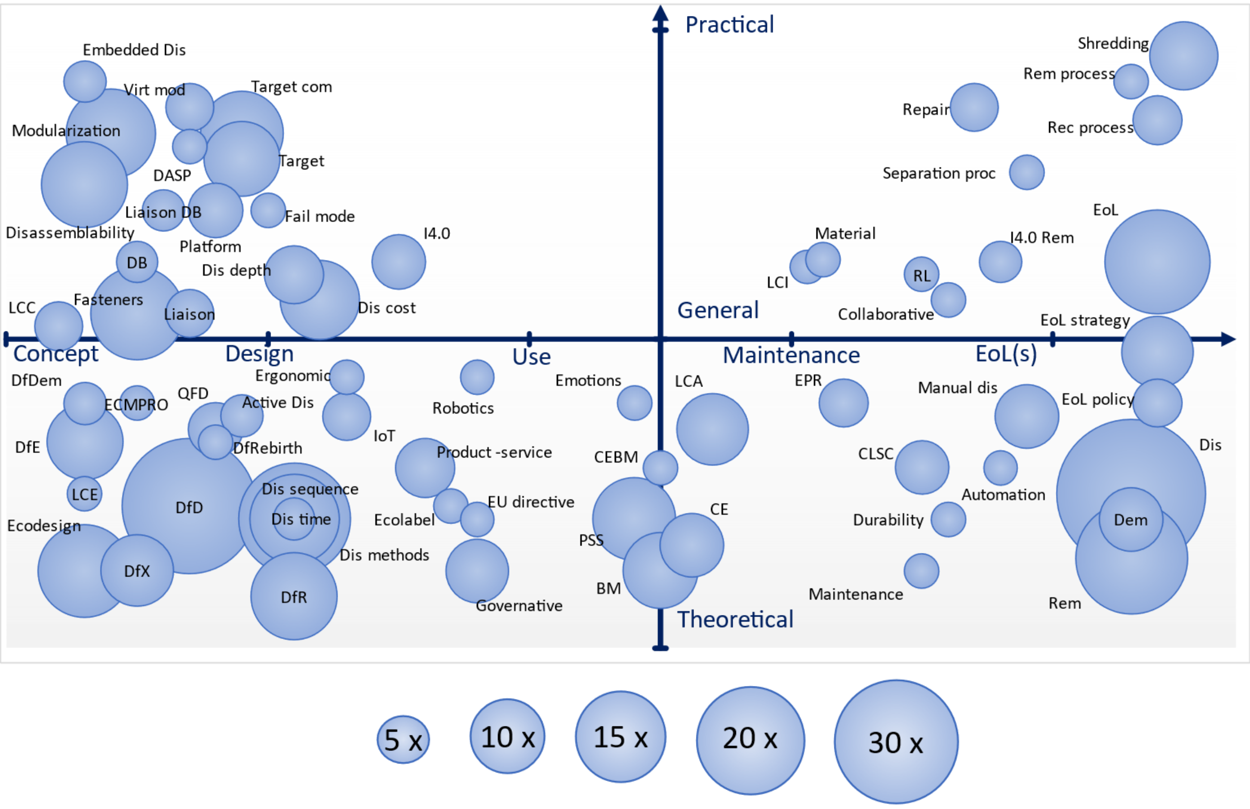

Fig. 4 Tags matrix PLC - implementation status.

3 Results

At first, an analysis regarding the terminology of de-manufacturing is provided, and then the authors propose the CREDIT Analysis: it summarizes the main topics to which the retrieved papers attribute the difficulties of implementation of de-manufacturing and prioritizes their importance and need to tackle them.

3.1 De-manufacturing definition

The available literature about de-manufacturing is controversial and there is not any all-over-accepted definition. Colledani et al. [9] and Pigosso et al. [36] agree to the definition given by Duflou et al. [37] and define de-manufacturing as the breakdown of a product into its parts to reuse and re-manufacturing parts or recycling the remainder of the components. Chung et al. [38] affirm that de-manufacturing is a process to disassemble certain parts or components from a product. The parts or components may be selected for recycling, re-use, maintenance or disposal. While some perceive de- and re-manufacturing as different ends to the same product, for others the main difference lies in the partial (in case of re-manufacturing) or total (de-manufacturing) account of the product [39]. The concept of de-manufacturing is seldom strictly connected to recycling and is seen as an approach to multi-component product recycling [40]. Among economical aspects related to de-manufacturing, Krikke [41] sees de-manufacturing activities as short-term profit-maximizing decision making; Johnson & McCarthy [39] affirms that de-manufacturing focuses on evaluating the economic and environmental implications of material recycling, part reuse, shredding and landfill options and continues by saying that it aims at saving any remaining economic value (in this it is different from re-manufacturing). Johnson & McCarthy are not alone in wondering how much effort should be invested in disassembly to derive value from the retired products: Peeters et al. [42] investigate how to determine the RoR of investing in design for de-manufacturing. Authors who investigate environmental aspects of de-manufacturing agree on the positive impact determined by it, but it is not clear how it exactly contributes to reducing products impacts; sometimes it matches with re-manufacturing and together they are deemed appropriate for achieving sustainable operations [39] and provide technical solutions for an efficient and systematic implementation of CE. Both include the set of technologies and systems, tools and knowledge-based methods to systematically recover, reuse, and upgrade functions and materials from industrial waste and post-consumer products, to support sustainable implementation of manufacturer–centric CE businesses [43].

In the present work, de-manufacturing is conceived as the critical solution for an efficient and systematic implementation of CE. Imagining linear economy as a metal chain, where every product lifecycle phase (i.e. concept, design, extraction of raw material, manufacturing & production, transport & distribution, use & maintenance, disassembly, re-manufacturing, recycling, etc..) is a link, in the traditional framework of Take-Make-Dispose the chain is straight and open; the introduction of de-manufacturing closes the chain, modeling the circle of Make-Use-implementation of R-strategies. It is the only able to link EoL stages with BoL ones, leading those who manage the different stages to think about the whole lifecycle.

De-manufacturing is a comprehensive concept that potentially incorporates all EoL strategies: re-using, re-manufacturing, re-purposing, recycling, depending on the status of each module. De-manufacturing differs from CE since the last one contemplates also other lifecycle stages (i.e. use). CE is the wide framework intended to optimize resources and energy use, that embraces other essential topics that enable it, such as de-manufacturing or CBMs. In fact, CE is defined as an industrial system that is restorative or regenerative [44], whose foundations are the recognition of the limits to planetary resource and energy use, and the importance of viewing the world as a “system” where pollution and waste are viewed as a defeat [45]. The concept of the circular economy originates in the inability of linear production models to reconcile current levels of production and consumption with the limited availability of resources [46]. De-manufacturing instead, is a fundamental technical solution for an efficient and systematic implementation of CE. Although essential to CE, it differs from it, since it focuses on evaluating the economic and environmental implications of material recycling, part reuse, shredding and landfill options, thus in EoL [39].

De-manufacturing attributes a suitable EoL strategy to every part of a good. Re-use, RL, disassembly, recycle, remanufacture, disposal, landfill, upgrade, repurpose, etc. are often studied, analyzed and proposed in taxonomies [45] [34] [48] [49] [50] to get the best out of their implementation is necessary to consider them during the design process and practice them only when required by the status of the components. Colledani et al. [51] depict a plausible de-manufacturing system and define it as a set of resources (human and technological), organization, IT infrastructure, associated BM to enable product de-manufacturing. With this perspective, every EoL strategy is included. De-manufacturing not only returns used products to at least as good as new conditions, which happens for re-manufacturing [52] [53] [54] but also includes the proper management of the remaining modules/components, as shown in Fig. 5.

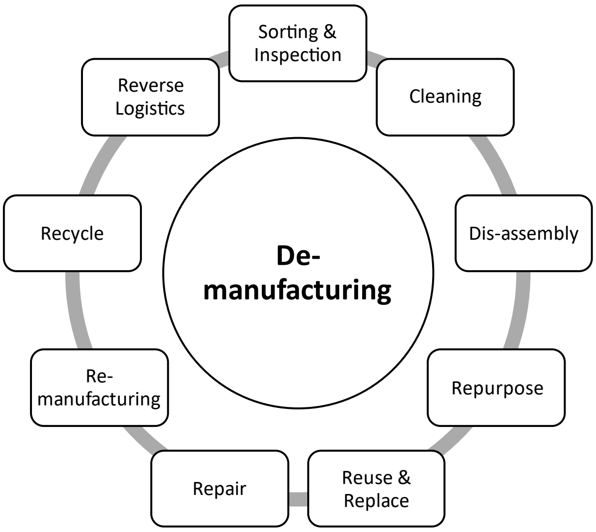

Fig. 5 EoL alternatives for components in de-manufacturing systems.

3.2 CREDIT analysis

Decisions made at the early design phases have impacts on the whole product lifecycle [55] [56]. It is acknowledged that with their choices designers can prevent or facilitate up to 80% of downstream activities [33] [57] [58] [59]. They are empowered to configure products that have closed-loop lifecycles, allowing the reintroduction of parts or materials into the productive chain [58]. This is why literature agrees on the need to use eco-design tools early in the design process to produce environmentally friendly products [36]. Research provided many solutions to designers, even though there is still a lack of benchmarks to evaluate the performances of the proposed methods and tools [60]. Outcomes go from guidelines [3] [40] [61] [62] to software tools [49] [63], mathematical models [64], fuzzy graph approaches [65] and many MCDM [66] [67] [68]. Even in case designers were able to systematically manage all in their power, there still would be some unpredictable factors that weigh on the application of methods for circularity; for this reason, fuzzy techniques have been approached: to evaluate different EoLs [69], to enhance product rebirth and green supply chain [70], to evaluate recyclability, toxicity, cost, energy indexes [71].

The authors, starting from the analysis of the literature, proposed the CREDIT Analysis that sums up all macro sectors conceived to be the main barriers for proper implementation of de-manufacturing systems.

The CREDIT analysis is defined by the authors starting from a similar approach, the PESTEL analysis, but it specifically considers the main criticalities concerning a de-manufacturing system, clustering them into the following factors: culture, resources, economy, design, information and technology.

As the PESTEL analysis [72], it is a multifaceted approach to assess big-picture forces to better understand the strategic orientation of an organization and to assist in making considered and informed decisions about organizational activities. By considering key external drivers of change, CREDIT analysis can encourage firms to consider long-term goals and to choose sustainable business innovation and strategies. The discrepancies of topics and obstacles outlined by the retrieved papers and the factors involved in the PESTEL analysis made it necessary to identify new areas of analysis. The six factors of the CREDIT analysis derive from the analysis of the papers involved in the review. In particular:

- All factors related to customers behavior and governance actions were grouped under the factor Culture; consumerism is a framework that struggles against CE and recovery and at the same time is strictly related to the customer behavior and, together with second life market, to their perception about products, costs, etc. Moreover, governance is an additional important sub-factor that alters markets and customers behavior;

- Resources concerns both material (operators, machines, etc) and immaterial (i.e. skills) assets required under certain circumstances;
- Costs matters and competitive advantage deriving from strategies fall under the Economy sphere;
- Design includes all the methods, tools used by product designers and their attitude;
- Information involves both how the product data flow back and forth the supply chain and how methods and tools are disseminated and trained to who should use them;
- Technology gathers all hints and feedback about the lack or (mis)use of innovative technologies.

Table 2 answers to RQ1 and shows the reasons hidden behind the barriers and obstacles that hinder de-manufacturing systems to be successful. It classifies them in the factors of the CREDIT analysis and groups the papers depending on whether they are more oriented towards product servitization (PSS in the table), more inclined to traditional BMs (Sale in the table) or deal with the eco-design topic. Barriers and obstacles were derived directly from the analysis proposed in the analyzed papers as they are presented in Table 2. The sheet “full table” of the additional material contains the extended version of the table; while the one below groups the papers, the methods they propose and the reason they claim, the one contained in the additional materials summarizes the information for each paper, line per line. Moreover the paper ID column is next to the reference. The numerosity of the methods analyzed or proposed by the papers stands for a wide heterogeneity in approaches, methods and tools available and investigated. On their right, two columns summarize the main barriers to de-manufacturing highlighted by the papers. The numbers under CREDIT factors report how many authors claimed that factor as the main obstacle and the columns “Reason 1” and “Reason 2” explain why.

They will be further analyzed and discussed in the next sub-sections. Papers that deal with PSS or support them more frequently (71%) attribute obstacles to the sphere of the culture, while those supporting the traditional BM linked obstacles with product/process design and designers (61%). 76 papers deal with the eco-design topic; nevertheless, they allocate de-manufacturing obstacles to factors of heterogeneous nature. The different nature of the obstacles (technical, economic, social...) highlights the need for cooperation all along the product value chain and different professional figures throughout the whole society. As shown in Fig. 6, among the two most critical groups, the costs of the activities that occur at the EoL stage (26%) and the urgency to train designers to approach design thinking to the whole Product Lifecycle (26%) are the most cited; here an innovative focus of research can be more incisive. On average, Design and Information are the classes with higher attribution of difficulties (they are addressed by 22% and 18% paper respectively). Authors who believe in product servitization report higher issues with the availability of a second life market (50%) than sales-oriented (30%). An opposite trend is registered for the classes of Product status uncertainty, Operator, Cost since EoL and Value of recovered products; this may be explained by saying that authors who support PSS may have already experienced realities of returning and re-manufacturing products. Authors PSS and Sales-oriented do not have the same perception about the CREDIT factors; neither there are similar trends for the CREDIT sub-factors; for example, considering Culture, consumerism and governance are almost heavenly reported as main obstacles, while second life market reports higher discrepancy between PSS and Sales (the opposite happens for Resources category).

Table 2 - Classification of methods and tools proposed by papers and main barriers identified.

Ref	**PSS**	**Sale**	**Eco-design**	**Method & Tools proposed/ analysed**	**Main obstacles**						**Reason 1**	**Reason 2**
					C	R	E	D	I	T		
[1] [18] [68] [102] [120] [122] [123]	×	×	×	CRR; Modularity matrix; TCE, HALG; GAIA, PROMETHEE	5		4	4	3	2	Disparity of recycling processes adopted; Cannibalization; Difficulties to share information; Lack of product modularization; Non-standard driver to lead make or buy decision; Product complexity; Low cost, mass products discourage re-manufacturing	Controversial guidelines; Need for corporates to include customers in their circular endeavors and create awareness; Product status uncertainty; Need for focus on fasteners; Lack of legislation
[26] [29] [34] [35] [47][64] [77] [92] [108]	×		×	Mathematical formulation; CAD tool for disassembly; Development of a new BM; QFD; Repurposing; Protocol analysis of a PSS design process	6	2	2	5	2		Lack of legislation; Need to consider all pillars of sustainability; Different purposes of design; Need to rethink the product in rem. point of view prior shift to PSS; Lack of parallel focus on QFD and environmental aspects; Need for DfX approaches to fit with circular design perspective; Need to think about the strategy for the distribution on the market; Cannibalization	Re-manufacturing needs a remanufactured products' market; Need for cooperation with retailers to manage logistics; Decisions arising from design are not limited to the product; Critical access to cores
[39] [76] [104] [112]	×			Mathematical formulation; RIFF, RemPro matrix	3	1	2	2	1	1	Need for contact with customers; Need for harmonic laws in favor to re-manufacturing; Need for OEM to get information feedbacks	Low use of big data by designers; Re-manufacturing (and transport) too costly
[3] [36] [55] [59] [62] [66] [78] [89] [121][75]		×	×	EDIT, D4N, EDST, MAAP, LCP; ECMPRO; Learning goals for designers; TOPSIS; ECPD	5	2	5	6	4	1	Value of recovered products < value Disassembly cost; Features required are considered in isolation and not in an integrative fashion; Difficulties to apport changes to product design; Lack of legislation; Product status uncertainty; Little knowledge of DfD concepts; Lack of integrated information techniques to support innovative (Eco-design); High labor cost (in EU)	De-manufacturing and re-manufacturing processes do not close the loop on their own; Labor costs for dismantling cannot be balanced by material recovery value; Reluctance to share product information; Self-standing design; Need for parallel product and process design
[9] [10] [12] [17] [20] [21] [40] [44] [48] [60] [67] [70] [71] [85] [88] [109] [110] [111] [125]				DFMLC, MLCA; D/APP, D/ALB, D/ASP; Multiscale, multilevel recycling approach; Dism. tool; Analytical model; PBM; ARTODTO; Circularity degree of companies; Eco-design policy process; ε constraint; ACO model; ELSEM, fuzzy; GFDA; Product Suitability for Rem. Assess Portfolio	3	9	9	9	6	9	Skill operators for manual labor; AP causes subproblems in ASP, ALB, APP; Lack of multistage mechanical design; Smart tools are costly and not robust enough; Future economic conditions uncertainty of recycled materials; Product status uncertainty; High variability of products makes challenging developing recycling machines; Product status uncertainty; Circularity measures are not the reality in companies yet; Accurate metrics depend on product variability; Accepting the rules is different from believing in the rules; Disassembly takt time different from assembly takt time; Dismantling techniques; Recycling technology; Rem industry is both huge and hidden	Nonsatisfying metrics to assess Design for Recycling strategies; EoL management complex, costly and long or even impossible; Different design for similar products; Need to 'operationalize' CE principles; Dismantlers know disassembly times and costs; Unknown disassembly tack time; Cost of recycling

Ref	**PSS**	**Sale**	**Eco-design**	**Method & Tools proposed/ analysed**	**Main obstacles**						**Reason 1**	**Reason 2**
					C	R	E	D	I	T		
[73]	×	×		System dynamics	1		1	1		1	Lack of practice of eco-design	Product longevity affects and replacement rates
[14] [30] [51] [57] [97] [114]		×		DSP; LC option selection of dis parts; Design method for value recovery; Fuzzy for dis; Integrated multi-disciplinary research framework; FDM, TISM, MICMAC	1	5	3	3	2	2	Lack of modularization of parts subjected to wear; Manual disassembly; Disassembly cost; For complex product full disassembly is not economically viable; Inefficiency of disassembly processes, low productivity and labor cost of manual disassembly; Low customer demand	Cost of labor; Materials incompatibility; For complex products full dis. is not environmental viable; Lack of EOL-oriented design practices that would ease automate disassembly; Challenge of collaborative innovation among SC partners
[2] [6] [7] [8] [11] [13] [15] [16] [19] [22] [23] [28] [31] [33] [42] [43] [45] [46] [49] [50] [56] [58] [61] [63] [65] [66] [74] [75] [79] [80] [81] [82] [83] [84] [86] [87] [94] [95] [96] [98] [99] [100] [101] [103] [113] [105] [107] [117] [118] [119] [126]			×	MLCA; Lean DFD; Design feature-based metrics; LCA, LCC, FMEA; DSS; V-Design; Liason_DB; DOG; DSP; G.EN.ESI; Disassembly of Critical Components; ARDET; Modify entropy theory; DEI; PDC; DisKnowDB, DKTool; Multi-objective; EoL value recovery; ELSEM; layout and fastening optimization; DSSG; Topological disassemblability analysis; Collision detection method; CE product and business model strategy; Multi-objective fuzzy graph approach for modular formulation; Online DSS; EoL indices; IDEAss; LCED; RDMF; Dis petri-net model; P.P.BM.; CE levels; SMA or SMP; SWOT, Triple-layered CBM innovation framework.	14	18	20	23	22	13	Need boost for MLC in design; Difficult to estimate disassembly time and costs; Suppliers retain most product information; Value recovered < disassembly cost; Lack of parallelism Lifecycle thinking and costing; Fasteners accessibility; Need to know previous generations of products; Targets must be set to speed shift to CE; High level design needed to face Close Loop and CE; Long-time existing tool, late application; Low connection and operability between traditional and eco-design; Difficulties to implement KET of I4.0; Lack of DfX; Product status uncertainty; Product complexity; Difficulties to share info; Product components accessibility; High capital and labor cost; Manual disassembly; Product components accessibility; Disassembly is the bottleneck; Lack of Environmental Product Profile; Full disassembly is not convenient; Lack of modular design; Lack of recycled materials market; Low reuse rate of remanufactured parts; Lack of legislation; RL; DfRecycling must be paired to other strategies; Too specific tools available for a single lifecycle stage; Lack of a comprehensive structure; Lack of consideration of consumption patterns and citizen inclusion; Knowledge or experience required; Need for system or financial incentive to motivate R-strategies	Recycling technologies are not able to cope with products complexity; Lack of legislation; No incentives to buy second-hand products; Disassembly complexity; Reverse Logistics; Lack of information and systematic approach; Disassembly time uncertainty; Design focused on hiding company IP; Difficulties to accept I4.0 KETs; RL; De-manufacturing occurs late in time and far in space from design; Multitude of tools needed; Lack of Disassembly embedded design; Materials incompatibility; Knowledge Capitalization is not based on forward e backward knowledge sharing; Dismantlers have no product design info; Multiple tools that require too many info or money or time; Vergin materials have higher quality than second life ones; Need for time dimension (narrowing and slowing loops); Need for homogeneity of materials; Lack of design for re-manufacturing; Need for a second life market (different from second hand); Lack of integration of material, strategic, and consumer perspective; Automated disassembly needs high investment costs.

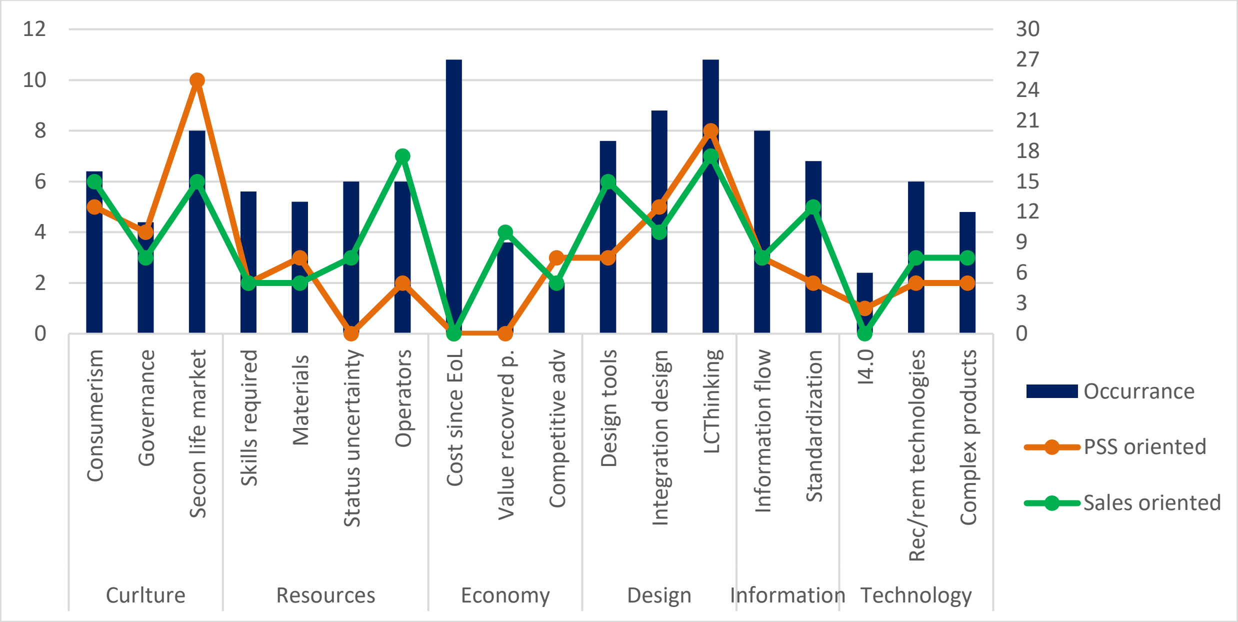

Fig. 6 Trends of barrier related to PSS and sale-oriented papers.

After the identification of the main barriers related to the practical implementation of de-manufacturing, possible actions to overcome them, are identified from the literature and clustered according to the factors of the CREDIT analysis.

Fig. 7 and related description presented from paragraph 3.2.1 to 3.2.6 answer the RQ2 and shows the main challenges and obstacles for each of the six identified factors providing hints and tips for academies and organizations to foster and improve cooperation, to fill actual gaps of research or raise the level of actual results.

The left side of the picture shows the factors of the CREDIT analysis and their sub-factors concerning de-manufacturing strategies.

CREDIT sub-factors frequency in the analyzed literature (Fig. 7) is expressed using open circles. The openness/closeness of circles is proportional to the times that barriers have been cited in the analyzed literature. The most recurrent obstacles have numerosity of 27 (Life Cycle Thinking and Cost since EoL); based on this, four ranges were identified and attributed to each cake: to the first range 0-6 (numerosity of the papers that cite that barrier) only one-quarter of cake is painted, second range 7-13 half of it, follow three quarters and full cake for ranges 14-20, 21-28 respectively. This frequency can be interpreted as the urgency to face these questions, both in the academic and industrial contexts. The last column reports the main action needed in order to overcome the actual state and the obstacles.

Thanks to the CREDIT analysis, the hints cover a wide variety of aspects: from a technical level (investigate the use of new materials or rationalize existing and innovative tools) to an external, all-encompassing (i.e. need for harmonic laws in favor of CE) passing by the strategic level of a company (i.e. introduce de-manufacturing strategies at management level).

CREDIT analysis is useful both for organizations and academies. Industries, when approaching de-manufacturing, can self-measure and state where they must focus on. Whenever encountering new scenarios or challenges the CREDIT analysis may be useful to assess whether the current state of research or the enterprise is ready to face the action or needs to improve and where it should put more effort.

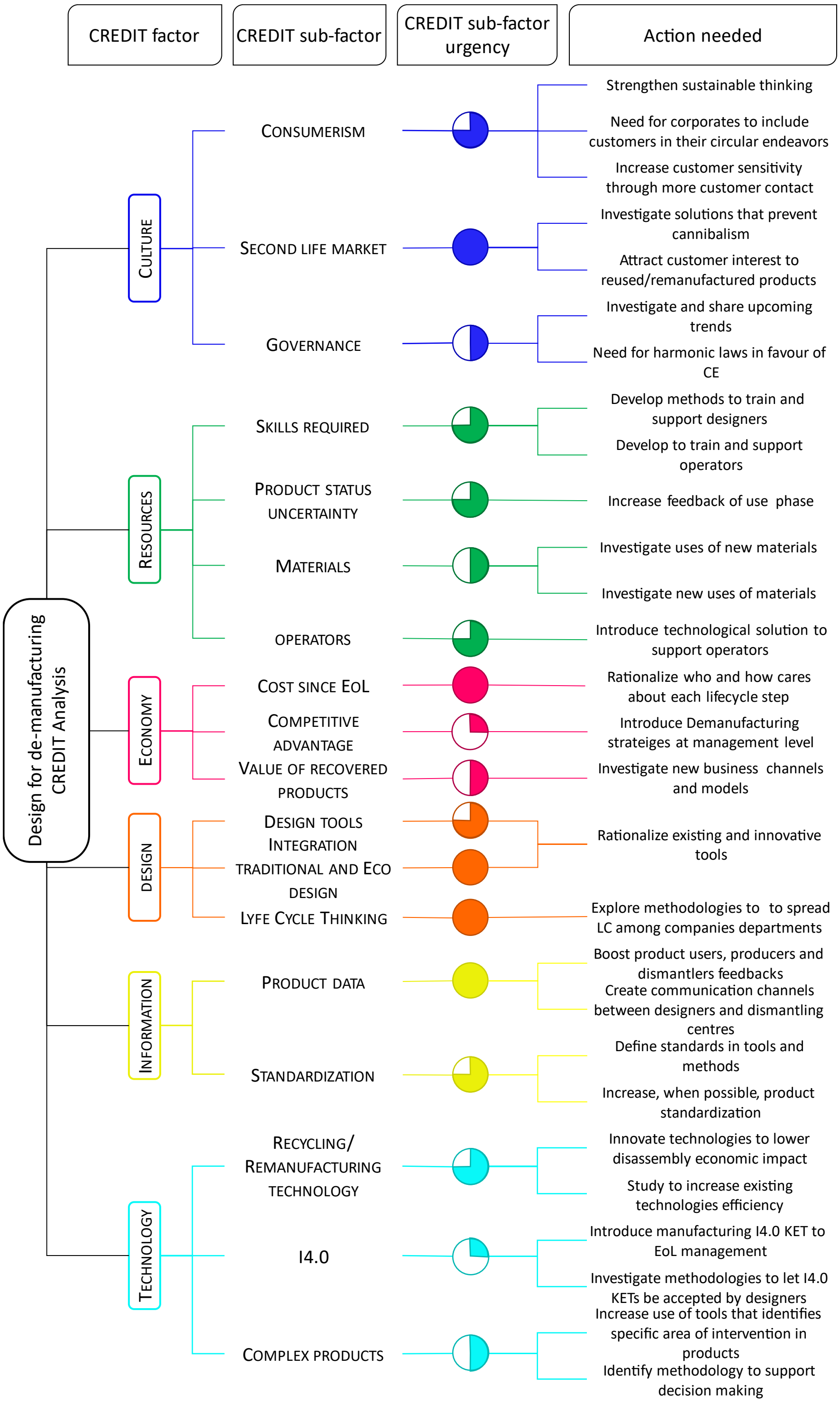

Fig. 7 De-manufacturing CREDIT Analysis.

3.2.1 Culture

- *Consumerism.* Among the social behavior affecting the decision process, De Almeida [48] highlights the feeling of physiological obsolescence that causes the consumer to change the item with a new one, instead to re-use one. There is the need to merge the goal of design practices (maintaining materials at their highest value at any time) and BM (the way products are commercialized and consumed) [73]. How extend the product lifetime and feed consumers' desires at the same time? In this sense, there is much work to be done, so that customers perceive fancy and on-trend goods that are repaired or re-generated. OEMs and academy should join their forces to design de-manufacturing systems that ease and make it convenient to repair goods, persuade customers on the products' values also studying methodologies together with both technical and marketing departments.

- *Governance.* Political settlements and strategies have a great impact on de-manufacturing systems, directly (directives) or indirectly (local markets cope with consequences from foreign governments' choices). Morseletto [74] studying which targets can facilitate the transition towards a CE notices that governance targets promote a pragmatic view on what to reach. Talens et al. [75] analyze the difficulty of removing battery packs of computers and discuss also how the achievement could be included in the EU eco-design regulation. Nevertheless, laws and directives do not cover yet all commercialized products and for this reason not all organizations as obliged to design goods to be de-manufactured. The literature addresses the lack of proper legislation as a missing guide for organizations. Researchers with their findings can contribute defining suggestions and requirements of upcoming regulations.
- *Second - life market.* Availability of resale market can be an additional barrier to re-manufacturing. Arnette et al. [45] investigate that not only consumer perception, but also patents, obsolescence, and shifts within an industry can restrict the practice of re-manufacturing. Mascle [50] depicts re-certification as a great stratagem to enrich the second-life market. On the other side, Quariguasi et al. [76] refer to the Brazilian case, where the second-life resources market is so widespread in the private sector that it is hard for OEMs to take back products. Mont et al. [77] throw down a challenge by introducing leasing and re-manufacturing practices in the baby-prams market, where 65-75% of total sales are in second-hand markets between privates (in Sweden). The challenge for a successful de-manufacturing system is to provide high-quality products in such a like-new condition to discourage C2C second-hand market. Given their competitive value proposition, remanufactured products are often blamed by OEM for cannibalizing new product sales revenues [35]. The challenge for Academy is to support OEMs in developing de-manufacturing systems that encourage the second life market, next to the main revenue streams of industrial realities.

3.2.2 Resources

- *Skills required.* Abuzied et al. [23] argue that disassembly may need specific tools whose use requires special knowledge or experience. Antipodean, a fully manual disassembly and inspection require high knowledge and understanding of product and process, expertise, usually acquired in a long time. Due to the high variability in the disassembly and dismantling process, the academic world should support the designers to obtain feedback on the EoL phases, so they can design the products so they are easier to disassemble; moreover, training and methods to accept technological support must be directed to dismantling operators.
- *Materials.* The choice of materials influences the product's durability and recyclability. Multi-material components have very low recycling efficiency. Stavropoulos et al. [63] provided a PSS that helps the designer to become aware of the component's particular and total condition at post-disassembly. Peeters et al. [18] shared a methodology that helps to determine the economic and environmental value of design for disassembly. They calculate the CRR on investing in design for disassembly and the resulting environmental impacts.

  The academy and industrial world must cooperate to investigate alternative materials to ores and investigate how conventional resources can face new fields of applications. De-manufacturing and materials recovery can lower the dependency on critical sources of certain materials, with consequences on market flows and companies' brand preservation.
- ***Product status uncertainty.*** Several are the reasons why OEMs lose track of their products once they are sold. In a de-manufacturing system contest, this may obstruct the feasibility of disassembly; in fact, besides the difficulties of returning the goods, if they reach the disassembly

point, their status is different each time (i.e. they are used under different conditions or they break for disparate reasons and failure modes). All these facts hinder the disassembly scheduling, altering times and costs of this phase. A prodigious contribution may stand on the implementation of innovative solutions into the products so that they can update their status via sensors and cloud and bring forward the time when their status is analyzed.

- *Operators.* An active debate focuses on resources required in the EoL process. Some argue that disassembly is a workplace incubator for low skill labor [78], others spread the need for skilled operators in disassembly activities, provided with characteristics such as: i) practice in specialized and specific facilities, ii) disassembly planning, iii) product design for disassembly [48]. The literature agrees on the fact that manual disassembly is the best way to disassemble products because only operators can adjust upon different, unpredictable conditions. In this sense, research can play a great role in placing innovative solutions next to the operators (KETs in the manufacturing field have provided solutions for several similar circumstances).

3.2.3 Economy

- *Cost since EoL.* Disassembly is the ground-breaking of all downstream activities in de-manufacturing. It may be performed to achieve different goals, partial or to recover materials or cores [79]. Product status unpredictability and products variance make it hard to predict when disassembly is economically sustainable or not. Pigosso et al. [36] increase the value of the recovered product by applying EDIT, EDST, MAAP: decisions must be taken with a strategy, so disassembly is less costly and has higher success rates. Aligned to this mindset Smith et al. [80] propose a disassembly model for SDSP to be applied at the design stage. Products that can be rapidly disassembled into parts can be more easily re-manufactured and recycled [34]. Disassembly cost is not always proportional to the number of components to disassemble: the status of the product at the EoL may jeopardize expectations. At the moment too few companies use tools to ease disassembly, since they are not thought to be worth the investment or to be flexible enough [81]. Design for disassembly tools mainly focuses on: i) picking targets components; ii) identifying the best disassembly sequence; iii) quantifying the disassembly process efficiency; iv) reducing disassembly time. Design for Disassembly is the most analyzed DfX technique [45]. According to Marconi et al. [82], a target component can be established according to its compliance with the maintenance/service plan during the use phase or in compliance with EoL regulations/directives. By identifying target components also disassembly depth is set [81]; if this does not encompass the full product, disassembly time reduces. This is the main reason why selective disassembly is preferred to complete disassembly [83]. The literature provides guidelines and tips to encourage designers to evaluate different liaisons and fasteners that can be removed with minimum time [84] [75]. Peeters et al. [42] develop a methodology to quantify the benefits of investing in fasteners, detachable by the application of a specific external stimulus (pressured air, heat, etc..). Kobayashi et al. [84] use a genetic algorithm to explore the optimal component layout and fastening methods produced following constraint conditions and considering i) face, ii) type and iii) the number of fasteners as design parameters. The iterative algorithm of Shabanpour and Colledani [85] looks for optimal disassembly line design without forgetting high disassembly tasks times uncertainty; they provide a sequence of disassembly tasks and optimize the allocation of buffers to reach maximum profit and satisfy the desired cycle time. Bracke et al. [86] stress the robustness and weaknesses of previous generations of products to get information; from their KPIs they design a new, improved, generation. HALG proposed by Dong et al. [87] defines four indices that allow them to compare and evaluate different disassembly alternatives at the same time. There is the need for harmonizing or clustering the multitude of tools since any proposal failed to be the best suitable one [88].

- *Competitive advantage.* Companies aspire to maintain a competitive advantage over competitors; while this makes the product unique in the market, it is also a huge barrier for de-manufacturing: products are designed to hide the technical solution inside them being not-dismountable [75]. Moreover, patents and industrial secrets, although protecting the company, indeed prevent the product know-how to pass down to EoL responsible. Academy in such circumstances should work hard to develop strategies and approach that protects OEMs and improve the environmental performance of the product. In such cases, customized solutions may be needed.
- *Value of recovered products.* Disassembly is both time and resources consuming; this makes its costs very high and not comparable with the low revenues achievable by commercializing used or re-manufactured products. Endeavour is needed on both sides: methods and technologies must be implemented to reduce time and cost of disassembly and to ease the re-manufacturing so that their cost lowers to the market standards.

3.2.4 Design

- *Lifecycle thinking.* If lifecycle thinking is not well-rooted in a company, designers will give priority to traditional drivers (functional and manufacturing) and only later (maybe) would consider environmental aspects [49] [89]. The most effective way to boost re-manufacturing is an integrated product and process design approach [78]. Designers should be encouraged by management to make a difference by applying eco-design tools [90] [91]. Cappelli et al. [92] propose a method to automatically obtain all the possible disassembly sequences from a CAD model, while Smith & Chen aim at finding a near-optimal heuristic selective disassembly sequence [80]. Besides departing from different assumptions and manners to analyzed BoM [83] [93], CAD [94] [95], or other documentation, many papers make use of matrices to define the disassembly sequence. Francia et al. [96] use wave propagation to get the sequence, while other authors prefer indices to rank the component to disassemble. Concurrent engineering gives a powerful boost to lifecycle thinking, but it can be hard for an enterprise to allocate the resources needed. Research can give a great contribution in this direction by providing solutions, in the form of methods or tools, that can extend designers' know-how (i.e., the introduction and involvement of EoL process features and feedbacks); and widen their overview of the product lifecycle.
- *Design tool integration.* Arnette et al. [45] claim the need for an integrated approach for managing DFX considerations in the design process. Ghandi & Masehian [60] complain about the lack of benchmarks to enable the APP/DAPP. Most evaluating methods are self-standing, not widespread techniques. Belhadj et al. [97] use data from industrial practices to evaluate the performance of the design planning, generated after identifications of parts that could face wear. Harivardhini [99] uses IdeAssemble tool to simultaneously evaluate: quality of design, profit, labor cost and environmental impact. Favi et al. [49] [58] [98] define six indices to evaluate product disassemblability from an economic and environmental perspective and similarly Soh et al. do [100]. The most recurrent indices to assess part accessibility and product disassemblability are related to time and cost. Academy should put the effort into harmonizing the existing tools: if they worked fluently together, higher standards would be reached.
- *Traditional and Eco-design.* Work must be done to strengthen the reciprocal link between traditional and eco-design tools [101]. Innovative tools should be integrated into the traditional ones, or at least they should have links and communication channels. Researchers must enforce the integration between conventional tools -such as CAD, ERP, etc.- and eco-design tools so that the use of the latter would not be perceived as time-consuming and would occur simultaneously with the use of other design tools.

3.2.5 Information

- *Product data.* Along with the value chain a bi-directional information flow must run: i) designers are called to share and make available data and intentions of the design phase and ii) feedback annotations must travel backward to them. Suppliers for example retain much more information than the OEMs [22]. There are tools specifically developed to contain, in the form of database [61] [102], rates [42], tables [70] the information collected. Cong et al. [103] prove how important can be to quantify the improvements produced at EoL stages to generate new design features. Haziri & Sundin [104] present a framework that supports design for re-manufacturing by the implementation of structured feedback from re-manufacturing to design that makes the process more efficient and effective. By centralizing de-centralized information, designers are provided with the proper knowledge to design both circular and sustainable products and processes [105]. Having access to good information is an arduous challenge, since data may be disrupted, uneven, chaotic or inaccessible [106]. Lifecycle actions are eased when the product circularity is managed by the OEM [104]. Academy is called to fill this gap and make the information flow smoother and richer.
- *Standardization.* Standardizing a process can make it more efficient, guaranteeing repeatability and reproducibility. A leading sector in this way is automotive. ELVs handling is becoming an industrialized procedure increasingly performant, that achieved to dismantle a vehicle in 3 hours [2]. Standardization may be dictated by directives and standards or defined as the process develops. By using AHP, Subramoniam et al. [107] refine and prioritize the strategic decision-making factors to develop a RDMF. Standardization and guarantees increase consumer confidence [70] [78] and product quality [108]. Research is needed in this sense, so those achievements reached in de-manufacturing are consolidated and can enter the loop of continuous improvement. Standardization may be applied also on a product level, designing modular and easy-to-access goods.

3.2.6 Technology

- *I4.0.* The implementation of KETs related to the de-manufacturing systems has been less investigated and in a less structured way [43] than in manufacturing. The existing results in this sense are optimistic: advanced robotics, in combination with AR and/or cloud, has the power to speed and optimize disassembly tasks [109]; management of huge data volumes in clouds may be a way to store, analyze and share information of the whole PLC [110]; it is common, especially for metal components, to give products new life through full/combined additive and subtractive techniques [46][111]; big data and analytics can help in designing smart products, enabling a continuous improvement of product life cycles [112]. KETs of Industry 4.0 may come to help, by connecting realities located far from each other and fastening the flow exchange. I4.0 shed some light on addressing the re-creation of product knowledge that existed at the product design stage, by improving data transferability and building the knowledge/data-sharing platform [112]. The introduction of innovative technologies in information exchange would be a great opportunity to standardize the way data, knowledge and feedbacks move back and forth along the value chain.
- *Product complexity.* Technology can simultaneously be a great partner and enemy to de-manufacturing systems [62] [113] [114]. I4.0 opportunities and potentialities must be explored both in manufacturing and de-manufacturing; at the current stage, it happens that products are too complex to be efficiently disassembled or their dismantling process is too expensive and thus unfeasible. Besides their architecture, the use of multiple materials makes the product complex and hard to handle at the EoL. The more dismantling processes increase in efficiency, the higher number of resources will be available for further life cycles [70] [22]. Technologies and

innovative solutions may be investigated to trace product features and identify how DfX approaches can be introduced in complex systems.

- *Recycling/ Re-manufacturing technology.* The economic sustainability of the de-manufacturing system is given by the positive balance of the de-manufacturing costs and revenues. This may be altered by the efficiency and productivity of the processes included. Recycling processes, also when eased by low-contaminated material flows, are still addressed as too resource-using [70]; in addition to that, re-manufacturing machines and tools are too expensive: they require too high investment costs to make the process efficient [23]. Design can play a huge role in this sense, improving the product disassembly by working on the product architecture.

4 Discussion

Through the CREDIT analysis the main criticalities concerning the practical implementation of de-manufacturing systems were clustered in seven factors and among them 18 sub-factors were identified. Moreover, the CREDIT analysis quantitatively evaluates the urgency for certain topics to be addressed by the academy, by a four-level scale.

The transition from the “Take-Make-Dispose” mindset to the “Make-Use-R-strategies” requires the whole system to change; in fact, the categories of obstacles identified encompasses not only technical/technological aspects (i.e. recycling/re-manufacturing technologies, materials), but also concerns economic and social matters (i.e. cost of activities for EoL management, governance, second life market).

The analysis pointed out that there is a need for very strong cooperation between academies and enterprises to find a balance among the several DfX existing or unveil and tackle their single limitations, before optimizing EoL processes.

Available tools should be revisited and integrated with conventional tools used in design, so that designers can develop a lifecycle thinking by using tools and applying the “learning by doing”. By acting on design, supported by useful and integrated tools, OEMs together with researchers can reach for something greater, such as foresee and getting prepared for tighter regulations, involve customers in a sustainable close loop, introduce innovative technologies that strengthen the information and material flow along through all the value chain and at the same time make processes more efficient, competitive and/or shorter.

The highest challenges perceived are the high cost of EoL activities and the need for disseminating and making life cycle thinking a natural mindset. One of the lowest is the fourth industrial revolution (6%): unfortunately, this topic is still too far from seeing practical implementation in the context of de-manufacturing, although the experimented case studies are confident in pursuing this direction. Nevertheless, big effort must be put to harmonically introduce KETs in shopfloors to the operators and enable the feedback return to designers.

A de-manufacturing system necessarily shapes a business to be circular; consequently, an obstacle to its implementation hampers a multitude of steps over the product lifecycle phases. Since, on a chronological base, design is the first one, this is the first to be tackled. It cannot be optimized without questioning the EoL phase. These are far phases, both in time and space; at the current state, only KETs of I4.0 can link them, in the form of sensor-provided goods, cloud data storage, artificial intelligence, etc. For one side they can establish a connection between the two phases, that consists in a seamless, constant information flow that both enriches the knowhow of designers, their awareness of actual issues encountered at the EoL and develop the knowledge of the product architecture in EoL dismantlers; on the other side KETs can support the balanced, fluent integration of design tools. Finally, I4.0 could make the process more competitive, as it is happening in manufacturing. Nevertheless, all innovative solutions must be meant to bring feedback of the improved process to the design phase; only this would enable a loop of information that characterizes the material and product flow so that they will observe the de-manufacturing principles.

This deduction agrees with Kerin and Palm [115] that outline the lack of evidence of Additive Manufacturing (AM) for low-value mass re-manufacturing and little consideration has been given to the exploitation of the data carrying opportunities to already "smart" product for re-manufacturing; concerning the equipment, they report that there are few demonstrations of existing smart I4.0 technologies (already used in manufacturing) being applied to re-manufacturing, neither demonstrations about how virtual product/process twins or big data could be utilized in re-manufacturing. Although not investigating I4.0 KETs, Bagalagel and ElMaraghy [116] propose a mathematical model whose aim is to determine the optimum manufacturing/re-manufacturing product mix that maximizes the company profit.

Besides the boost that I4.0 would give from a technological perspective, there are additional actions that necessarily must be paired to the technical considerations:

- Consumers must be included in the BM and product design, to provide them with fulfilling products that increase their sensitivity toward sustainability matters. Therefore, this would ease the management of market share and market segments, with the benefits for OEMs of preventing cannibalization. Moreover, the support of the academy is essential to watch further than the present state and identify the directions governments will lead enterprises to. Changes must start from the management level.
- Either innovative materials applications or innovative applications of existing materials should be explored (use in new products, biobased materials, etc..) to lower Earth exploitation and decrease the dependency on world sources of critical raw materials. Concerning human resources, training methods or tools should be identified so they easily would cope with product and process complexities.
- Academy is called to harmonize the multitude of tools proposed to manage disassembly since the design stage; in doing so, their workflow should be smoother so they would be perceived as successful and not time/cost consuming anymore.
- Available eco-design tools should be revisited and integrated with conventional tools used in the design, so that designers can develop lifecycle thinking by learning by doing. There is a strong need to gather expertise and know-how regarding different aspects of one product. Designers should be provided with tools that let them integrate sustainability into the design process.

A common aspect to all the factors of the CREDIT analysis is the need for research and applications in all R-strategies since up to now re-manufacturing, repair and reuse occur one order of magnitude less frequently than recycling. In a PPBM perception, this review is part of a wider work, that includes all the moments of PLC where de-manufacturing is involved: this work focused on the planning of de-manufacturing; there is the need for future works to focus on the literature regarding how innovative BMs could ease the spread of de-manufacturing and the production about the processes involved (reverse supply chain, disassembly, re-manufacturing, etc).

5 Conclusion

Design for de-manufacturing is at the basis of the Industry of the Future that competitively and sustainably will manage natural resources. The current review retrieved 106 papers related to de-manufacturing and CE, investigating which are the main obstacles to de-manufacturing implementation at industrial scale, the related hidden reasons and possible actions that can be implemented to overcome these obstacles, both in the industrial and academic sector, raising the level of actual results. The reviewers first showed the method followed to analyze the research documents. Concerning the results, the concept of de-manufacturing has been firstly investigated; the current literature often confuses and improperly uses the concepts of CE, de-manufacturing, disassembly and re-manufacturing. In the present work, de-manufacturing is conceived as the critical solution for an efficient and systematic implementation of CE. It is the only able to link EoL stages with BoL ones, leading those who manage the different stages to think about the whole lifecycle. In this view, de-manufacturing is different both to CE, re-manufacturing and disassembly. In fact de-manufacturing, for the sake of CE, is a comprehensive concept that encompasses all EoL strategies: re-using, re-manufacturing, re-purposing (for those disassembly is needed), recycling, depending on the status of each module.

Then, the identification of the main barriers related to the practical implementation of de-manufacturing and possible actions to overcome them, are identified from the literature and clustered according to the factors of the CREDIT analysis, which was proposed by the authors. CREDIT analysis is useful both for organizations and the academy. Industries, when approaching de-manufacturing, can self-measure and state where they must focus on. Whenever encountering new scenarios or challenges the CREDIT analysis may be useful to assess whether the current state of research or the enterprise is ready to face the action or needs to improve and where it should put more effort.

The CREDIT analysis highlights among the two most critical groups, the costs of the activities that occur at the EoL stage and the urgency to train designers to approach design thinking to the whole Product Lifecycle; here an innovative focus of research can be more incisive to overcome the actual barriers. As a consequence, the main conclusion is to focus the attention on the potentialities hidden behind a strong cooperation between academies and enterprises in order to find a balance among the several existing DfX or unveil and tackle their single limitations.

By acting on design, supported by useful and integrated tools, OEMs together with researchers can reach for something greater, such as i) foresee and getting prepared for tighter regulations, ii) involve customers in a sustainable close loop, iii) introduce innovative technologies that strengthen the information and material flow through all the value chain and at the same time iii) make processes more efficient and competitive. To guarantee success to the reached achievements, methods to standardize the gained condition are needed. Ultimately, one of the main gaps literature should focus on is the discrepancy of iv) I4.0 KETs application in manufacturing and de-manufacturing.

I4.0 KETs have been too little investigated in de-manufacturing; deeper research is needed to experience and quantify the benefits that innovative technologies could bring, not only to processes but mostly to the improvement of quality and quantity of information flow (to and from designers/manufacturing/people responsible of EoL of products).

In conclusion, if the cost of EoL and lack of standardization of tool and information flow are the main barriers (RQ1), only cooperation (industrial symbiosis, academy, etc) and innovative technological solutions (RQ2) can pave the way to make CE reality and not just a utopia.

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