



DOTTORATO DI RICERCA IN SCIENZE DELL'INGEGNERIA

**De-manufacturing method and tool: the link
between design and circular business models**

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Abstract

The traditional business as usual exploits the supply of minerals, metals and fossil resources as if they were unlimited and replenishable, but they are not. This attitude is exacerbated by the recent population and economic growth of developing countries that gives rise to i) increasing demand for industrial and consumer goods worldwide, ii) permanently damaged quality of natural resources such as water, air and soil. This heightened consumption and unsustainable production have gradually increased the pressure to change production and consumption behavior, especially in the business sector, making it necessary to shift toward a circular economy. De-manufacturing is a critical solution for supporting this metamorphosis. It enables the implementation of environmentally sustainable End of Life strategies e.g. reuse of components, especially when it is introduced in the design stage, next to the traditional drivers. Starting from the de-manufacturing principles, the present work proposes and applies approaches intended to support the design phase in enabling valuable and creditable EoL strategies. Four tools are developed to overwrite existing goods' linear destiny and sketch circular loops for new products. A cross-sectioning approach is developed to have technical solutions taking off in the economic one. Results show promising effects from implementing the approaches and using the developed tools: the Durabot tool dynamically assesses the sustainability of durable products; PReSCoM finds new applications for composite materials' scraps, heavily lowering their environmental burden. The DfD tool introduces quantitative feedback to evaluate the goodness of design from the environmental perspective. The correlation matrix exploits hidden potentialities of the above-cited and digitalization tools for the sake of economically sustainable circularity. All the approaches, both reactive and proactive, are meant to subsume all the challenges of the present economy. When the Life Cycle Assessment methodology is involved, multiple indicators are available for analysis. This effort contrasts the more and more companies that pledge to become carbon neutral, net-zero or climate positive, overlooking the huge challenges the Earth and humankind are facing (resources scarcity and contamination above all). Future works should focus on extending the application of the tools to new products, validate them through a structured validation procedure, and define the indicators that would evaluate when an organization is ready to implement a new CMBs.

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Abbreviations

ACO	Ant Colony Optimization	IPCC	Intergovernmental Panel on Climate Change
ALCA	Attributional Life Cycle Assessment	IR	Independent Re-manufacturer
AHP	Analytical Hierarchy Process	IS	Industrial Symbiosis
AI	Artificial Intelligence	KBE	Knowledge-Based Engineering
AM	Additive Manufacturing	KET	Key Enabling Technologies
APP	Assembly Path Planning	KPI	Key Performance Indicator
AR	Augmented Reality	LCA	Life Cycle Assessment
ARDET	Augmented Reality Disassembly Evaluation Tool	LCC	Life Cycle Costing
ARTODTO	Advanced-Re-manufacturing-To-Order-Disassembly-To-Order system	LCCP	Life Cycle Climate Performance
BE	Brushing Electroplating	LCI	Life Cycle Inventory
BM	Business Model	LCIA	Life Cycle Impact Assessment
BoL	Beginning of Life	LCED	Lifecycle Engineering Design
BoM	Bill of Material	LCES	Life Cycle Extension Strategies
BoP	Basket of representative Products	LCP	Product Life Cycle Planning
CC	Climate Change	LCT	Life Cycle Thinking
C2C	Customer to Customer	MAAP	Method to assess the adaptability of products
CAD	Computer Aided Design	MCDM	Multi-Criteria Decision-Making
CAE	Computer Aided Engineering	MDF	Medium-density fiberboard
CAM	Computer Aided Manufacturing	MICMAC	Matrix of Cross-Impact Multiplications Applied to a Classification
CBM	Circular Business Model	ML	Machine Learning
CBR	Case-Based Reasoning	MLC	Multiple Life Cycle
CE	Circular Economy	MRS	Mineral Resource Scarcity
CESN	CE Supply Network	NPD	New Product Development
CLCA	Consequential Life Cycle Assessment	OEM	Original Equipment Manufacturer
CLSC	Close Loop Supply Chains	OWL	Ontology Web Language
CNC	Computer Numeric Control	PBM	Population Balance Model
CREDIT	Culture Resources Economic Design Information Technology	PCB	Print Circuit Board
CRR	Composite Rate of Return	PDC	Product Disassembly Complexity
CS	Component Substitution	PEF	Product Environmental Footprint
CSC	Circular Supply Chains	PESTEL	Political, Economic, Social, Technological, Environmental and Legislative
DAPP	Disassembly Assembly Path Planning	PET	Polyethylene Terephthalate
DASP	DisAssembly Sequence Planning	PFK	Primary Foreign Key
DB	DataBase	PK	Primary Key
DEI	Disassembly Effort Index	PLC	Product Life Cycle
DfD	Design for Disassembly	PMMA	Polymethyl methacrylate
DfX	Design for X	PReSCoM	Processes and Products' Re-design, Involving Scraps from Composite Materials.
DOG	Disassembly Order Graph	PSP	Plasma Spray
DSS	Design Support System	PS	Product Substitution

Abbreviations

DSSG	Disassembly Sequence Structure Graphs	P/S	Product or service
ECMPRO	Environmentally Conscious Manufacturing and Product Recovery	PSS	Product Service System
ECPD	Environmentally Conscious Product Design	PVC	Polyvinylchloride
EDIT	Environmental design industrial template	QFD	Quality Function Deployment
EDST	Environmental design support tool	RBR	Recyclability Benefit Rate
EEC	Electric and Electronic Components	RC	Resource Capabilities
ELSEM	EoL Scenario Evaluation Method	RCR	Recycling Rate
ELVs	End of Life Vehicles	RDMF	Re-manufacturing Decision Making Framework
EoL	End of Life	RIFF	Re-manufacturing Information Feedback Framework
EoLRIR	End Of Life Recycling Input Rate	RL	Reverse Logistics
EPD	Product Environmental Declaration	RM	Revenue Model
EPR	Extended Producer Responsibility	RoR	Rate of Return
ER	Entity - Relation	RPP	Re-manufacturing Process Planning
ERP	Energy Related Products	SBM	Sustainable Business Model
ESG	Environmental, Social, and corporate Governance	SD	System Dynamics
EU	European Union	SDSP	Selective Disassembly Sequence Planning
FDM	Fuzzy Delphi Method	S/M	Segment/Market
FEM	Finite Elements Analysis	SMA	Shape Memory Alloy
FMEA	Failure Mode and Effect Analysis	SMP	Shape Memory Polymer
FSC	Forward Supply Chain	SoA	State of the Art
FU	Functional Unit	SW	Software
G.EN.ESI	Green ENgineering dESIgn	SWOT	Strengths, Weaknesses, Opportunities and Threats analysis
GFDA	Green Fuzzy Design Analysis	SWRL	Semantic Web Rule Language
GHG	Green House Gas	TCE	Transaction Cost Economics
GIS	Geographic Information Systems	TISM	Total Interpretive Structural Modelling
GWP	Global Warming Potential	TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
HALG	Hierarchical Attributed Liaison Graph	TRL	Technology Readiness Level
HR	Human Resources	UCD	User Centered Design
HW	Hardware	VIP	Vacuum Insulating Panel
I4.0	Industry 4.0	VC	Value Chain
IIoT	Industrial IoT	WEEE	Waste Electric and Electronic Equipment
IoT	Internet of Things	WU	Water Use
IP	Intellectual Property		

1 Introduction

The sustainability race is on [1]. It is expected that an immediate implementation of the most stringent resource-saving measures could extend the estimated exhaustion periods of most of the scarcest raw materials by an average factor of approximately four, even while simultaneously increasing the global service level of these resources by a factor of four as well [2]. Entering this period of sustainability-driven scarcity brings new risks and opportunities, potentially changing the dynamics of competition in many industries for the decade ahead [3]. This requires manufacturers to look beyond their gates and supply chains to make their products and scraps secondary material for different chains. Industrial networks come about in three ways: top-down planned, emerging bottom-up, or combinations thereof, where planned and self-organizing elements are combined [4].

Corporations, investors, and governments worldwide have made ambitious commitments to reduce their operations' negative environmental and social impacts, as impending sustainability scarcities are already visible in several categories. Forward-looking companies are already trying to secure the necessary resources before sustainability scarcity becomes the norm. By identifying and anticipating critical bottlenecks, forward-looking companies can take the moves necessary to alleviate constraints and turn them into a competitive advantage. Faced with sustainability scarcity, companies must develop a portfolio of strategic and tactical responses to mitigate risk and capitalize on opportunities. Besides the openness to cooperation and integration with new realities, this cannot forget methodologies and tools for de-manufacturing and re-manufacturing, applied since the product design stage [5]: End of Life (EoL) must constantly induce suggestions and feedback towards previous lifecycle stages, design in the first place[6]: Circular Economy (CE) is pursuing this objective.

Furthermore, enterprises should adopt the continuous sustainable Business Model (BM) innovation to address and leverage sustainability scarcities (i.e., expanding their BMs canvas, stressing the current BM, modeling and testing BM innovation, determining which move to collectively address, etc.). To win through sustainability, a company must move swiftly, mapping out a plan for delivering on its promises, securing the required inputs, and capturing the value new sustainable BMs offer. Besides benefiting the

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company, these actions will accelerate the world's investment and development of scarce resources — propelling society toward a sustainable future.

In the context of CE, de-manufacturing is able to link EoL stages with Beginning of Life (BoL) ones, leading those who manage the different stages to think about the whole lifecycle. The design phase is crucial as important sustainable drivers can enter and facilitate further activities of upcoming lifecycle stages. By acting on design, supported by valuable and integrated tools, Original Equipment Manufacturers (OEMs) can i) foresee and get 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.

Nevertheless, designers need support to introduce innovative drivers in the design process. Multiple tools are provided, but their awareness of lifecycle thinking still needs to be improved and more information returning from all the product lifecycles is needed. The design phase, both as the first stage of the lifecycle or in a late re-design, can boost the promotion and implementation of multi life cycle approach: products' lifecycles can be extended, goods can maintain their initial shapes and characteristics or enter a new life, in different guises, as new secondary raw material. Design methods and tools should enable the valorization of waste and scrap; particular attention should be given to circular strategies applied to composite materials. The integration between commercial/existent tools should be spurred, to harmonize workflow and encourage the dissemination of lifecycle information.

The CE paradigm outlines how traditional ways to commercialize products are inappropriate for valorizing resources and product functionalities. If the linear concept of Take-Make-Dispose is unsustainable and unsuitable to cope with human needs and Earth's capacity, similarly the traditional way to provide products to the customers does not fit with the multiple opportunities of revenue streams and market strategies that come together with CE.

Indeed, each enterprise must choose its winning strategy, which may mean embodying one or more Circular Business Model (CBM) that results in addition to the traditional one.

In this context, it is evident that much support must be provided to designers and project managers to establish a system that sustainably employs and valorizes resources.

Introduction

The present work aims to increase awareness of environmental sustainability and the choices made yet in the first design phase; moreover, to support industries and increase their competencies in developing products with a life cycle perspective, so it is optimized (in environmental terms). The need for this work arose from an accurate and well-aimed literature review, reported in Section 2. That retrieved in detail the most recent State of the Art (SoA) related to i) the main barriers that prevent de-manufacturing and consequently CE to become the new standard, ii) the innovative BMs that recently appear when opportunities of CE have been partially exploited, iii) how the traditional process (manufacturing) is coupled with the de-manufacturing one and iv) how enterprises have been successfully applying the principles of CE. Section 3 shows the lifecycle-based methodology that aims at overcoming the most urgent needs identified by the SoA.

The methodology's core is de-manufacturing, adequately capitalizing and exploiting to deliver improved products and services. From the primary approach, four sub-cases are identified. Two are mainly purposed to transform linear behaviors into circular loops. Their first implementation is on existing products, whose design, production and subsequent lifecycle phases are focused solely on traditional drivers, such as technical feasibility and economic benefits. The first, presented in Section 3.1, squeezes in the wide world of Life Cycle Assessment (LCA), that is acquiring a more assertive and decisive role in the decision-making processes and governmental regulations; therefore, the objectivity and reliability of results must reach high standards. It combines the linearity of the Attributional LCA (ALCA) and a deep level of detail, able to faithfully describe the entire lifecycle, including the effects of time over it.

Furthermore, it provides the effects of the upcoming changes that directly influence the flows included in the analysis. The variable quantities flowing to and from the product system can either concern the evolution of the analyzed system or external factors. Finally, a tool is derived from it (Section 4.1): it implements the principles of the dynamic approach while assessing the environmental sustainability of durable products. The case study, shown in Section 4.2, involves a refrigerator, for which different aging scenarios are analyzed and the effects of implementing of the dynamic approach are quantified.

The PReSCoM approach, shown in Section 3.2 and applied in Section 4.3, faithfully implements the CE principle of joining and bonding EoL and design phases involving a system rather than a single organization. Furthermore, it aims to establish symbiosis

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among enterprises that are active in different sectors and involve optimizing composite materials' EoL treatment.

The third tool, the DfD tool described in Section 4.4, is developed from the proactive approach described in Section 3.3. Unlike the previous, it aims at developing brand new products with their lifecycle in mind. Its goal is to include and provide product lifecycle information to designers to make them aware of their choices. Through highly usable interfaces, the tool returns the designers information about sustainability (i.e., recyclability) and de-manufacturing (disassembly complexity) and highlights the main product criticalities. Through this, the designer becomes aware of the most impacting components, potential recyclability flows, disassembly complexity. The design guidelines explain the reason behind each criticality and suggest solutions. The analysis of a sub-assembly of an electrospindle (Section 4.5) proves the main tool functionalities.

Ultimately a cross-sectional approach (Section 3.4) is at the bases of the correlation matrix, presented in Section 4.6 and applied to both companies provided with digitalizing tools (Section 4.6.10.1) and the ones developed in this work (Section 4.6.10.2). It is meant to identify which market strategy and BM is the most appropriate for a specific product and enterprise. Since the choice of a BM, especially when it comes to the selection among the multiple CBMs that recently appeared, can be extremely hard, much more complicated if a company is approaching CE for the first time, the tool aims at starting the journey toward circular loops by exploiting secondary functionalities and purposes of tools introduced in the industrial context for different purposes.

Section 5 critically reviews and discusses the main results; ultimately, the conclusion (Section 6) closes the dissertation.

2 State of the art

2.1 Plan De-manufacturing: Design

The transition from linear to CE determines whether humans can rationalize exploiting natural resources. The main challenge is to join forces with multiple players since the circularity of a product goes beyond the product itself and involves stakeholders, customers and administrative bodies [7]. Frameworks [8] and circular industrial cases (such as Audi, Nokia, Ikea) have been proposed to successfully act the transition as guidance for other companies seeking to tackle climate change [9].

CE is receiving increasing attention worldwide to overcome the current production and consumption model [10]; it requires companies to rethink their supply chains and BM [11] since today they do not feel any responsibility for the EoL of products. Reverse Logistics (RL) tries to account for EoL products in the most environmental-friendly manner possible [12]. Implementing durable design, maintenance, repair, re-use, re-manufacturing, refurbishing, and recycling operations and processes can support this. The main goal is to launch a product in an MLC loop [13], [14], where recycling concerns a minimum percentage of the product and is more efficient [15], as goods are designed for this purpose [16], [17]. De-manufacturing represents the sustainable approach encompassing all the EoL strategies; it requires reasonable design decisions from the early stages to optimize the product and components' circularity.

In some cases, industries may feel environmental restrictions as obstacles to innovation in product design [18]. On the contrary, research has actively proposed methods and tools to face product circularity. The following, also presented in Table 2.1, are the main clusters of 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 their influence over strategic and managerial issues, defining their fundamental role in establishing CBMs. In this group, some papers propose Design for X (DfX) 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 2.1 Main limits identified

Cluster	Theme	References	Primary limits identified by research
Disassembly strategies	Product accessibility	[19], [20]	Although necessary, active disassembly cannot be coupled with idle/automatized/manual disassembly; limited application.
	Disassemblability	[21]–[29]	
Design approaches/ Design for X	Definition and application of r-strategies	[30]–[35]	Support in prioritizing environmental issues over time and cost drivers.
Sustainability dimension	Integration level of sustainability pillars	[36]–[38]	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).

Recently review papers concerned with the matter of CE and de-manufacturing, for example:

- Sassanelli et al. [39] explore how design can contribute towards a CE transition by adopting of DfX approaches. The challenge is determining when to apply each strategy to address prevention, re-use, 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;
- Schöggel et al. [37] affirm that the CE body of literature comprises management and technically oriented studies with either a BoL or an EoL focus. The authors sketch thematic maps and carry out quantitative analyses highlighting that only a limited number of environmental aspects (such as waste, resource use and CO₂ emissions) are centrally addressed. In contrast, other environmental and social aspects form the periphery of CE research. Schöggel et al. focus on research in the context of CE but do not identify which would be more beneficial to overcome the CE implementation barriers;
- De Kwant et al. [40] conduct a review article on the CE literature foundation, including definitions, challenges, and business model frameworks needed to understand the role of product design better; however, they only paid attention to electric vehicles and white goods. Focusing on specific product categories leads to

State of the art

identifying distinctive barriers of a particular sector and may prevent the identification of common challenges that may provide hints for innovative solutions;

- Okorie et al. [41] investigate the relationship between re-manufacturing and cannibalization, whose blurred connection often prevents re-manufacturing activities from being scaled. This work provides many hints (taxonomies, risk of cannibalization, guidelines, etc.). First, however, they must provide a clear picture of SoA and why the practice too infrequently follows the expectation.

The present work:

- Provides 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);
- Includes EoL strategies' analysis, which can support the transition from linear to CE.

The review of the SoA is focused on mechanical and mechatronics products (i.e., textile and construction sectors were discarded) but does not narrow down to a specific product category. The research deeply investigated papers in the context of CE to clarify the role of de-manufacturing and aims at answering identifying the main obstacles to de-manufacturing implementation at the industrial scale and the related hidden reasons, which are possible actions to overcome these obstacles, both in the industrial and academic sectors, raising the level of actual results. The SoA reviews how the literature approaches the shift from Linear to CE by proposing strategies to enable it from the design phase.

2.2 Material & methods

Figure 2.1 shows the method followed in analyzing the current SoA. The first step consisted of selecting articles in electronic scientific DataBases (DB). Then, the keywords “design”, “disassembly”, “de-manufacturing”, “tools”, “methods” and “Circular Economy” were chosen and combined for the research. Unfortunately, the results were highly diversified or scarce when the word de-manufacturing appeared. This was the first sign of the variety and the absence of a standard definition. The word de-manufacturing was then substituted with *manufacturing to collect paper related to re-manufacturing, de-manufacturing, re-manufacturing and de-manufacturing. Subsequently, 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 DB research provided a collection of 767 papers. Those were reduced by removing duplicates and sorting the articles by reading their title, abstract and conclusion. The remaining papers were fully read the papers and maintained. The last part of the literature research was the cross-referencing that allowed to discover additional interesting works.

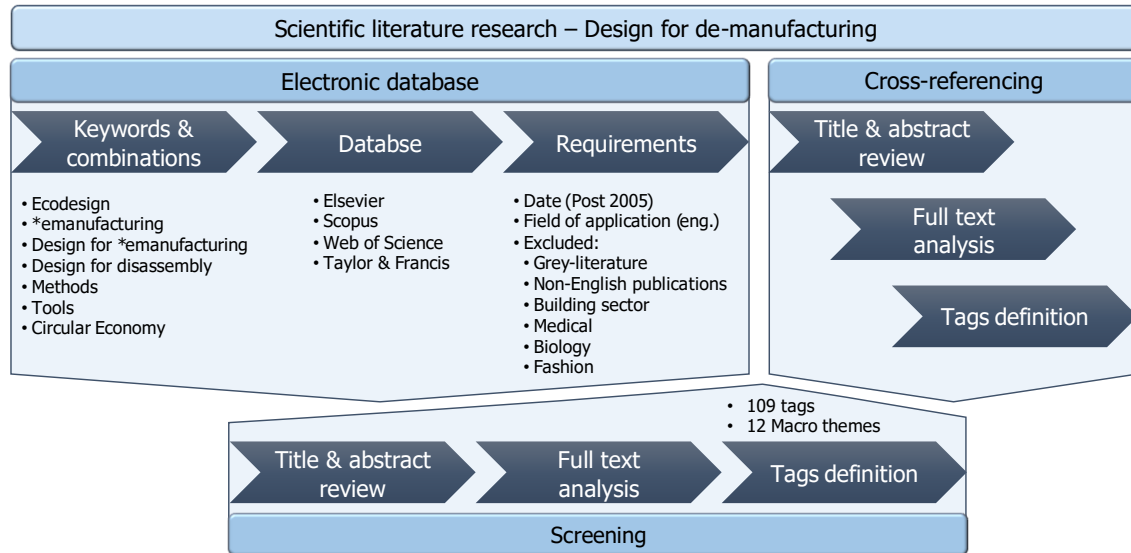


Figure 2.1 Research methodology, adapted from [26]

The debate about design for de-manufacturing is broad and concerns simultaneously many different aspects. This explains why the work dealt with papers published by 60 journals; Figure 2.2 shows the 20 most common.

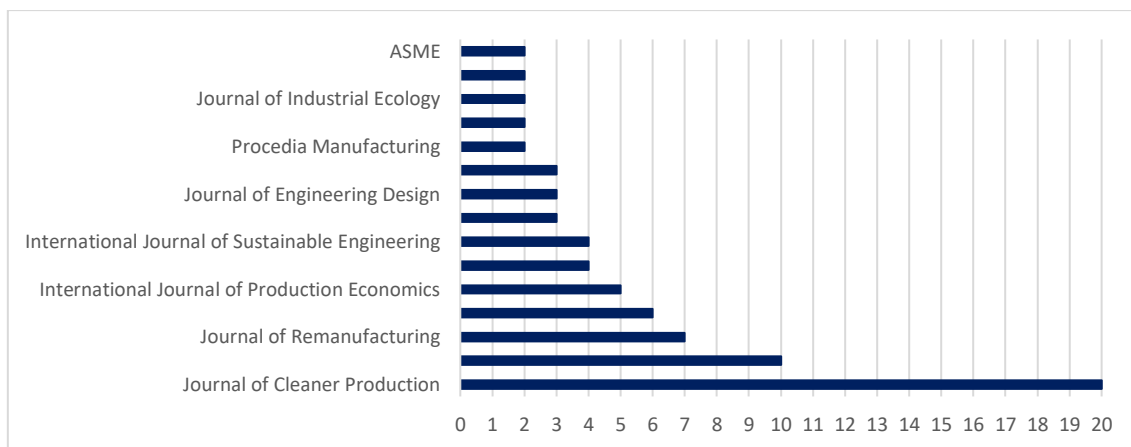


Figure 2.2 Most common journals

The analysis focused on industrial engineering. Figure 2.3 sums up the products analyzed in the retrieved papers. The blue group is electronics and encompasses both small household appliances (such as hairdryers, microwaves, toasters), big household appliances (under the label “white goods”, such as refrigerators, hoods) and electronic

devices and components (phone, laptop, pc battery). All components and/or total 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 do not belong to the previous categories.

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

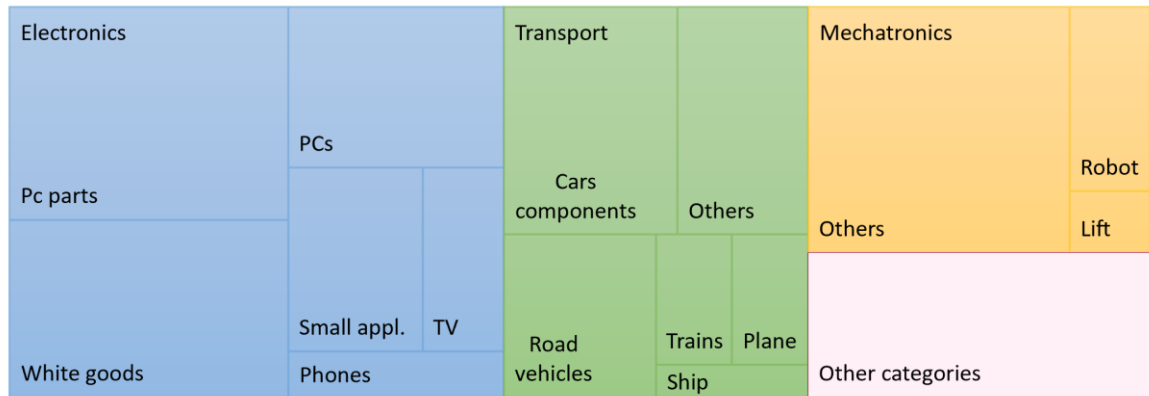


Figure 2.3 Products presented by retrieved papers

Tags allowed a more significant interaction with papers. Tags are like keywords: they were attributed while retrieving the papers; they are unlimited per paper, and they can refer not only to the subject of the paper but also to structure or single 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, already-analyzed papers 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 Figure 2.4 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. 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 product disassembly and thus allow the valorization of materials and parts (15 or more articles). The concepts of embedded disassembly (i.e., fasteners) or product modularization bring many suggestions. 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.

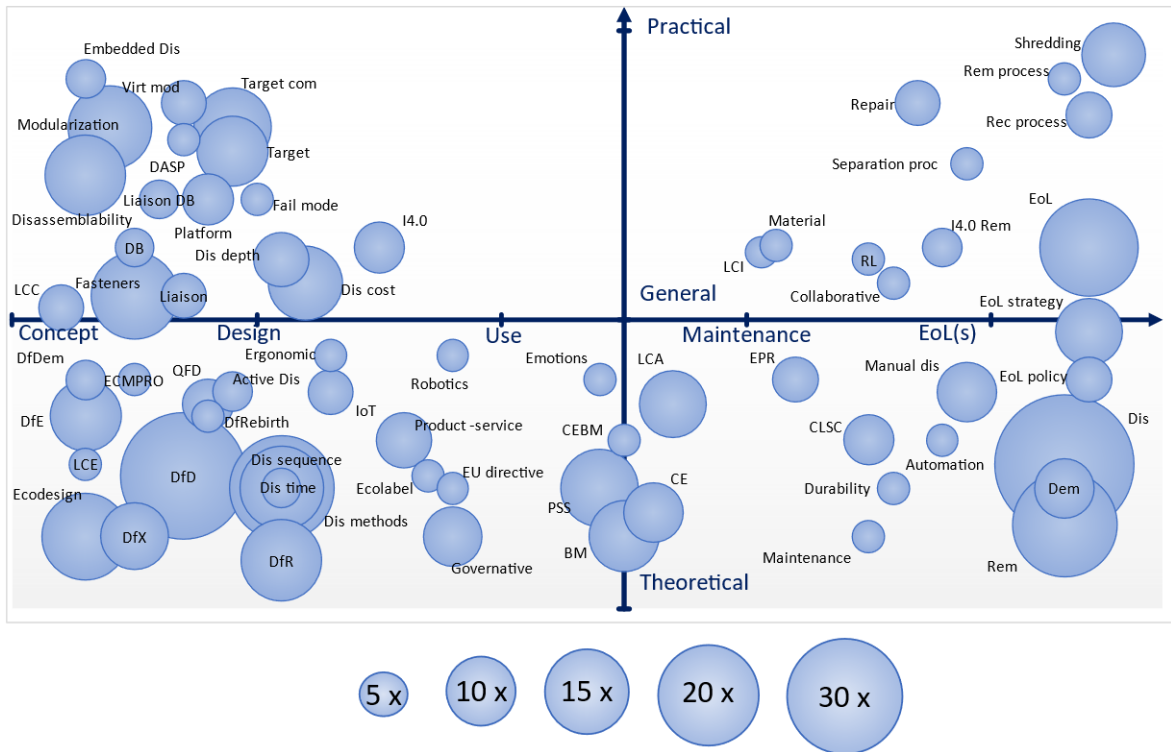


Figure 2.4 Tags matrix Product Lifecycle (PLC) - implementation status

At first, the terminology of de-manufacturing is analysed, and then the CREDIT (Culture Resources Economic Design Information Technology) analysis is proposed: 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.

2.3 De-manufacturing definition

The available literature about de-manufacturing is controversial and there is not any all-over-accepted definition. Colledani et al. [42] and Pigosso et al. [43] agree with the definition given by Duflou et al. [44] and define de-manufacturing as the breakdown of a product into its parts to re-use and re-manufacturing parts or recycling the remainder of the components. Chung et al. [45] affirm that de-manufacturing is a process of disassembling 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 the case of re-manufacturing) or total (de-manufacturing) account of the product [46]. De-manufacturing is seldom strictly connected to recycling and is seen as an approach to multi-component product recycling [47]. Among economic aspects related

to de-manufacturing, Krikke [48] sees de-manufacturing activities as short-term profit-maximizing decision-making; Johnson & McCarthy [46] affirms that de-manufacturing focuses on evaluating the economic and environmental implications of material recycling, part re-use, 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. [24] investigate how to determine the Rate of Return (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 [46] and provide technical solutions for an efficient and systematic implementation of CE. Both include the set of technologies, systems, tools and knowledge-based methods to systematically recover, re-use, and upgrade functions and materials from industrial waste and post-consumer products, to support sustainable implementation of manufacturer-centric CE businesses [49].

The present work conceives de-manufacturing 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) is a chain link, in the traditional framework of Take-Make-Dispose the chain is stretched and open; the introduction of de-manufacturing closes the chain, modeling the circle of Make-Use-implementation of R-strategies (Figure 2.5). It can 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 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 also contemplates other lifecycle stages (i.e., use). CE is the comprehensive 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 [50], 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 [51]. The concept of the CE originates in the inability of linear production models to reconcile current levels of production and consumption with the limited availability of resources [52]. De-manufacturing instead, is a total 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 re-use, shredding and landfilling, thus in EoL [46].



Figure 2.5 De-manufacturing is the missing link between Linear and CE

De-manufacturing attributes a suitable EoL strategy to every part of a good. Re-use, RL, disassembly, recycle, re-manufacture, disposal, landfill, upgrade, repurpose, and others are often studied, analyzed and proposed in taxonomies [34], [51], [53]–[55]; 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. [56] depict a plausible de-manufacturing system and define it as a set of resources (human and technological), organization, IT infrastructure and associated BM to enable product de-manufacturing. This perspective includes every EoL strategy. De-manufacturing not only returns used products to at least as good as new conditions, which happens for re-manufacturing [57]–[59], but also includes the proper management of the remaining modules/components, as shown in Figure 2.6. Design strategies can favor the implementation of strategies not only to improve the recyclability level of composite material (by selecting the suitable composition) but also can make possible the re-use of scraps through the application of design for de/re-manufacturing and disassembly rules. The literature claims ways to improve product designs regarding circularity [60]. The present work fills the gap of minimal offers available for possible design solutions, especially regarding application-oriented solutions. As product development for the CE faces stricter challenges than traditional New Product Development (NPD), design for de-manufacturing and re-manufacturing, together with Design for X, are allies in tackling

these tough challenges. The design actively participates in the proposed method and is intended as an Environmentally Conscious Product Design (ECPD) and diverges from traditional NPD.

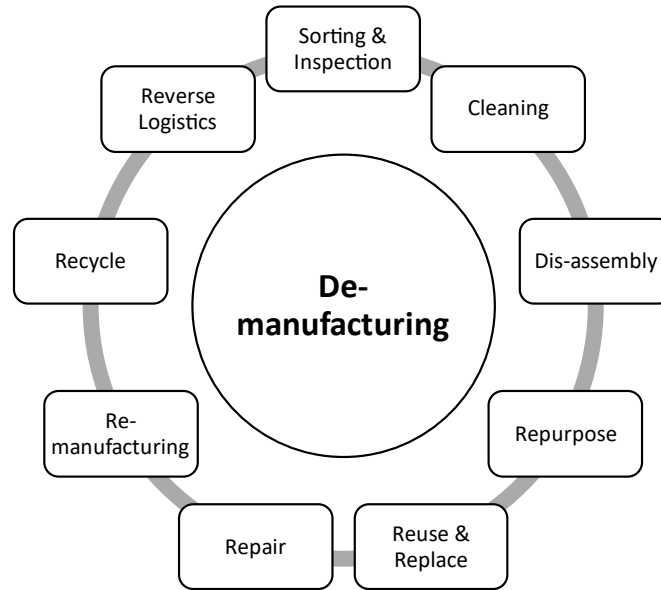


Figure 2.6 EoL alternatives for components in de-manufacturing systems

2.4 CREDIT analysis

Decisions made during the early design phases have impacts on the whole product lifecycle [61], [62], including disposal [63]. It is acknowledged that with their choices designers can prevent or facilitate up to 80% of downstream activities [34], [64]–[66]. They are empowered to configure products with closed-loop lifecycles, allowing the reintroduction of parts or materials into the productive chain. This is why the literature agrees on using use eco-design tools early in the design process to produce environmentally friendly products [43]. 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 [67]. Outcomes go from guidelines [9], [47], [68], [69] to SW tools [54], [70], mathematical models [71], fuzzy graph approaches [72] and many Multi-Criteria Decision-Making (MCDM) [73]–[75]. Even in case designers were able to manage all their power systematically, 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 [76], to enhance product rebirth and green supply chain [77], to evaluate recyclability, toxicity, cost, energy indexes [78]. Starting from the analysis of the literature, the CREDIT analysis is proposed. The analysis

is important to cluster and prioritize the main lacks and needs of the current literature. It summarizes all macro sectors conceived as the main barriers to properly implementing de-manufacturing systems. The CREDIT analysis is defined from a similar approach, the PESTEL (Political, Economic, Social, Technological, Environmental and Legislative) analysis. However, it considers explicitly 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 [79], it is a multifaceted approach to assess big-picture forces to understand the strategic orientation of an organization better 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. Table 2.2 shows the reasons hidden behind the barriers and obstacles that hinder de-manufacturing systems from being successful. 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.

Table 2.2 classifies the factors of the CREDIT analysis and groups the papers depending on whether they are more oriented towards product servitization (Product Service System - PSS in the table), more inclined to traditional BMs (sale in the table) or deal with the eco-design topic (Eco in the table). The numerosity of the methods analyzed or proposed by the papers stands for a wide heterogeneity in approaches, methods and tools. 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. Appendix A shows the extended version of the table; while Table 2.2 groups the papers, the methods they propose and the reason they claim, the latter summarizes the information for each paper.

The six factors of the CREDIT analysis derive from the analysis of the papers. 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 and tools used by product designers and their attitudes;
- *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 2.2 Classification of methods and tools proposed by papers and main barriers identified.

P S E Ref S a c S l o	Method & Tools	C R E D I T					Reason 1	Reason 2
		C	R	E	D	I		
[24], [75], [80]– [84]	× × × CRR; Modularity matrix; TCE, HALG; GAIA, PROMETHEE	5	4	4	3	2	Disparity of recycling processes adopted; Cannibalization; Difficulties to share information; No product modularization; Non-standard driver for make/buy decision; Prod. complexity; Mass prod. discourage re-manufacturing	Controversial guidelines; Need for corporates to include customers in their circular endeavors and create awareness; Prod. status uncertainty; Need for focus on fasteners; No legislation
[35], [36], [39], [41], × [71], × [85]– [88]	× Mathematical formulation; CAD tool for dis.; Development of a new BM; QFD; Repurposing; Protocol analysis of a PSS design process	6	2	2	5	2	No legislation; Need of all pillars of sustainability; Need to rethink the prod. for rem. prior shift to PSS; No parallel focus on QFD and environmental aspects; Need for DfX approaches for circular design; Need for distribution strategy; Cannibalization	Re-manufacturing needs a re-manufactured prod.' market; Need for cooperation with retailers to manage logistics; Decisions arising from design are not limited to the prod.; Critical access to cores
[46], [89]– [91]	× Mathematical formulation; RIFF, RemPro matrix	3	1	2	2	1	Need for: contact with customers, laws for re-manufacturing, get feedback	Low use of big data by designers; Re-manufacturing (and transport) too costly
[92]	× × System dynamics	1	1	1	1	1	No practice of eco-design	Longevity effects and repl.rates
[20], [32], [56], × [64], [93], [94]	DSP; Design method for value recovery; Fuzzy for dis; Integrated multi-disciplinary research framework; FDM, TISM, MICMAC	1	5	3	3	2	No modularization of wear parts; Manual dis.; Dis. cost; For complex prod. full dis. is not economically viable; Inefficiency of dis. processes, low productivity, labor cost of manual dis.; Low customer demand	Cost of labor; Materials incompatibility; For complex products full dis. is not environmentally viable; No EOL-oriented design practices that would ease automated dis.; Challenge of collaborative innovation among SC partners

Ref	S _a S _e	P _S E _c	Method & Tools	C R E D I T						Reason 1	Reason 2
				C	R	E	D	I	T		
[8], [12]– [14], [17], [19], [21], [22], [25], [28], [29], [34], [37], [40], [49], [51], [52], [54], [55], [59], [65], [68], [70], [72], [73], [95]– [119]			MLCA; Lean DFD; Design feature-based metrics; LCA, LCC, FMEA; DSS; V- Design; Liason_DB; DOG; DSP; G.EN.ESI; Dis. 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 prod. 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.	1 4	1 8	2 0	2 3	2 2	1 3	Need MLC in design; Dis. Time and cost estimation; Value recovered < dis. cost; No parallelism LCT and costing; Fasteners accessibility; Targets must be set; High-level design needed to face Close Loop and CE; Long-time existing tool, late application; Low connection and traditional and eco-design; Difficulties to implement I4.0 KET; No DfX; Prod. status uncertainty; Prod. complexity; Difficulties to share info; Prod. components accessibility; High capital and labor cost; Manual dis.; Prod. components accessibility; No Environmental Prod. Profile; Full dis. is not convenient; No modular design; No recycled materials market; Low re-use of re-manufactured parts; No legislation; RL; DfRecycling must be paired to other strategies; Too specific tools available for a single lifecycle stage; No consideration of consumption patterns and citizen; Knowledge or experience; Need for incentive to motivate R-strategies	Recycling technologies cannot cope with prod complexity; No legislation; No incentives to buy second-hand prod.; Dis. complexity; Reverse Logistics; No information and systematic approach; Dis. time uncertainty; Design focused on hiding company IP; Difficulties to accept I4.0 KETs; RL; De- manufacturing occurs late and far in space from design; Multitude of tools needed; No Dis. embedded design; Materials incompatibility; Knowledge Capitalization not based on forward e backward knowledge sharing; Dismantlers have no prod. design info; Multiple tools that require too much info or money or time; Vergin materials have higher quality than second- life ones; Need for time dimension; Need for homogeneity of materials; No design for re-manufacturing; Need for a second life market; No integration of material, strategic, and consumer perspective; Automated dis. needs high investment costs.
[9], [43], [61], [66], [69], [73], [97], [120] – [122]		×	EDIT, D4N, EDST, MAAP, LCP; ECMPRO; Learning goals for designers; TOPSIS; ECPD	5	2	5	6	4	1	Value of recovered prod. < value Dis. cost; Features required are considered in isolation and not in an integrative fashion; Difficulties for changes to design; No legislation; Prod. status uncertainty; Little knowledge of DfD concepts; No integrated information techniques to support innovative Eco-design; High labor cost	De-manufacturing and re- manufacturing processes do not close the loop on their own; Labor costs for dismantling not balanced by material recovery value; Reluctance to share prod. information; Self-standing design; Need for parallel prod. and process design
[16], [18], [23], [26], [27], [42], [47], [50], [53], [67], [74], [77], [78], [123] – [128]			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; Prod. Suitability for Rem. Assess Portfolio	3	9	9	9	6	9	Skill operators; AP causes subproblems; Smart tools are costly and not robust enough; Future economic conditions uncertainty of recycled materials; Prod. status uncertainty; High variability of products; Prod. status uncertainty; Circularity measures are not the reality in companies yet; Accurate metrics depend on prod. variability; Accepting the rules is different from believing in the rules; Dis. 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 dis. times and costs; Unknown dis. tack time; Cost of recycling

They will be further analyzed and discussed in the following 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%). The papers which deal with the eco-design topic allocate de-manufacturing obstacles to factors of heterogeneous nature. The different nature of the obstacles (i.e., technical, economic, social) highlights the need for cooperation along the product value chain and different professional figures throughout society. As shown in Figure 2.7, 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).

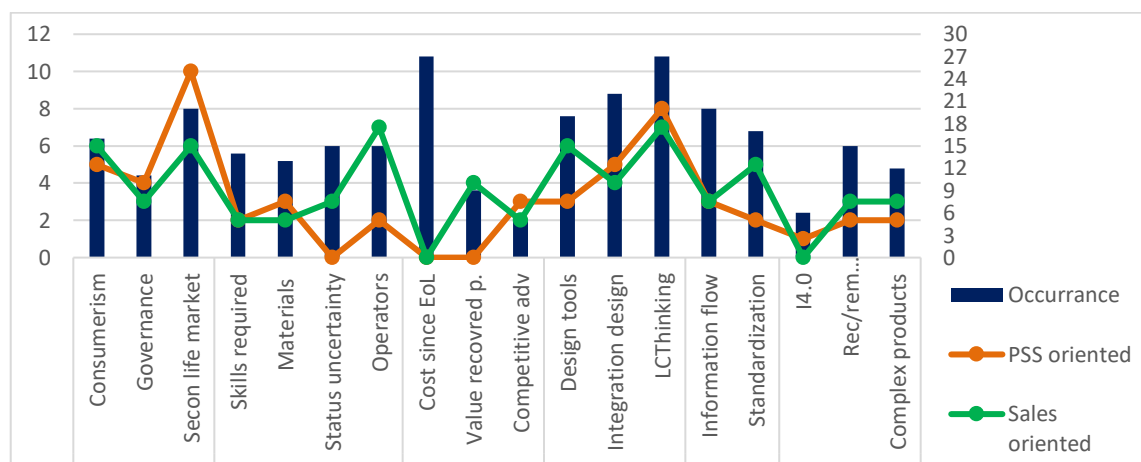


Figure 2.7 Trends of barrier related to PSS and sale-oriented papers

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 the realities of returning and re-manufacturing products. Authors PSS and Sales-oriented do not have the same perception about the CREDIT factors; neither are there 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). Figure 2.8 show the main challenges and

obstacles for each factor providing hints and tips for academics and organizations to foster and improve cooperation, fill gaps in research or raise the level of actual results.

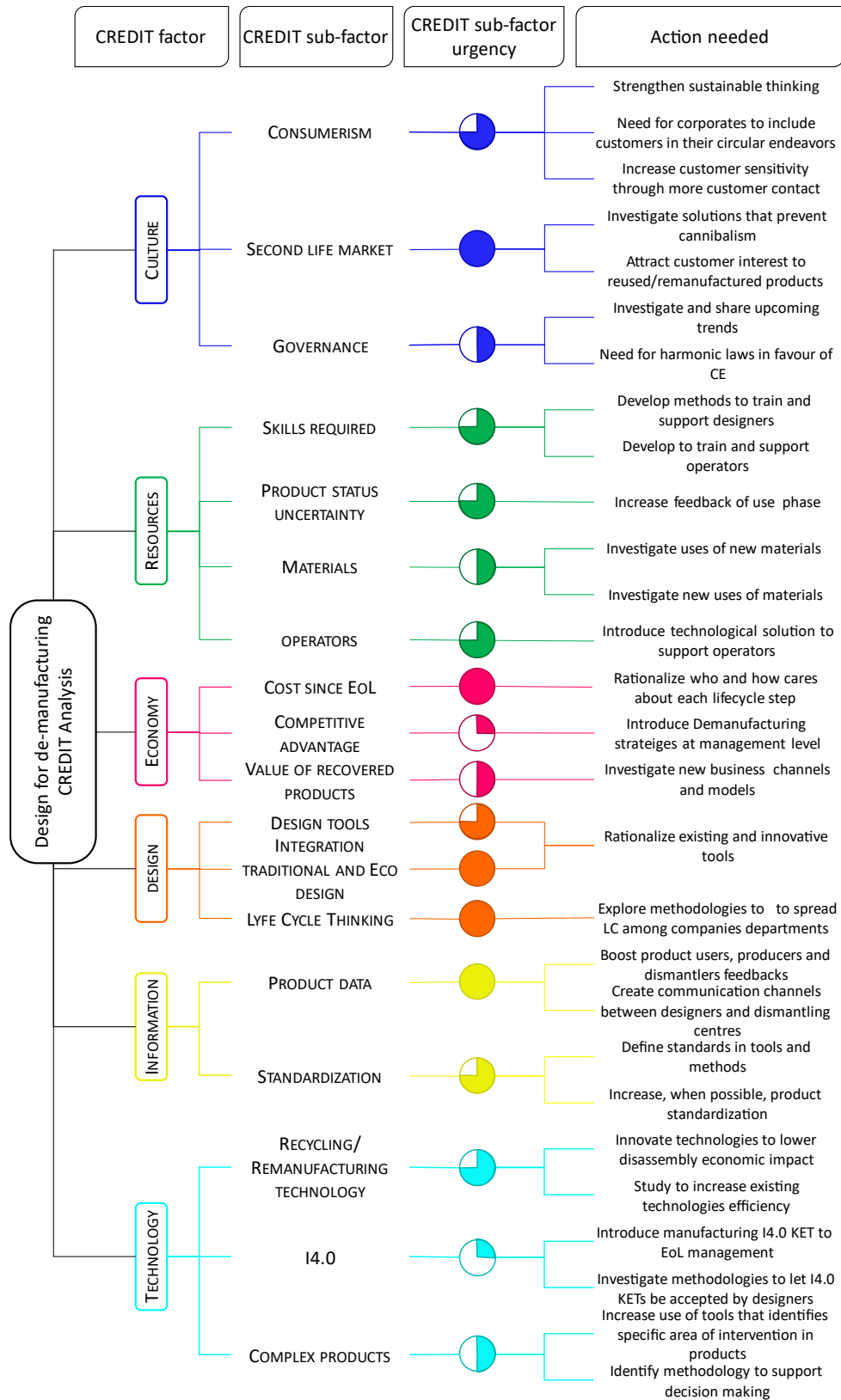


Figure 2.8 De-manufacturing CREDIT Analysis

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 is expressed using open circles. The openness/closeness of circles is proportional to the times barriers have been cited in the analyzed literature. For example, the most recurrent obstacles have a numerosity of 27 (*life cycle thinking* and *cost since EoL*); based on this, four ranges were identified and attributed to each cake: the first range 0-6 (numerosity of the papers that cite that barrier) has only one-quarter of cake painted, second range 7-13 half of it, follow three quarters and entire cake for ranges 14-20, 21-28 respectively. This frequency is the urgency to face these questions in the academic and industrial contexts. The last column reports the main action needed 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 academics. When approaching de-manufacturing, industries can self-measure and state where they must focus on. Whenever encountering new scenarios or challenges the CREDIT analysis may be helpful 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.

2.4.1 Culture

2.4.1.1 Consumerism

Among the social behavior affecting the decision process, De Almeida [129] 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 a 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) [130]. How extend the product's lifetime and feed consumers' desires simultaneously? Much work must be done so that customers perceive repaired or re-generated goods as fancy and on-trend. OEMs and academics should join forces to design de-manufacturing systems that ease and make it convenient to repair goods, persuade customers of the products' values, and study methodologies with both technical and marketing departments.

2.4.1.2 Governance

Political settlements and strategies significantly impact de-manufacturing systems, directly (directives) or indirectly (local markets cope with consequences from foreign governments' choices). By studying which targets can facilitate the transition towards a CE, Morseletto [96] notices that governance targets promote a pragmatic view of what to reach. Talens et al. [131] analyze the difficulty of removing computer battery packs and discuss how EU eco-design regulation could include the achievement. Nevertheless, laws and directives do not yet cover all commercialized products; for this reason, not all organizations are obliged to design goods to be de-manufactured. The literature addresses the lack of proper legislation as a missing organizational guide. Researchers can contribute to defining suggestions and requirements for upcoming regulations through their findings.

2.4.1.3 *Second-life market*

Availability of the resale market can be an additional barrier to re-manufacturing. Arnette et al. [85] investigate that not only consumer perception but also patents, obsolescence, and shifts within an industry can restrict the practice of re-manufacturing. Mascle [55] depicts re-certification as an excellent stratagem to enrich the second-life market. On the other side, Quariguasi et al. [89] 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. [86] 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 Customer to Customer (C2C) second-hand market. Given their competitive value proposition, OEMs often blamed re-manufactured products or cannibalizing new product sales revenues [41]. The academy's challenge is supporting OEMs in developing de-manufacturing systems that encourage the second-life market next to the revenue streams of new products.

2.4.2 Resources

2.4.2.1 Skills required

Abuzied et al. [29] argue that disassembly may need specific tools whose use requires special knowledge or experience. Antipodean, a fully manual disassembly and inspection requires high knowledge and understanding of the product and process, expertise, usually

acquired over a long time. Furthermore, due to the high variability in the disassembly and dismantling process, the academic world should support the designers in obtaining feedback on the EoL phases. By doing so, they can design the products to be easier to disassemble; moreover, training and methods to accept technological support must be directed to dismantling operators.

2.4.2.2 *Materials*

The choice of materials influences the product's durability and recyclability. Multi-material components have very low recycling efficiency. Stavropoulos et al. [70] provided a PSS that helps the designer to become aware of the component's particular and total post-disassembly condition. Peeters et al. [132] shared a methodology that helps to determine the economic and environmental value of design for disassembly. They calculate the Composite Rate of Return (CRR) on investing in design for disassembly and the resulting environmental impacts. The academy and industrial world must cooperate in investigating alternative materials to ores and how conventional resources can face new 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.

Composite materials required additional attention, as their EoL management is hugely delicate and hardly sustainable. The use of composite materials is growing and the global business sector for composite products has reached about £73 billion by 2020 [133]. Composite materials may contain recycled content, but it is tough to recycle them, as the matrix and the reinforcement are often very different. The employed material space from carbon fiber reinforced polymer, and epoxy/resin composites [134] to ensembles of recycled rubber and fiber-reinforced foamed Urethane and epoxy polymer [135]. Additionally, carbon fiber, glass fiber and hybrid fiber reinforced polymer composites [136] and clay, feldspar, felspathic sand, and kaolin [137] are used. A big challenge for the industrial expansion of composite materials is the development of approaches and technologies to optimize the waste generated from manufacturing operations and EoL products [138]. Three main options for treating EoL wastes are landfill, incineration and recycling. Oliveux et al. [139] calculated the related environmental impact of these strategies obtaining significant negative burdens on the environment (for Climate Change – CC -, Resources, ecosystem quality and human health impact categories) for landfilling and incineration treatments. Minor values were obtained for the recycling process, i.e.,

mechanical comminution techniques to reduce the size of the scrap to produce filler materials, chemical degradation to break polymeric matrices into simple chemical constituents [140].

Regarding recycling processes, they present lower Technology Readiness Level (TRL) (Table 2.3), while landfill and incineration is still the most common route. Landfill of composite waste is banned in Germany (in 2009), and other EU companies are willing to follow this route; furthermore, when incinerated, around 50% of the composite waste remains as ash and must be landfilled [141]. It is therefore evident the need to further investigate the question related to the EoL composite treatment scenario and the need for establishing design protocols that positively affect the EoL opportunity of this kind of materials, yet in the first phases of the design process. Re-use is the best option of the European Union's (EU) Waste Framework Directive [142], second only to reduction. The spread of Circular Supply Chains (CSC) may lead to higher environmental benefits and minimum negative impacts from re-use [143]. In CSC, scraps become input materials, reducing waste treatment costs and increasing the environmental benefits. The literature, however, does not provide enough hints and methodologies to make supply chains of composite materials circular.

Table 2.3 TRL level for EoL treatments for composites

Treatment	TRL
Landfilling	9
Incineration	9
Recycling techniques	
Mechanical grinding for Glass Fiber	8.3
Pyrolysis for Carbon Fiber	8.3
Pyrolysis for Glass Fiber	6.25
Mechanical grinding for Carbon Fiber	6.3
Fluidized bed pyrolysis and solvolysis	4.2 and 2.24
Microwave heating	3

2.4.2.3 Product status uncertainty

There are several reasons why OEMs lose track of their products once sold. In a de-manufacturing system contest, this may obstruct the feasibility of disassembly. Besides the difficulties of returning the goods, their status differs each time they reach the disassembly point (i.e., they are used under different conditions or break for disparate reasons and failure modes). All these facts hinder this phase's disassembly scheduling, altering times and costs. A prodigious contribution may stand on implementing

innovative solutions into the products to update their status via sensors and cloud and bring forward the time when their status is analyzed.

2.4.2.4 Operators.

An active debate focuses on resources required in the EoL process. Some argue disassembly is a workplace incubator for low-skilled labor [144] 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 [53]. Nevertheless, the literature agrees that manual disassembly is the best way to disassemble products because only operators can adjust to unpredictable conditions. In this sense, research can play a significant role in placing innovative solutions next to the operators (Key Enabling Technologies -KET- in the manufacturing field provided solutions for several similar circumstances).

2.4.3 Economy

2.4.3.1 Cost since EoL

Disassembly is the de-manufacturing activities' ground-breaking, regardless of why performed (i.e., partial to recover materials, cores [107]). Product status unpredictability and product variance make it hard to predict when disassembly is economically sustainable. Pigosso et al. [43] increase the value of the recovered product by applying Environmental Design Industrial Template (EDIT), Environmental Design Support Tool (EDST), and Method to Assess the Adaptability of Products (MAAP). According to the authors, a strategy must lead to decisions for less costly disassembly and higher success rates. Aligned with this mindset, Smith et al. [99] propose a disassembly model for Selective Disassembly Sequence Planning (SDSP) to be applied at the design stage. Rapidly disassemblable products can be more easily re-manufactured and recycled [34]. However, disassembly cost is not always proportional to the number of components to disassemble: the product status at the EoL may jeopardize expectations.

Too few companies use tools to ease disassembly since they are not considered worth the investment or flexible enough [145]. Design for disassembly tools mainly focuses on: i) picking target 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 [51]. According to Marconi et al. [101], 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, disassembly depth is set [100]; disassembly time reduces if this does not encompass the entire product. This is why selective disassembly is preferred to complete disassembly [102]. The literature provides guidelines and tips to encourage designers to evaluate different liaisons and fasteners that can be removed with minimum time [97], [103]. Peeters et al. [95] developed 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. [103] 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 [123] 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. [104] stress the robustness and weaknesses of previous generations of products to get information; from their KPIs they design a new, improved generation. Hierarchical Attributed Liaison Graph (HALG) proposed by Dong et al. [105] defines four indices that allow them to compare and evaluate different disassembly alternatives at the same time. There is a need for harmonizing or clustering the many tools since any proposal failed to be the best suitable [124].

2.4.3.2 Competitive advantage

Companies aspire to maintain a competitive advantage over competitors. Although at the same time, 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 [131]. 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 product's environmental performance. In such cases, customized solutions may be needed.

2.4.3.3 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. Endeavor is needed on both sides: methods and technologies

must be implemented to reduce the time and cost of disassembly and to ease the re-manufacturing so that their cost lowers to the market standards.

2.4.4 Design

2.4.4.1 *Lifecycle thinking*

If lifecycle thinking is not well-rooted in a company, designers give priority to traditional drivers (functional and manufacturing) and only later (probably) would consider environmental aspects [54], [146]. An integrated product and process design approach is the most effective way to boost re-manufacturing [120]. Management should encourage designers to make a difference by applying eco-design tools [146]. Cappelli et al. [87] propose a method to automatically obtain all the possible disassembly sequences from a Computer Aided Design (CAD) model. Smith & Chen aim at finding a near-optimal heuristic selective disassembly sequence [99]. Besides departing from different assumptions and manners to analyze Bills of Materials (BOM) [102], CAD [106], [107], or other documentation, many papers make use of matrices to define the disassembly sequence. Francia et al. [147] 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 challenging for an enterprise to allocate the resources needed. Research can contribute significantly 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.

2.4.4.2 *Design tool integration*

Arnette et al. [85] claim the need for an integrated approach for managing DFX considerations in the design process. Ghandi & Masehian [67] complain about the lack of benchmarks to enable Assembly Path Planning (APP)/Disassembly Assembly Path Planning (DAPP). Most evaluating methods are self-standing, not widespread techniques. Belhadj et al. [93] use data from industrial practices to evaluate the performance of the design planning generated after identifications of parts that could face wear. Harivardhini [110] uses the IdeAssemble tool to simultaneously evaluate design quality, profit, labor cost and environmental impact. Favi et al. [54], [65], [109] define six indices to evaluate product disassemblability from an economic and environmental perspective and similarly Soh et al. do [111]. The most recurrent indices to assess part accessibility and product disassemblability are related to time and cost. Academy should put effort into

harmonizing the existing tools: if they worked fluently together, higher standards would be reached.

2.4.4.3 *Traditional and Eco-design*

Work must be done to strengthen the reciprocal link between traditional and eco-design tools [112]. Innovative tools should be integrated into the traditional ones, or at least they should be provided with links and communication channels. In addition, researchers must enforce the integration between conventional tools, such as CAD, enterprise resource planning Software (SW), etc., and eco-design tools. By doing so, using the latter would not be perceived as time-consuming and would co-occur with other design tools.

2.4.5 Information

2.4.5.1 *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 OEMs [28]. There are tools specifically developed to contain, in the form of DB [68], [81], rates [148], and tables [77] the information collected. Cong et al. [113] prove how important can be to quantify the improvements produced at EoL stages to generate new design features. Haziri & Sundin [90] present a framework that supports design for re-manufacturing by implementing structured feedback from re-manufacturing to design that makes the process more efficient and effective. By centralizing decentralized information, designers have the proper knowledge to design circular and sustainable products and processes [114]. Access to good information is difficult since data may be disrupted, uneven, chaotic or inaccessible [149]. Lifecycle actions are eased when the OEM manages the product circularity [90]. Academy is called to fill this gap and make the information flow smoother and more affluent.

In the present market, CAD and Computer Aided Manufacturing (CAM) represent many tools to achieve better design and optimize the manufacturing phases. Currently, manufacturers aim to produce customized, high-quality products with little lead time and reduced costs [150]. However, the conventional CAD/CAM tools are developed to meet the general needs of the market, but not the market's or customer's rapid or specific requirements. Consequently, companies are looking to customize or tailor these tools to improve their effectiveness. Among these strategies, one is the application of Knowledge-

Based Engineering (KBE) in commercial CAD/CAM systems. It is applied to automate repetitive design tasks favoring time savings and enabling designers to explore a more significant part of the design space during the design phases [151].

Numerous approaches and methodologies have been developed [152], [153]; they are generally universal, but sometimes they focus on specific, narrow substantive, or scope context [154]. Mainly oriented in optimizing several general aspects, e.g., assembly and manufacturing, some are focused on specific aspects or production processes, like casting [155].

Despite these achievements, the more effective and efficient application of KBE in the industry still encounters various difficulties, both in its application development and its further development. Difficult in structuring modelled engineering design knowledge represents one of the main barriers [154] together with difficulties in favoring knowledge re-use [151].

Furthermore, among the limits of actual CAD/CAM and KBE solutions is the complexity of addressing emerging knowledge issues, e.g., environmental sustainability. Today it's not faced by available KBE approaches, but it is a significant driver to include in the design process. The growing interest of the academic and industrial world in environmental sustainability is widely recognized and consumers consider a priority the prevention of pollution¹. Academics and researchers developed many methods, tools, and approaches to address environmental issues yet in the first phases of the design process [156]. However, two primary limits emerge: on the KBE side, the need to include new essential design drivers, such as environmental sustainability, and to increase the knowledge sharing to support design activities. Regarding the integration between CAD and environmental methods and tools, the focus on the capitalization of knowledge can guide designers toward identifying the best design choice from the environmental perspective.

2.4.5.2 Standardization

Standardizing a process can make it more efficient, guaranteeing repeatability and reproducibility. A leading sector in this way is automotive. End of Life Vehicles (ELVs) handling is becoming an industrialized procedure that is increasingly performant, achieved to dismantle a vehicle in 3 hours [8]. Standardization may be dictated by

¹ New Eurobarometer Survey, <https://ec.europa.eu/commfrontoffice/publicopinion/index.cfm/survey/getSurveydetail/instruments/special/surveyky/2257>

directives and standards or defined as the process develops. By using Analytical Hierarchy Process (AHP), Subramoniam et al. [157] refine and prioritize the strategic decision-making factors to develop a Re-manufacturing Decision Making Framework (RDMF). Standardization and guarantees increase consumer confidence [77], [120] and product quality [88]. Research is needed in this sense, so those achievements in de-manufacturing are consolidated and can enter the continuous improvement loop. Standardization may also be applied on a product level, designing modular and easy-to-access goods.

2.4.6 Technology

2.4.6.1 *Industry 4.0*

Implementing KETs related to the de-manufacturing systems has been less investigated and in a less structured way [49] than in manufacturing. The current results in this sense are optimistic: advanced robotics, in combination with Augmented Reality (AR) and/or cloud, has the power to speed and optimize disassembly tasks [125]; management of enormous data volumes in clouds may be a way to store, analyze and share information of the whole PLC [126]; it is possible, especially for metal components, to give products new life through total/combined additive and subtractive techniques [52], [127]; big data and analytics can help in designing innovative products, enabling a continuous improvement of product life cycles [91]. KETs of Industry 4.0 (I4.0) may 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 at the product design stage by improving data transferability and building the knowledge/data-sharing platform [91]. Introducing innovative technologies in information exchange would be an excellent opportunity to standardize how data, knowledge and feedbacks move back and forth along the value chain.

2.4.6.2 *Product complexity*

Technology can simultaneously be a great partner and enemy to de-manufacturing systems [69], [94], [116]. I4.0 opportunities and potentialities must be explored both in manufacturing and de-manufacturing; at the current stage, products are too complex to be efficiently disassembled, or their dismantling process is too expensive and thus unfeasible. Besides their architecture, multiple materials make 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 [28], [77].

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

2.4.6.3 *Recycling/re-manufacturing technology*

The positive balance of the de-manufacturing costs and revenues gives the economic sustainability of the de-manufacturing system. However, 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 [158]; in addition to that, re-manufacturing machines and tools are too expensive: they require too high investment costs to make the process efficient [29]. Design can play a huge role in improving the product disassembly by working on the product architecture.

2.5 Giving value to de-manufacturing: Circular Business Models

Figure 2.9 shows the research method, where techniques, methodologies and results achieved by industrial entities were investigated. As for the last part, all organizations not acting around the engineering field were discarded, so all companies doing business only outside Europe.

The main scope of an institution is to make a profit by satisfying customers' interests and providing solutions to their issues and needs. In order to achieve the goal, it needs to gain a competitive advantage over competitors, selecting the best strategic and management solutions. The BM describes the rules that make an organization create, distribute and gain value. The definition of a specific BM requires the definition of strategic entities and actions [159], for example: i) the key partners and resources, such as internal or external people and organizations that help at making the business successful, through the ii) key activities that distinguish and make the business unique; iii) the customers to whom the organization proposes the iv) value, selecting the best v) channels to reach every vii) customer segment; last but not least, a proper BM must quantify costs and monitor them through a viii) cost structure and, at the same time, foresee ix) revenue streams, in other words, decide how to be compensated by customers. Over the last few years, many BMs have arisen, making it feasible for customers to access products and services dynamically. The most common, traditional BM relies on selling, on e-commerce or at physical store, a product at a set price resulting from production and provision costs. Those arising as technology or new customer needs appear, do not sell a physical object. Instead, offer a service for a fee.

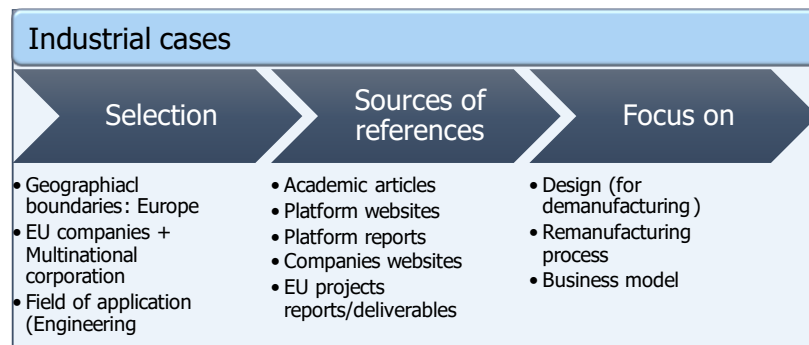


Figure 2.9 Research strategy for industries

Figure 2.10 shows a collection of BMs encountered by reviewers throughout the papers' analysis. The main characteristics will be further explained. First, it is necessary to highlight how important it is for an organization to revise, update, or pull together traditional BM with new ones when it comes to de-manufacturing. In fact, it often happens that the customer segment interested in the new object differs from the cluster of customers interested in the re-used or re-manufactured one. Creating value from entire product life cycles and related returns means establishing the proper system for Close Loop Supply Chains (CLSC), Sustainable Business Model (SBM) and CBM that include RL, but are an extension of it: of course, RL is a step towards circularity, but it still concerns mainstream returns traditionally conceiving the supply chain; CLSC instead, activates recovery flows perceiving the supply chain as restorative [160], [161].

Investing in a re-manufacturing system is like investing in a new business venture [162]. To give a quick gauge of whether the investment is going to be economically viable, a similar process for innovative product introduction to market is followed. This requires for example an initial market research, a market analysis, etc. Literature suggests well-known business tools, such as Strengths, Weaknesses, Opportunities and Threats analysis (SWOT), PESTEL analysis or Porter's forces analysis [163]; also new methods to evaluate, sufficiently in advance, if a product or BM may be successful or not, such as the hypothesis-testing framework of business model innovation proposed by Linder et al. [164]. A business approaching CE and intended to launch a re-manufactured or re-used product must ensure that it will not cannibalize the products of primary production. It also must deal with the actual price perceived by customers, who may unexpectedly feel too low from a low price of a re-manufactured object. On the other hand, customers might not be willing to pay (what they consider) too much for a like-new (but not new) product; by contrast, servitization support circularity as it defines market packages or bundles of

customer-focused combinations of goods, services, support, self-service and knowledge [165]. The paradigm of I4.0 is often perceived as a good incentive to ease CE development, introducing pathways to provide solutions and address supply chain bottlenecks and would reach more and more digitalized customers [166]. Enterprises often consider durability; nevertheless, the affinity between durability and environmental sustainability is not always valid. The similar meaning of durability and sustainability is up to the nature of the product.

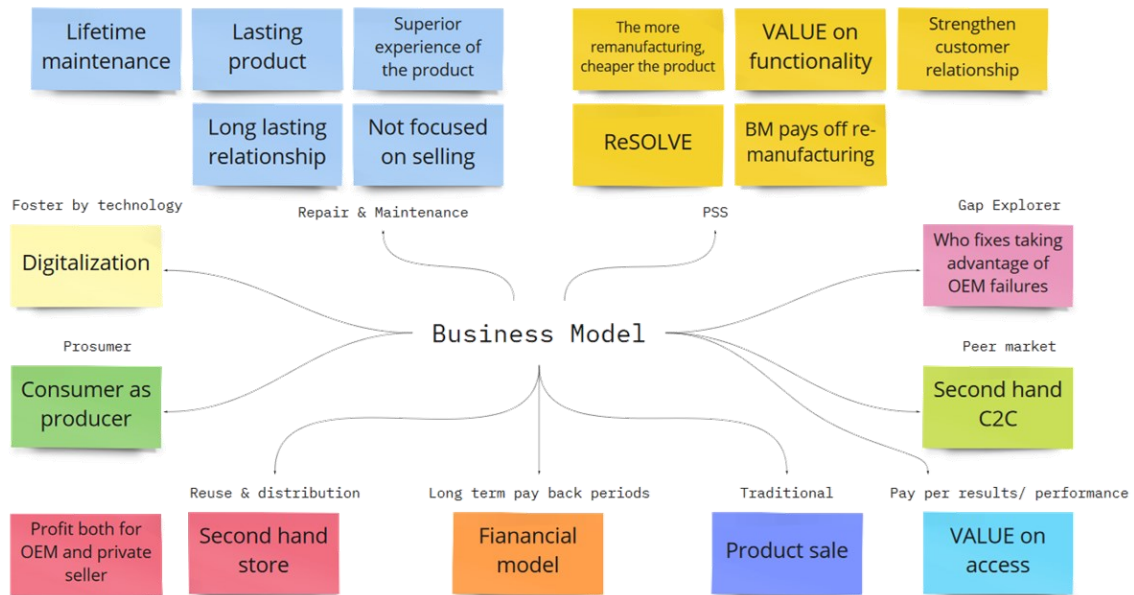


Figure 2.10 Traditional and innovative business models

From a general perspective, environmental sustainability is referred to systems, behaviors, and activities to maintain a particular entity or resource [167]. According to Iraldo et al. [168], durability refers to the ability of a product to endure its lifetime. Durable is comparable to sustainable when products do not require any flow of energy or other sources during their lifetime. Concerning Energy Related Products (ERP), especially those requesting energy, preserving and using a product for a long time does not always leave a positive mark on environmental sustainability due to components degradation and performance worsening.

This awareness raised the need to assess durability and understand whether and when durable is also environmentally sustainable. Several indexes spread in the literature. Some approaches assess efficiency by comparing two or more scenarios by applying standards, such as CEN/CENELEC EN 45552 [169], [170]. Some authors prefer assessing the sustainability of durability from the economic and environmental perspective by

comparing sale and servitization or other BMs, as Kanatli et al. [171] or Iraldo et al. [168]. Others couple technical information on products' lifetimes, failures, stresses, and degradation mechanisms with LCA and Life Cycle Costing (LCC) considerations [172]. When the durability question is faced, it is crucial that LCA also comprises all the aspects of the product lifecycle, including factors not desired, such as wear, aging, deterioration, etc., as product durability relies on those factors to guarantee a long, useful lifetime.

Mesa et al. [173] in defining the research gaps and research agenda regarding product durability highlight the need for developing more design methods and indicators to measure, determine, and predict product durability in different lifecycle scenarios. Alfieri et al. [172] present an approach and associated method for assessing how to increase the durability of ErP and assess the associated impacts. The authors assess the benefits associated with the durability of a product through LCA-based indices. The approach might find practical application in identifying design options to improve a product's durability. However, it allows a static comparison between the two scenarios.

2.5.1 Product Service Systems

PSS greatly fosters CE even though they were not explicitly born as circular; many organizations shift to PSS to dampen maintenance, re-manufacturing, and up-grading issues, either from an economic or legal point of view [174]. By doing so, the more the object is re-manufactured, the cheaper the service will be; in PSS, the value does not stand on the resources employed, but on its function. ReSOLVE is a comprehensive framework developed in order to organize the principles of circularity and apply them through six fundamental actions: regenerate, share, optimize, loop, virtualize and exchange [91], [175], [176]. In addition, frequent meetings with customers may help strengthen the relationship between them and the company, resulting in an improved image.

2.5.2 Repair & maintenance

This can occur not only when servitization replaces sales but also whenever the OEM, or whoever is in charge, allocates the value on a durable product that ensures the customer a superior experience, ensuring a full-time guarantee and maintenance. Furthermore, from the environmental perspective, this is undoubtedly a smart strategy to extend the product life cycle [11].

2.5.2.1 Durability

Besides sustainability, another topic often recurs in many enterprises' daily business: durability. Is durable also sustainable? Sustainability refers to systems, behaviors, and

activities to maintain a particular entity or resource [167]. Instead, durability refers to the product's ability to endure its lifetime, and this term apply to every type of good, from food to textile, from buildings to electronics [168]. However, sustainability cannot always be coupled with durability. Durability is a synonym of sustainability for all those products that do not require any flow of energy or other sources during their lifetime and are not subjected to fast technology aging. For example, Mutala et al. [177] explore the sustainability properties of imposing a durability standard in clothing markets. Consequently, a durability standard may be considered a politically achievable improvement in overall sustainability (environmental, social and economic) and an effective tool for promoting collaborative consumption via clothing libraries. However, when it comes to ERP, especially those requesting energy and not only indirectly impacting energy use, preserving and using a product for a long time does not always leave a positive mark on environmental sustainability.

Several approaches in the literature aim to define whether durability is exchangeable with sustainability. Recently new standards have been published to evaluate durability, sustainability, recyclability, etc; alternatively, the evaluation of durability and sustainability is mainly carried out through BM comparison and environmental burden quantification. While the last two approaches are likely to assess the efficiency by comparing two or more scenarios, the application of standards (such as CEN/CENELEC EN 45552) it is possible to quantify the durability of a single product, to the point that new material efficiency standards are a point of reference for upcoming eco-design requirements [170]. However, the standards are self-standing and do not correlate with R-bilities (i.e., re-usability, repairability, re-manufacturability, etc), durability and sustainability.

Kanatlı et al. [171] compare servitization to selling in terms of economic and environmental performance, and the first results in higher durability levels than selling. Moreover, they affirm that servitization is likely to perform better environmentally but not necessarily economically. Iraldo et al. [168] applied comparative LCA and LCC to assess the environmental impact of increased durability of domestic refrigerators, freezers and domestic electric ovens. Several sensitivity analyses have been performed on the purchase price, cost of electricity and energy efficiency. They conclude that from an economic point of view for the user more durable products are always the preferred choice, but this is not always the case from the environmental point of view. The current

literature lacks the embodiment of events or tendencies that occur during the lifecycle and can hamper the sustainability of a durable product. The approach and associated method proposed by Alfieri et al. [172] mention this; their approach allows the assessment of how to increase the durability of ERP and assess the associated impacts. In doing so it couples technical information on the lifetimes, failures, stresses and degradation mechanisms of products with LCA and LCC considerations. However, the approach is at a high level and does not explicate how to embed the failure analysis in the durability evaluation, nor does it underlines the role of time.

The scarcity of resources and the urgency to exploit them persuade to think that the more a product lasts, the better it is, as lower resources are employed to produce a new one. However, the question is more complex, especially for ErP products:

- Their components and/or materials are affected by aging;
- Energy grid mix, especially in European Countries, aims at full decarbonization; using a higher percentage of renewable resources to produce electricity makes the unitary environmental impact of energy consumption less impacting.

Those factors have opposite trends on product durability and environmental sustainability; due to the peculiar features of every product, it is impossible to predict if it is less impacting to maintain the old product or substitute it with a new one. The chance to upgrade the old product should be a noteworthy, proactively option [178]. Haines-Gadd et al. [179] investigate strategies that help develop more emotionally engaging product experiences, as the consumer, with choices and preferences, highly interfere with durability [180].

Mesa et al. [173] highlight the strict relation between durability and its boost derived by innovative circular BM and servitization practices; moreover, the authors identify 9 topics associated with product durability, such as fatigue, failure, and reliability, sustainability and eco-design, lifecycle assessment/thinking, product service systems, etc.

Preferable lifecycle phases to evaluate durability are the design phase [181], the EoL [182] when lifetime extension strategies are implemented, and the maintenance phase when the convenience of replacing a module/component or the whole product is evaluated. Kirkizoglu and Karaer [183] analyzed three alternative models for a durable goods manufacturer's after-sales service channel structure when the customers evaluate the total cost of ownership of a product when they make their purchasing decision.

2.5.3 Re-use & distribution

Nowadays, the customer does not necessarily own the product. He instead wants it just for the time he needs it. If, from one point of view, it leads OEMs to offer objects as services (as previously seen), from the other side, it results in initiating a second-hand chain. Second-hand shops can be mono-brand stores owned by OEMs or managed by independent sellers. In this case the OEM has no inference on the product nor on consumers, and CE principles are implemented without participation or planification [11].

2.5.4 Peer Market

The spread of C2C second-hand markets, a well-established attitude that grew in volumes, expanded across borders thanks to the Internet [159].

2.5.5 Digitalization

Digital devices reconsider the value proposition; one aspect is the one previously stated, according to which the customer has his own means to reach and evaluate products even far from him. In other cases, a digital service has entirely replaced the traditional product, also known as Virtualise [91].

2.5.6 Pay per result/performance

This kind of BM can be easily confused with the branch of PSS; it expects the product to be delivered to the customer for a finite or endless period, during which the customer is charged; the fee amount is proportional to the use. Such models enable consumers to access the product/service only as much as they need, reducing the burdens of high capital costs and the loss of value. Moreover, from an environmental point of view, both resources and assets are used more efficiently and sustainably [184].

Figure 2.11 shows how the willingness to shift from linear to CE made new BM bloom; persistent success cooperation. CE paradigm introduces a new concept of product, that goes beyond its mere functionality and being pushed to the market, but rather it entails sustainability aspects. In this mission, a single customer or organization's activities would not endorse the whole system.

There must be a bundle of customers, entities and organization operating for the same goal, formally or not formally organized. At the moment, this was not the whole society in any case, but wherever people and organizations cooperated, circular flows on information and resources were established. Nevertheless also being structured does not hide difficulties. Technology and economy-related issues have been overcome with sharing-based BMs; these structures allowed companies to manage de-manufacturing

systems complexities innovatively. Simultaneously the customers are unconsciously involved in greener cycles [185]. Which are the most important benefits? There are two main aspects: i) the customer faces lower initial investments and has access to the product whenever he wants, for the desired time; ii) resources are used more sustainably and efficiently: manufacturers decrease the primary resources requirements and customers ease their use extension, by sending them back to specific sites, whose processes are optimized to disassemble, repair, recycle or re-work products.

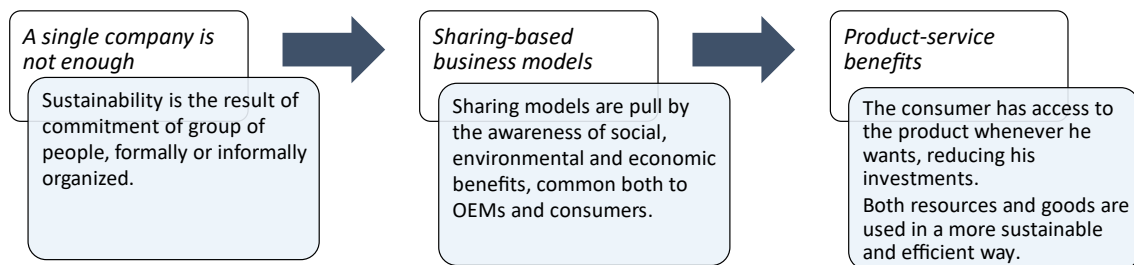


Figure 2.11 How product became a service

2.6 Make de-manufacturing happen: EoL management

This section analyses the practical aspects of the de-manufacturing process and how the literature addresses it. Despite the growth that has been characterizing it over the last years, there is not yet an equivalent discipline to manufacturing technology in production in the de-manufacturing context. In other words, given an object's characteristics and status (i.e., wear out, cracked, rusted, scratched), its activities in the de-/re-manufacturing process are not well stated [186]. Figure 2.12 shows the main identified steps, collecting suggestions in the documents. Depending on supply and sub-contracts, different sequence steps can be managed by different companies.

2.6.1 Product return

Taking back the product is essential to handle it at its EoL properly. The first step is strictly related to how the product is commercialized; thus it can be handled by OEM, Independent Manufacturer (IR) or 3rd part re-manufacturer or the customer himself. Here it is assumed that the product reached the end of (its first, second, and third) life and the maintenance option is not contemplated.

2.6.2 Product inspection & disassembly

The status in which products come after the use phase is unknown and unpredictable, so the related de-manufacturing activities are. Nevertheless, it is usually the main reason

a component is discarded or selected for re-use, re-manufacture, re-purpose. The first inspection determines if the product remaining value is too low. Thus only recycling is convenient, or some components may still be valuable and suitable for re-installing and re-using. This is a superficial inspection, whereby superficial is meant that only the external features are analyzed since the object is not disassembled yet. A second, more detailed inspection will occur after disassembly, whose efficiency step can determine whether activities will take place afterward. If expected and supported since the design stage, disassembly should not consume too much time and resources.

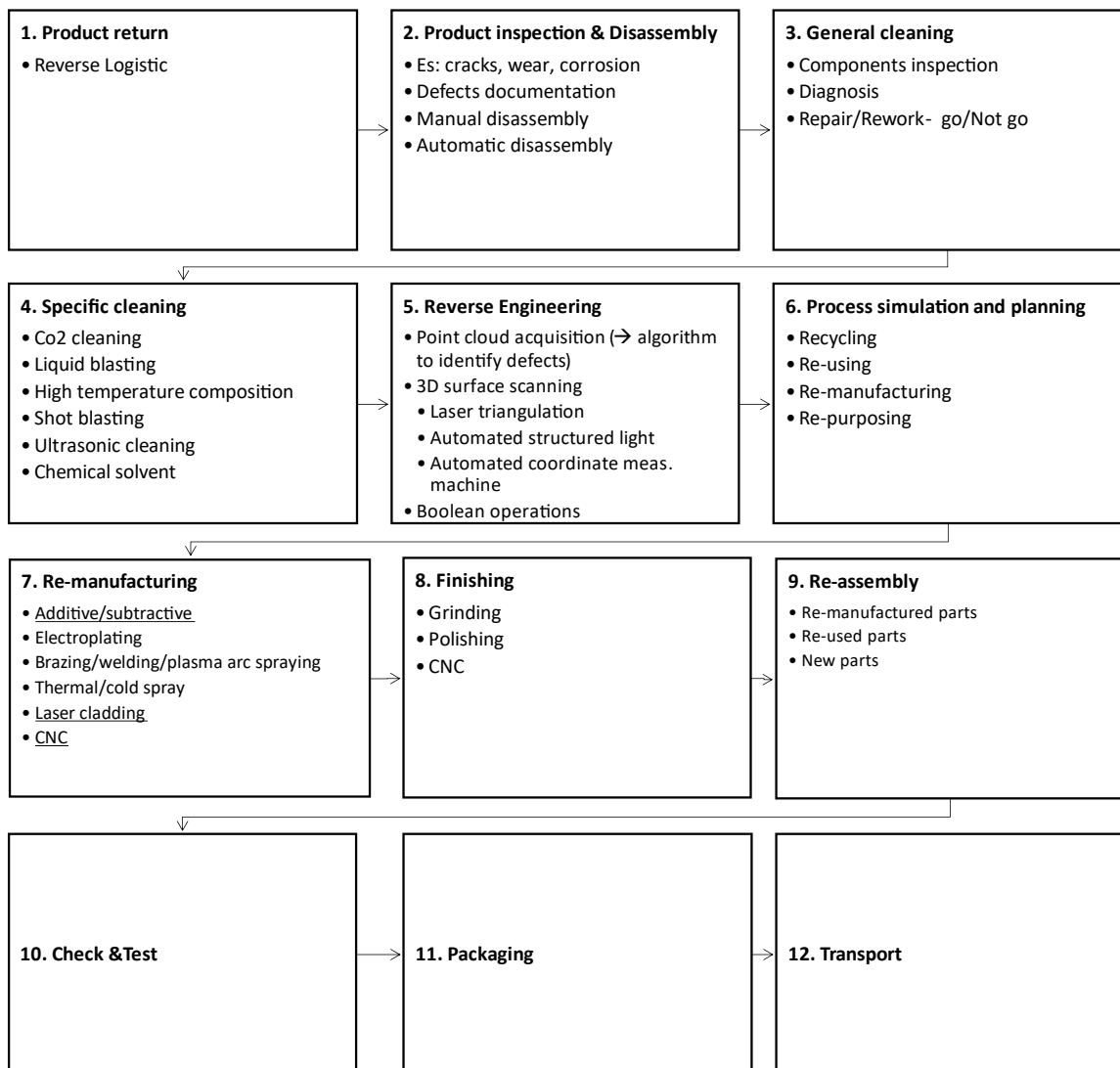


Figure 2.12 De-manufacturing process

According to the disassembly sequence and the nature of the product, disassembly can pull apart modules and/or single components. Disassembly can be either manual or automated. The first one prevails among the non-destructive, while in destructive

disassembly, the automated is more common but related to recycling only (i.e., shredding process). Hopefully, in the future the trend for disassembly will change: automated disassembly lines will then be high in number also to disassemble products aimed to be re-manufactured, re-used, re-purposed, upgraded. Disassembly automation can bring many advantages to disassembly tasks by applying the latest developments in Industry 4.0, especially cooperative and collaborative robots [125]. Some studies induced a physical phenomenon under controlled conditions to ease product de-manufacturing [187] or investigated eco-friendly approaches such as ultrasonic chemical treatment to separate all layers and components of PCBs [10]. Moreover, disassembly processes regarding recycling do not take place at dismantling centers nor the re-manufacturers. Operators' experience plays a vital role for two reasons: i) eases the failure detection, ii) speeds up the decision of latter activities. KETs of I4.0 may help a lot: a good may be provided with identification tags. Information may travel through the tags from OEM to the user and who is responsible for the maintenance and reach the dismantler [188]. Additionally, a vision system along the line may retrieve the operator's workload highlighting defects or, if connected to a neural network, could even autonomously cluster pieces to demolish or save.

2.6.3 General cleaning

Many products may be used under specific circumstances. In certain cases hygiene, temperature, pressure, vacuum, conditions are controlled; other application circumstances may cause the parts to get dirty or dust to deposit on the good. Thus, it is necessary to clean the components, starting from those expected to be re-used, re-purposed, re-manufactured, up-graded. This consists of a rough cleaning, like artificial rinse for the convenience of disassembly and sorting with no expenditure of much energy and materials [189]. After having cleaned the object, the core's re-manufacturing suitability is estimated, and the processes to be used are evaluated based on the inspector's knowledge and scheduling constraints [190]; this is also called the component diagnosis. Finally, the go-not-go decision is taken, estimating the convenience of the process and assigning an EoL policy to each component. At this point the de-manufacturing system becomes specific. Besides the ones already discarded, some may be re-used as they are, and others will need specific cleaning technologies and/or will be slightly reworked before being re-installed. The inspection phase gains access to helpful information; defects and failure documentation, if shared with designers and manufacturers, would be

a treasure for them. Some authors suggest analyzing the failure mode of components, so you will also determine under which conditions they have been used [191]. By collecting and interpreting data coming from dismantlers designers can obtain information about i) which components are most likely to break, ii) how parts reach their EoL, iii) feedbacks regarding disassembly process. Sitcharangsie et al. proposed an interesting classification of decision factors when evaluating whether the part must be re-ordered [192]. The factors can have economic, engineering, legal or environmental nature; results about integrated decision-making were collected, although decisions are often assigned to operators' experience.

2.6.4 Specific cleaning

As previously anticipated, some parts may require specific technologies to remove what remains from the use phase, such as paint, carbon deposit, grease, and rust. This process paves the way to examine the wear pattern, failures and microcracks and determine the parts' re-manufacturability [193]. Deep cleaning can be manual or with machinery. In both cases, cleaning costs must be analyzed to evaluate the impact of depreciation or labor; the latter can reach up to 30% of the total de-manufacturing cost [194]. There are six most recurrent cleaning techniques; they may be polluting and thus reduce the environmental benefits of de-manufacturing. Research has been done in these field and developed new technologies.

- i. High-temperature composition is suitable for iron casting, but metal with low melting point; the process can last up to 16 h; using air and working at 315- 530°C it changes the physical properties of fouling and heat decomposed the structure [189], [195].
- ii. Shot blasting cleans components applying mechanical principles: it is good for removing rust or paint coat by casting surfaces; with similar mechanism of shot peening [59] it utilizes frictional force between abrasive and component surfaces and remove contaminants [196].
- iii. Supercritical CO₂ cleaning is suitable mainly for heat-sensitive and precision metal parts or Printed Circuit Boards (PCB) recycling. It works with a cleaning agent at about 65-85°C for less than two hours and lets the fouling dissolve and disperse into the supercritical CO₂; the bubble burst effect then cracks the contaminants [196]. This technique is relatively recent and, together with liquid blasting cleaning, is replacing high-temperature decomposition and shot blasting.

- iv. Liquid blasting; blasting to remove surface contaminants can be both dry and wet [194], [197]. The liquid one makes use of a flow of high pressured water borne abrasive, with no media impregnated into the component; it is specific for paint or rust removal, less successful with greasy surfaces.
- v. Ultrasonic cleaning is one of the most environment friendly cleaning techniques; on the other hand, it requires more experience setting the cleaning parameters [192]; it uses ultrasounds to enhance and intensify the cleaning process by producing imploding bubbles.
- vi. Chemical solvent cleaning is suitable on most surfaces, depending on the solvent used. For example, it produces good results on PCBs, through the dissolution of brominated epoxy resin and makes the separation of layers feasible; it can also be combined with ultrasonic treatments [10].

2.6.5 Reverse Engineering

As more specifically explained in the following steps, many re-manufacturing activities are automated; for example, they are carried out by CNC machines, whose tool path needs to be planned, starting from the CAD model. Clearly the original CAD model (assuming available) cannot be used since it would not contain the information related to the defect that occurred during the use phase. Therefore, it is necessary to generate a new model starting from the physical object [198], [199]. Reverse engineering comes to help; the main steps are: i) point cloud acquisition by ii) 3D surface scanning and then iii) Boolean operations. The point-cloud form of the object is the scanning output, usually realized by three-dimensional scanning methods: laser triangulation, structured light, and probing methods [200], [201]. Once the digital twin of a real object is obtained, it is time to compare this model (As-is) with the original one (To-be), usually by Boolean operations. Yang et al. call the original digital design of the part the golden sample or nominal data [35]; the geometry difference between the golden sample and the model of the used product represents the repair volume [202].

2.6.6 Process planning and simulation

Two levels of planning can be defined: one regarding the EoL policy, and the second one is related to specific activities for each EoL strategy. For example: all parts that must be re-used are ready to be re-assembled. Depending on the BM, goods can be transported and/or stored in warehouses (waiting for a new product to be installed in) or left aside just for the time needed to re-manufacture or receive other components to be installed in the

same assembly they came from. If parts are repurposed, they will be installed in new products fulfilling new needs [35]. When a product has a too low retained value, recyclers will try to preserve it as much as possible by sorting its material as the best of their abilities.

This step is the core of de-manufacturing since multiple options are analyzed and evaluated for components. The system is often addressed as re-manufacturing, but this contrasts with the well-accepted re-manufacturing definition as a process of returning used products to at least as good as new condition [57].

Compared with other EoL strategies, re-manufacturing is one of the most time-consuming and labor-intensive, for sure the less projectable. Literature has been very active and prolific on this side. Cues and results were collected and explained over the next two steps. He et al. aim to identify a customized Re-manufacturing Process Planning (RPP) to tackle the individuality of returned used products [59]. History and experience may be very convenient: by using Case-Based Reasoning (CBR) the most suitable re-manufacturing solution is determined quickly and effectively by retrieving past cases from case DB, which contains process planning information for the re-manufacturing of previous cores [57]. Fuzzy logic can also be helpful to determine the best re-manufacturing technology [194].

2.6.7 Re-manufacturing

Additive techniques and the opportunity to join additive and subtractive processes in a single operation flow boosted re-manufacturing, enabling many components to be restored for a reasonable price [203], [204]. In the following, the technologies that according to literature are most eligible for an efficient re-manufacturing process are presented.

1. Electroplating: this restoring method belongs to the electrochemical deposition method: it deposits the metal ion from the electroplating liquid on the surface of waste component. Besides the high electric current and voltage required, there is also the relative velocity and pressure between the Electroplating Brush (BE) and the surface of the wasted part [205]. Developing a comprehensive MCDM approach for the application to the re-manufacturing process, the authors considered the environmental impact, economic cost, and technical property. They also applied the fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) approach to select a proper restoring technology. Their final results indicated BE as a preferential ranking. On the

other hand, Yao et al. claimed deficiencies of electroplating for their application, because they observed that electroplating has poor bonding, insufficient wear resistance and limited thickness [206].

2. Welding is a common technique to apport new metal to a used part, by melting and depositing with welding robots. There are different welding techniques appropriate for re-manufacturing, such as brazing [201], Plasma Spray (PSp) or wire welding [207]; the latter is one of the most popular whilst machining of the worn surfaces to create the original geometry and surface roughness is often required for the repair of stamping forming molds [208]. Plasma arc uses the plasma arc as a heat source to melt the alloy powder and substrate, which will form a new alloy layer [209].
3. Cold spray is a valuable alternative to mainstream welding techniques [199]; its advantage is the minimum thermal stress over fusion welding techniques because it is a high kinetic energy coating process and operates at room temperature and does not involve the melting of materials [201], [208]. Furthermore, as the particles accelerated to very high velocities by a supersonic compressed gas jet remain in the solid state and are relatively cold, they impart slight oxidation to the substrate material. Meanwhile, low temperatures also resulted in compressive residual stress, low porosity and little thermal degradation of the coating and substrate materials, all desirable characteristics that cannot be achieved using thermal coating processes.
4. Laser cladding is a re-manufacturing technique utilizing a laser heat source to deposit a thin layer of the desired metal on a substrate, which can produce a better coating with minimal dilution and distortion, and better surface quality [206], [210], [211]; the authors deeply investigates crack formation and surface porosity in order to contribute to process optimization of laser cladding; similarly did Zhu et al. on a broken steel gear tooth [212]. It has been proved that a re-manufactured component via laser cladding has a lower environmental impact than a brand new [197] and impacts have also been compared with other re-manufacturing techniques [205].
5. CNC like boring, turning, gross grinding, slotting etc. are often used in re-manufacturing [205], [213]. Their advantage over other processes is the experience gained with time by an organization; however, there must be consciousness that re-manufacturing must not necessarily follow the manufacturing process path.

RPP highly alters the re-manufacturability of a product [212], [213]: quite a big issue of re-manufacturing process planning lies in establishing which activities come first,

especially when it comes to hybrid processes. Hybrid processes consider both AM and subtractive manufacturing to provide a more flexible, capable, and efficient manufacturing approach, which makes full use of the individual processes' advantages [201], [204]. It is potentially very successful but still faces challenges since it requires human intervention to recognize AM or subtracting features. The main steps are: i) intersection part extraction, ii) intersection part modification, and iii) feature extraction. AM features can be geometrical form and dimensions, build direction, starting surface, estimated material to be added, tolerances, etc. Once AM and machining features and their relationships are identified, they are extracted from the technical information of existing and final parts. Finally, an appropriate process is defined for each feature based on its attributes [214].

2.6.8 Finishing

Either a subtractive or an additive technology is chosen, as in primary production, the desired surface quality must be reached in the end; this can require the grinding operation or similar CNC processes or polishing/painting so the component returns to the original appearance and conditions [59], [215].

2.6.9 Re-assembly

In the re-assembly phase, components/modules are brought together to form a finished product, be it the same di-assembled at stage two or a different one. Finally, the product is almost ready to start a new loop of its MLC; it may be composed of components/modules that are i) used, ii) used and re-processed, or iii) new [216], [217].

2.6.10 Check & test

Once the product has been equipped with all modules, quality and functional tests must be conducted to verify that the re-manufactured product has reached a like-new condition [218].

2.6.11 Packaging

As for first the manufacturing process, the final product is packed to safely reach the new destination where it will be used, sold, or installed.

2.6.12 Transport

The last steps are the same as the linear economy paradigm; nonetheless, literature specifies them in de-manufacturing systems to ensure their evaluation. Transport alongside Forward Supply Chain (FSC) and RL could have a high environmental or

economic impact on de-manufacturing systems at a point to make them not viable anymore.

The multiple kinds of transport is a non-neglectable factor: since each module/component can follow a different route (i.e., some are re-used, some re-cycled) there are multiple transport steps, depending on the outsourced activities of EoL.

2.7 How companies are carrying out L2C transition

The present section concerns the investigation of real, well-established or in the state of running projects, implementation of de-manufacturing and CBM. Multiple papers related the importance of design in setting up a circular system, following the economic issues to overpass to support customer relationships and behavior and properly manage de-manufacturing processes.

Industrial scouting has been carried out for two main reasons:

- Compare how academics and industries have faced the shift from Linear to Circular;
- Compare the results achieved, evaluating if there has been cooperation between them.

When it comes to CE, despite the customer, three primary actors take the stage: i) OEM, ii) outsourced re-manufacturer and iii) IR [217].

- OEMs are all the original producers and in traditional selling models, they own the products until they are sold (to a retailer or the customer). Sometimes they are re-manufacturers themselves. Since they master the process for the initial product to commercialization, they have the expertise and know the valuable information for re-manufacturing; moreover, they gain benefits out of re-manufacturing, such as material, labor and energy savings, while creating new market opportunities and positive social image [121].
- Outsourced re-manufacturers are one kind of third-party re-manufacturer; they carry out operations under contract from either the customer or the OEM (who continue to own the product). There might be close cooperation between outsourced re-manufacturer and OEM (for example, delivering information and training workers).
- The second type of third-party re-manufacturer is the IR, who buys the used products from users and re-manufacture and re-sells them. However, unlike the previous one, there is no cooperation with OEM. Therefore, there may be conflicts of interest indeed.

CE is receiving increasing attention worldwide to overcome the current production and consumption model [159]; it requires companies to rethink their supply chains and BM [11]. The traditional machinery supply chain approach does not feel any responsibility for EoL products. The reverse supply chain that is slowly making its way tries to account for EoL products in the most environmentally friendly manner possible [12]. Sustainable EoL management can be enabled by a durable design and many optimizations of maintenance, repair, re-use, re-manufacturing, refurbishing, and recycling strategies. The main goal should be to launch a product in a MLC loop [14], where recycling concerns a minimum percentage of the product, and is more efficient [42] as goods are designed for this purpose [16], [17]. De-manufacturing is the sustainable approach that encompasses all the EoL strategies and requires reasonable design decisions from the very early stage [6].

BM can ease or obstacle products circularity; over the last decades a multitude of innovative, sustainable BMs has arisen, and launching a product now requires also to identify which BM most appropriately creates, delivers, and captures economic value while simultaneously contributing to environmental and/or social sustainability [82]. There are several methods to assess the circular performance of a system [50] and several frameworks and new practices have been developed to assist organizations in the implementation of circular products and processes [118]; ReSOLVE is one of the most frequently used [91].

In their review, Fontana et al. [219] pack up the field of CE and Life Cycle Extension Strategies (LCES) through a revised taxonomy. They placed new strategies and methods in their deserved place. The authors outline that several obstacles relate to the EoL management, such as the product return via the RL, its inspection and disassembly, activities concerning cleaning, re-manufacturing, re-assembly and reintroduction to the market. There are multiple aspects to be considered, such as product and volume uncertainties, design constraints, brand reputation, Intellectual Property (IP), etc. [83]. Several technologies were born to specifically treat goods at their EoL [128], [187] - especially when it comes to recycling and material treatments and breakdown [187]. At the same time, manufacturing processes technologies combine subtractive and additive ones [217].

Nowadays shopfloors are pervaded with multiple tools intended for digitalizing products and processes. KETs such as big data, cloud technology, Artificial Intelligence

(AI) and Machine Learning (ML), enhanced robotics, data analytics, 3D printing, blockchain and I4.0 are disrupting industrial businesses on a vast scale [220] and are boosting the development of systems that monitor industrial processes and prevent machines downtimes. KETs can support workplace monitoring and improvement [167]; collaborative robotics enables the meeting between the skills expressed by operators and robots [221]. Besides all potentialities brought by KETs, there is the need to find convergence between digitalization and sustainability from a managerial perspective [222].

There are not many cases in which a BM has completely replaced the old one: either organizations found a loophole to make their business greener without interfering with their customer relationship, or they opened new market channels, coexisting with the traditional ones. The construction sector is maybe the most outstanding example: together with selling new machinery, Liebherr is now providing their customers fleets for hire too, together with the fleet management system – LiDAT. The benefits are multiples: Liebherr machinery may require high initial investments; the OEM does not encounter the risk of cannibalization since companies that often make use of specific machinery would buy them as well; by letting them be rented, Liebherr can reach all the construction companies that would not stand the investment. Acting in this way allows the company to extend its market shares while ensuring greater management of resources: the OEM owns the machinery for the whole time and is responsible for punctual maintenance; the product life cycle is elongated and resources saved. Liebherr has been extending the re-manufacturing program over the last decades and can now offer different options for certain ranges of components, such as exchange, general overhaul and repair². Likewise, Hilti is similarly managing its portfolio, optimizing the repairing process and providing equipment at monthly, fixed fees and guaranteeing full-time tools availability, also in case of damages or less effectiveness³. The threat for OEMs is that possible independent organizations on their own provide a similar service, i.e., the Finn company eRent⁴. The construction sector is putting much effort into combining economic and environmental sustainability. Many companies realized that firms' environmental responsibility is not inconsistent with the creation of economic value and that re-manufacturing generates

² Liebherr. (s.d.). *Rental services for construction machines*. Liebherr: <https://www.liebherr.com/en/usa/about-liebherr/service-services/service-services.html>

³ <https://www.hilti.group/content/hilti/CP/XX/en/services/tool-services/fleet-management.html#nav/close>

⁴ eRent: <https://www.arent.fi/en/>

higher environmental gain than recycling. Caterpillar perceives re-manufacturing as a new era of profitability. CAT REMan is an IR division that generates up to 8% of the total revenue and also established a proper program - Cat Certified Rebuild- that guarantees the quality of re-manufactured products⁵.

When approaching the new paradigm of CE, each company evaluates which solution best joins environmental benefits with overall revenues. Some focus only on cores or parts with high added value, while other practice the Extended Producer Responsibility (EPR) by (re)working the whole product. Bosch, with the Bosch eXchange program, is making repair shops of common rail components more and more competitive, both in time and costs terms⁶. In its re-manufacturing plan, Volvo trucks gives a new lease of life to worn-out engines for heavy-duty trucks, bringing them to like new condition passing through a less impacting process⁷. French-based Schneider Electric employs 142,000 people, it uses recycled content and recyclable materials in its products, prolongs product lifespan through leasing and pay per use, and has introduced take-back schemes into its supply chain. Circular activities account for 12% of its revenues⁸. Valtra is one example in agricultural machinery that provides customers with spare parts, new and/or re-manufactured⁹; they also rely on outsourced re-manufacturers like SR Harvesting OY¹⁰.

There are sectors in which customers or product functionality are unwilling to give up on traditional design, or products have such long use phases that sustainable issues did not take part in the design process when they were designed. As much value as possible out of them with proactive approaches is exploited. The case of aircrafts is an example: from PAMELA and AFRA projects, responsible for studying the potential benefits from recyclable materials in aircrafts^{11,12}, a de-manufacturing hangar came out: Tarmac Aerosave is now the company in charged to disassemble aircrafts, sort and trace their parts intended to be recovered¹³. Smartphones, tablets and laptops are instead part of the first case: here, design is still too focused on functionality and aesthetics and there are

⁵ Caterpillar. (s.d.). *Cat Reman*. <https://www.caterpillar.com/it/company/brands/cat-reman.html>

⁶ Bosch. (2014). *Bosch eXchange*. https://www.boschaftermarket.com/xrm/media/images/country_specific/it/xx_pdfs_28/parts_5/gamma_bosch_exchange.pdf

⁷ Volvo. (2018). *Magazine - online*. Volvo trucks: <https://www.volvotrucks.com/en-en/news-stories/magazine-online/2018/may/remanufacturing-engines.html>

⁸ Scheider Electric. (s.d.). *Scheider Electric*. <https://www.se.com/uk/en/>

⁹ Valtra. (s.d.). *Parts and services*. <https://www.valtra.co.uk/service/services-and-repair/spare-parts.html>

¹⁰ SR Harvesting. (s.d.). *Recycled parts*. <https://www.srharvesting.fi/valparts>

¹¹ Airbus. (2012). *Process for Advanced Management of End-of-Life of Aircraft*.

¹² Costes, B. (2007). *PAMELA - Process for Advanced Management of End of Life of Aircraft LIFE05*.

¹³ Tarmac. (s.d.). *Tarmac*. <https://www.tarmacaerosave.aero/about-us>

almost no traces of design for de-manufacturing. There are isolated exceptions, although they are not the standards yet; the Fairphone case: to minimize resources exploitation, the phone is not provided with any charger nor headphones and the smartphone is made out of modules, making the product easily repairable even for not experts¹⁴. Hyla Mobile re-manufactures common mobile phones, giving them new life (lives)¹⁵; similarly Taitonetti finds new application for old business computers, selling them to privates¹⁶. When re-introducing IT products into the market, it is crucial to guarantee that all sensitive data from previous owners are destroyed; there are companies specialized in these activities like CCL North¹⁷ and 3 Stepit¹⁸. To withstand regulations, organizations in this sector mainly address disassembly and recycling: Apple built two robotic cells, called Liam¹⁹ and Daisy²⁰, intending to disassemble specific models of smartphones and get as many components out of them: the disassembly process is highly efficient since a robot is designed for only specific products; however, time this is not an excellent example of life cycle thinking [78]. Sony shortened the distance between OEM and recyclers by suggesting designers to disassemble themselves the products they design [145]. Over the last years, targets have been set²¹, but a proper circular system is still far, despite the results achieved^{22,23,24}.

The world of printing has been the leader for ages in re-manufacturing and PSS practice, starting from the single-use, almost entirely re-manufacturable and recyclable cameras of Kodak [223]: it was a starting point for the company that still today is engaged in findings new means to be more responsible, without letting down quality²⁵; examples

¹⁴ Fairphone. (s.d.). *Fairphone*. <https://www.fairphone.com/it/impact>

¹⁵ Hyla Mobile. (s.d.). *Hyla Mobile*. <https://www.hylamobile.com/#content3>

¹⁶ Taitonetti. (2017). https://taitonetti.fi/index.php?route=blog/article&path=2&article_id=15

¹⁷ CCL North. (s.d.). <https://www.cclnorth.com/>

¹⁸ 3 Step it. (s.d.). *Acquire Manage Refresh*. Tratto da <https://www.3stepit.com>

¹⁹ Apple. (2016). *An Innovation Story*. https://www.apple.com/environment/pdf/Liam_white_paper_Sept2016.pdf

²⁰ Apple. (2018). *Apple adds Earth Day donations to trade-in and recycling program*. Daisy: <https://www.apple.com/newsroom/2018/04/apple-adds-earth-day-donations-to-trade-in-and-recycling-program/>

²¹ Philips. Decoupling growth from resource consumption. <https://www.philips.com/a-w/about/sustainability/circular-economy>

²² Hp. (2019). *Sustainable Impact Report*. <https://www8.hp.com/h20195/v2/GetPDF.aspx/c05179523.pdf#page=13>

²³ Dell. (2018). *Design for Environment*. <https://i.dell.com/sites/content/corporate/corp-comm/en/Documents/design-for-environment.pdf>

²⁴ Motorola. (s.d.). *Corporate Responsibility*. <https://www.motorola.com/us/about/corporate-responsibility-recycling>

²⁵ Kodak. (2017). *Corporate Responsibility Report*. <https://www.kodak.com/content/products/brochures/Company/Kodak-2017-Corporate-Responsibility-Report.pdf>

of Xerox²⁶, Canon²⁷ etc. describing the success of their take-back programs (with related re-manufacturing of multifunction, recycling of consumables) are strewn all over literature [122], [164]. Additional examples of implementation of CE concern biofuel made out of waste²⁸; many cases involved batteries²⁹. Additionally, attention is paid to responsible packaging³⁰ that becomes returnable instead of being disposed³¹; the original materials of tyres and asphalt³² are widely revisited and replaced with greener ones, coming from products of extremely different supply chains³³ or vice-versa, as are the cases of Eldan Recycling³⁴, Lehigh Technologies³⁵ or Timberland shoes soles³⁶.

2.8 Environmental sustainability assessment

The LCA is one of the most recognized and applied methodologies to quantify the environmental burden of products and services objectively. Multiple tools support the application of the methodology. However, the tools' sensibility and the choice of temporal and geographical system boundaries may limit a faithful representation of the analyzed case. LCA quantifies potential environmental impacts and the resource use throughout a product's life cycle: from raw material acquisition via production and use phases, to waste management [224]. Following UNI EN ISO 14040³⁷-44³⁸ four are the main steps of LCA: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and interpretation. However, the stakeholders the analysis is provided to, the chosen system boundaries and the quality of selected data may yield different results for a single functional unit (FU). The nature of the analyzed product, process or service plays a significant role too. In this sense, Depping et al. [225] focus on fractionated products that result from multi-product processes in which several products are created

²⁶ Xerox. (s.d.). Prevent and manage waste. <https://www.xerox.com/en-us/about/ehs/reduce-waste>

²⁷ Canon. (2019). Environmental circulation <https://global.canon/en/environment/circulation.html>

²⁸ Enerkem. (s.d.). Carbon Recycling. <https://enerkem.com/process-technology/carbon-recycling/>

²⁹ Clarios. (s.d.). The clarios difference. <https://www.clarios.com/products>

³⁰ AB InBev. (s.d.). Driving Sustainable Packaging. <https://www.ab-inbev.com/sustainability/2025-sustainability-goals/circular-pakaging.html>

³¹ Re Pack. (s.d.). Upgrade your unpacking. <https://www.originalrepack.com/>

³² Toner Plast. (s.d.). Cloose the loop. <https://www.closethe-loop.com.au/tonerplas/>

³³ Williams, C. (2015). MGMT7. South Western - Cengage Learning.

³⁴ Eldan Recycling. (2012). The best of tyre recycling. https://www.eldan-recycling.com/sites/default/files/BR_Tyre_1203_EN_r6_low.pdf

³⁵ Lehigh technologies. (s.d.). Micronized rubber powders. https://lehightechnologies.com/what_we_do/the_business_we_are_in/#gallery

³⁶ Timberland. (s.d.). Drive. Recycle. Wear. <https://www.timberland.com/blog/archive/timberland-tires.html>

³⁷ <https://store.uni.com/uni-en-iso-14040-2021>

³⁸ <https://store.uni.com/uni-en-iso-14044-2021>

simultaneously. In order to compare with the aid of LCA fractionated and non-fractionated products, the authors develop a generic scope-definition framework for multi-product processes. The authors state two main issues arise when applying LCA: FU definition and by-product handling. Therefore, they consider the potentials and limitations of ALCA and Consequential LCA (CLCA) and address the choice of an appropriate FU and allocation method.

2.8.1 LCA and households

The LCA method and tools have been applied since the end of the 90s in the assessment of electric and electronic devices, investigating most of the time specific types of appliances [226]–[228]. In their study, Hirschier et al. [229] systematically analyzed the environmental impact of 14 different household appliances to evaluate environmental hot spots and to understand benefits deriving from the implementation of “future scenario”, such as i) use of a more renewable electricity mix, ii) increase of efficiency, iii) increase of re-manufacturing and re-use rates, iv) increase of collection and recycling rates. Due to electricity use, the calculation results confirm the high relevance of the use phase over all the other life cycle phases considered. Within the use phase, the energy efficiency of the products as well as the consumer behavior (i.e., intensity of use) are the two main factors that determine the impacts. The study aims at assessing the potential environmental impacts of the consumption of an average European citizen and refers to a Basket of representative Products (BoP) purchased and used in one year.

The literature about household appliances is broad. Products such as refrigerators, water-heating boilers, air conditioners, cooker hoods, kettles and vacuum cleaners were analyzed. LCA methods and tools are also used to compare and analyze the differences in environmental terms of several products realizing the same function. Three main topics are covered: life cycle environmental impact evaluation by LCA, inclusion in LCA of emerging technologies and energy mix evolution and evaluation of environmental impacts of different EoL scenarios (i.e., recycling, re-use, re-manufacturing). Choi et al. [230] proposed and implemented a method to evaluate the environmental effects of household refrigerators in terms of Life Cycle Climate Performance (LCCP). The energy consumption model of the refrigerator is developed with three types of typical single-evaporator refrigerators. Xiao et al. [231] quantify the environmental impacts of recycling refrigerators under different scenarios through a comparative LCA. Baxter [232]

compares of EoL options for domestic refrigerators, specifically material recycling or product refurbishment and re-use, from the environmental impact perspective.

2.8.2 LCA at the base of design

LCA represents a solid and consolidated methodology to assess the environmental impacts of products/services or processes. Primitively, LCA was chiefly utilized for analyzing product systems and comparing them with one another. However, in the last few years, the utility of LCA has expanded multifold, be it infrastructure planning or government policy [233].

Today, data integration is the only question faced when the environmental sustainability issue is analyzed in correlation with CAD/CAM tools and/or KBE systems. The role of knowledge became predominant, and several works have been developed to extract and represent product-related information in a formalized format [234], e.g. OWL (Ontology Web Language), SWRL (Semantic Web Rule Language). In addition, research interest in the integration of CAD and LCA tools is growing [235]. When integration is achieved, it regards the LCI phase, i.e., to facilitate the data collection and related modeling phase inside the LCA tool: CAD-LCA data exchange plays a role in integrating progress [155]. Fang et al. [236] presented an approach for the machine design and analysis within the CAD/Computer Aided Engineering (CAE) environment, as well as Landi et al. [153], aimed at integrating simulation results and environmental data. Russo and Rizzi [237] proposed a computer-aided methodology based on integrating structural optimization and the LCA tool. Tao et al. [238] proposed a life cycle modeling approach based on a feature mapping scheme between product, operation, and inventory to address the discrepancy in the principles of the utilized methodological approaches of LCA and CAD/CAE and enable data transformation between CAD/CAE and LCA models.

2.8.3 LCA: Micro and Macro-system approach

A variety of LCA approaches is available in the literature; the most known and discussed in the literature are ALCA and CLCA [239], [240]. According to Finnveden and Potting [241], ALCA is defined by its focus on describing environmentally relevant physical flows to and from a life cycle and its subsystems. CLCA is defined by its aim to describe how these flows will change in response to possible decisions. More in detail, UNEP's global guidance principles for LCA DBs³⁹ defines CLCA as a modeling

³⁹ UNEP (2011), "Global guidance principles for life cycle assessment Databases - A Basis for Greener Processes and Products", Shonan.

approach that provides information on the environmental burdens that occur, directly or indirectly, because of a decision, generally represented by changes in demand. This definition paves the way to a much broader perspective, where processes and flows that influence the product lifecycle are considered, and the geo-political and socio-economical plots have their role in the analysis. It is thus reasonable to affirm that the CLCA is a macro-systemic approach, while the classical ALCA is generally applied at a micro-system level [242]. Putting the concept into practice implicates an extension of the system boundaries.

A second, practice, implication of the definition of CLCA is that the additivity-restricted mathematical model (linearity), typical of ALCA, is more likely replaced by free mathematical modeling (non-linearity) [243]. There are also linear models suitable for CLCA; however, those roughly approximate the analyzed case. One example is the consequential datasets of the Ecoinvent 3 (or superior) DB. Their main limitation is their static nature: even if they are willing to describe a future condition, they do not contemplate different conditions according to a chosen timeframe.

System Dynamics (SD) is a mathematical modeling method based on integrating multiple system elements in a network, usually composed of feedback loops defined by differential equations; besides its potentialities, there are conflicting opinions regarding its application, which may be a quite complex implementation [244] at the point that the use of Geographic Information Systems (GIS) is recommended to integrate the modeling of LCI. In their review Mc Avoy et al. [245] investigate the available literature about the integration between SD and LCA; two main approaches were identified. However, disadvantages of combining SD and LCA were reported as their integration may not yield results significantly different from LCA alone in relatively static or slow-changing systems. This ends up as an increased complexity despite a lower result detail increase. The discrepancy between the ALCA and CLCA emerges from the literature. The first focuses on the product, appearing short-sighted and isolated from the surrounding evolving system; instead, the second is willing to include the consequences of the surrounding system evolution in the FU lifecycle by a much complexity analysis. The trend is to employ CLCA when dealing with long-term analyses: referring to the construction sector, Almeida et al. [240] retrieved 13 out of 25 works referring to a long-term time horizon. It is essential that LCA also encompasses all aspects of the product lifecycle, including those not desired. For example, a product may worsen its performance

during the use phase (i.e., wear, components) for several reasons. Many researchers focus on the worsening behavior of materials and components with time; however, few correlate this to the lifecycle impacts assessment of the product they may be installed into.

2.8.4 LCA as a starting point, rather than a destination

Life Cycle Thinking (LCT) and LCA are essential for informing decisions comprehensively and holistically in both business and policy contexts [246]. LCT, LCA, LCC, and Product Environmental Footprint (PEF) have faced a remarkable evolution in policies and communications: their implementation increased tenfold in the last three decades [247]. Life cycle-based policymaking in the future must also address the means to implement policies (e.g., incentives, legislative obligations and thresholds) based on LCA results [248]. Several indexes are now based on LCA results, such as the conjoint economic-environmental indicator proposed by Fregonara et al. [249] and the Recyclability Benefit Rate (RBR) [250].

Concerning more limited realities, the LCA is acquiring a more decisive role in the product and process design too: design strategies are tested, and environmental benefits are highlighted thanks to LCA analysis [251], [252] or design strategies are defined according to the obtained results [253]. Consequently, the LCA results need to be assessed very accurately otherwise governmental and industrial decision-making processes would rely on an unstable basis. For example, taking the construction sector as an example, Säynäjoki et al. [254] outlined that the literature consists of highly varying results between the studies, even when the analyzed units are very similar. The authors add that this makes it doubtful if LCA can produce reliable data supporting policy-making.

Ensuring environmentally sustainable production and consumption patterns is becoming an increasingly relevant need for most societal actors (primary industries, citizens, businesses, policymakers, third sector organizations, etc.) [255]. Therefore, the need to link environmental sustainability with multiple strategies emerges in the CE, such as recycling, re-using, re-manufacturing and lifetime extension for impact reduction.

2.9 Main findings

Through the CREDIT analysis, the main criticalities concerning the practical implementation of de-manufacturing systems were clustered in seven factors and 18 sub-factors were identified among them. Moreover, the CREDIT analysis quantitatively

evaluates the urgency for specific topics to be addressed by the academy on 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 encompass technical/technological aspects (i.e., recycling/re-manufacturing technologies, materials) and economic and social matters (i.e., cost of activities for EoL management, governance, second life market). The analysis identified a need for solid 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 designers can develop a LCT by using tools and applying the “learning by doing”. By acting on design and supported by useful and integrated tools, OEMs and researchers can reach for something more significant, such as foreseeing and getting prepared for tighter regulations, involving customers in a sustainable close loop, introducing 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 LCT 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 de-manufacturing, although the experimented case studies are confident in pursuing this direction. Nevertheless, a big effort must be made to harmonically introduce KETs in shopfloors to the operators and enable the feedback to return to designers. A de-manufacturing system necessarily shapes a business to be circular; consequently, an obstacle to its implementation hampers many 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, AI. They can establish a connection between the two phases; this 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; in addition to that, 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 on 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 [256] that outline the main gaps. The first is the insufficient evidence of Additive Manufacturing (AM) for low-value mass re-manufacturing and the little consideration given to the exploitation of the data carrying opportunities to smart products for re-manufacturing. Secondly, concerning the equipment, they report that there are few demonstrations of existing smart I4.0 technologies (already used in manufacturing) applied to re-manufacturing, nor virtual product/process twins nor big data could for re-manufacturing. Finally, although not investigating I4.0 KETs, Bagalagel and El Maraghy [257] propose a mathematical model aiming to determine the optimum manufacturing/re-manufacturing product mix that maximizes the company's 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 academy's support 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 (i.e, use in new products, biobased materials) to lower Earth exploitation and decrease the dependency on world sources of critical raw materials. Furthermore, 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 LCT 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 of all the CREDIT analysis factors is the need for research and applications in all R-strategies since re-manufacturing, repair and re-use occur one order of magnitude less frequently than recycling. Furthermore, in the complex systems where products are currently designed and commercialized, the innovative ways products are designed, require widening the point of view, involving not only the product but also the way it is commercialized and released to the customer. The conducted research in the world of de-manufacturing has drawn out many challenges and obstacles; applying CE concepts in a company means dealing with copious different aspects, often new for the organization. Figure 2.13 shows the main critical aspects detected and elaborated by the reviewers from the analyzed documents. At first sight, the reader can guess the wideness of decisions and actions required when establishing a de-manufacturing system all around a product. LCT is the required approach to becoming mindful of the importance of design decisions and their subsequent effect on the environment. However, up to now, this is still overwhelmed by traditional design drivers, such as functional, geometrical, assembly or economic constraints. What could help to raise this mindfulness? How can environmental sustainability drivers be prioritized till their importance is equal to the traditional ones? So far, two main strategies seem to be the way:

- Tighter regulations: as soon as it becomes an obligation, then an argument ascends the priority scale;
- Customer requirements: companies try to fulfill their expectations as users become increasingly sensitive to environmental aspects.

The research that analyzed the most effective methods and tools provided to designers highlighted multiple solutions, but not of them has replaced the others or succeeded as the best suitable one [124].

When studying how to make a linear system circular, several factors would lead to complications if not adequately planned and at the right time.

2.9.1 Reverse Logistics

In a de-manufacturing system, in order to have modules and components analyzed, cleaned and directed to the proper path of EoL the product must go back to where these

activities are carried out: this may be the same or different OEM site, or the outsourced re-manufacturer, the dealer (and then the factory).

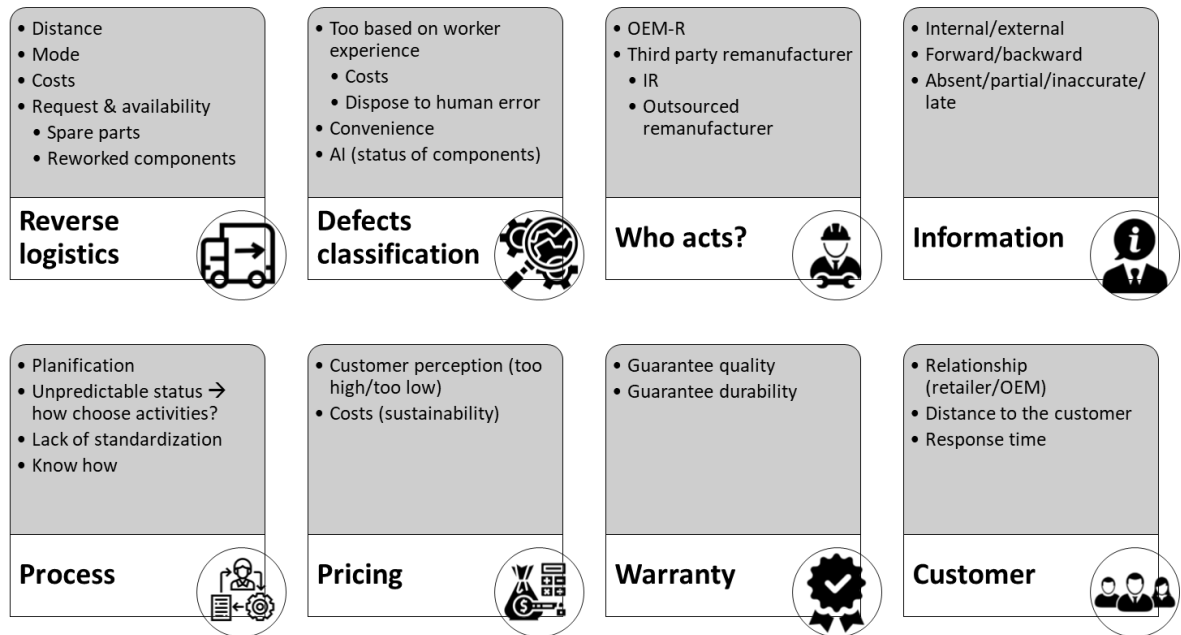


Figure 2.13 Challenges and fields to be investigated

To make RL economically feasible many factors must be optimized: i) consider the distance the product covers from the user to the facility to be reached; ii) which means of transport it will travel by (road, rail, air transport or ship), iii) how often a batch will be shipped, iv) who pays for the shipment (is the customer charged since the purchase of the shipment costs or these should be allocated to the downstream products?), v) carry out stock management, taking into account the quantities of products aimed to be re-manufactured and re-used: will they be enough or additional new spare parts will be required? How to handle the floating availability of re-worked modules/components? – missing, late, defective, and non-available spare parts are a big challenge for re-manufacturers [258] vi) how much does the core acquisition cost? [110], [192].

2.9.2 Defect classification

Defect classification is a crucial point in a de-manufacturing process, since the entities of the defects determine if a piece can be re-used, re-manufactured or must be discarded or employed in different sectors. The reconditioning process should first use product design engineering requirements to evaluate a regionalization of defects per engineering surface and then criticality rank an assessment of the defects [259]. Most of the time, the decision is up to the worker experience: an extensive human intervention is required for

feature recognition and knowledge interpretation [151], and makes the classification costly and vulnerable to human error. In this field AI can be mighty in detecting and clustering the status of components and making processes much more flexible [98]; in this case investment and training costs may be very high. When reaching the EoL, a single module or component could be feasible for one of multiples different strategies. It is not convenient to take into account an excessive number of EoL strategies to which redirect the incoming parts; the most likely ones will be selected as options to consider depending of what is foreseen at the design stage and when optimizing the de-manufacturing system. By doing so, the classification would be more straightforward, and each cluster is guaranteed to have a consistent number of parts.

2.9.3 Who acts?

As mentioned in the first point, it is important to plan who will be designated to handle the product at the EoL. The OEM is a great candidate to take back the product it introduced in the market and give it a new life; then the OEM can become re-manufacturer itself, or pass down the task to a specialized company to handle the case; would then the OEM become the new owner of the object, or rather would it be the external re-manufacturer? In cases where PSS is the chosen BM these argumentations may be skipped, since the OEM remains the owner, even where the product is in the user's hands. On the other side, the OEM must caution about cannibalization [260]: IR, upon which it has no control, would be a direct competitor to de-manufacturing activities; IR could beat the service provided by OEM with their closer relationships with customers because they are located closer to them and therefore, they might be quicker. Cannibalization is challenging to control because it depends on the customer's behavior and preferences.

2.9.4 Information

Information is a sore point in de-manufacturing, even more than it is in traditional manufacturing. For this reason, LCT is eased when the OEM manages the product circularity: information flow is smooth and greater (for example, notions concerning patented modules can be exchanged). OEMs are in a more favorable position than IRs to administrate and enhance information exchange within the value chain [90]. The ideal circular context sees not only goods but also information circulating in the loop: coming from the design office or production site, in the form of users or dismantler feedback, or more, they represent the point of view of maintenance men. Access to good information is a big challenge, since it is often disrupted, uneven, chaotic or inaccessible. Both

forward (from design to use) and backward (from EoL to design) flows face the challenge of increase the quantity and quality of knowledge exchanged. Once again, the KETs of Industry 4.0 may help by connecting realities located far from each other and fastening the exchange of flows. I4.0 shed some light on addressing the re-creation of product knowledge at the product design stage, by improving data transferability and building the knowledge/data-sharing platform [200]. Too often information is retained by value chain actors, such as suppliers that own most of the design information [28]. Suppliers must provide their respective component information for the manufacturer's design for disassembly/re-manufacture/re-use/recycling analysis. Designers can obtain the information to make desirable changes in the early stages of the design.

2.9.5 Process

Activities planning may be a great challenge, as the products status unpredictability may alter predictions [59]; for example, for two same parts disassembled from an assembly intended to be re-manufactured, the succession of additive and/or subtractive required processes for each may not be the same [214], [261], [262]. How to choose which activities to carry on and their sequence? In these cases the best solution is to follow a procedure. There are not any yet, thus, each company can arrange its process: a good way consists of making a forecast of the most common cases and defining a re-manufacturing process suitable for that case. Of course, this neglects the minority of the cases and sends them to lower levels of the waste hierarchy, but this is usually the best compromise.

2.9.6 Pricing

In this section reviewers will not just remind companies to design economically sustainable processes, since it is innate in their everyday operating. This requires comparing the price of the traditional process to the costs related to de-manufacturing activities. More aspects, apparently secondary, are not to be neglected: what view does the customer take on a re-manufactured/used product? He can consider the price too low or too high than its perception of quality and performance[263]. For example, when the re-manufactured or used product has a much lower price than the brand-new, the user may think that it does not reach the characteristics of an "original" one [217]. On the other hand, he may be unwilling to buy a used product for a price that does not differ from the new object's price. Therefore, market research is fundamental in order not to jeopardize all efforts put in setting the machine of de-manufacturing when it comes to (re)selling the product.

2.9.7 Warranty

There are a few alternatives to ease customers to accept the price set for a product; first of all, certification: providing certified products (for example from OEM) or guaranteeing price and durability easily overcomes the price question because this gives confidence to the user. A customer is reassured when offered a (re)/manufactured product following a certified and acknowledged process. There is still a way to go until we will reach a commonly accepted definition and standards for re-manufactured products in various sectors; this is lacking and has been identified as the most prevalent barrier to re-manufacturing [200].

2.9.8 Customer

There is no doubt that customers are the cause and effect of each activity in a company. How an organization interacts with them greatly impacts how a de-manufacturing system is designed. In a CE paradigm, customers and industries come in contact several times (for example, when the product is sold, repaired, returned, re-sold). The customer may have contacts with a multi-brand or a single-brand retailer; in the first case, even though the OEM takes care of de-manufacturing, it may be very far from the user and response time may be long. Therefore, the customer may rely on third parties, unrelated to the OEM and thus cause competition with the OEM. An OEM can only hope that besides the close distance and direct relationship between IR and customer, IR has neither expertise nor know-how to carry on re-manufacturing [217]

2.9.9 Industrial symbiosis for carbon reduction engineering

CE is strictly bounded to the concept of Industrial Symbiosis (IS) to use resources more sustainably than a traditional and linear economy. First, CE requires a single enterprise to approach it and a whole system to change. Looking at itself, a circular organization must harmoniously encompass all its resources; outside its boundaries, it must simultaneously collaborate with all actors of the product value chain and work to have its value chain to be part of other supply chains. IS is a form of brokering to bring companies together in innovative collaborations in which waste or by-products of an industry or industrial process become the raw materials for another. IS has a high potential to lower CO₂ emissions [264], both as IS and Urban IS [265]. The field of research in IS is immature and more research is necessary to demonstrate the economic, environmental, and social benefits and to get practical design insights related to IS [266]. CE and IS rely on the delicate EoL product phase: it must generate suggestions and feedback for

implementation in the design phase [76]. Finally, EoL must be planned to make it efficient; when it comes to EoL strategies such as re-use, re-manufacture and recycling, each product and material needs special consideration, mainly when composite materials are employed.

2.10 Main needs

In the very complex system that sees a product being designed, produced, commercialized, and disposed for the sake of sustainability, multiple factors must be considered. Consequently, the SoA focuses on two main drivers: de-manufacturing and CBMs. The first, by linking the first (design) and ultimate (EoL) phases of a product, can be seen as the crucial ring to make the economy effectively circular; the second enables the economic sustainability of the environmentally sustainable possibilities enabled by de-manufacturing.

The concept of de-manufacturing has been first 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 the critical solution for an efficient and systematic implementation of CE. It can only 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 from CE, re-manufacturing and disassembly. For the sake of CE, de-manufacturing is a comprehensive concept encompassing all EoL strategies: re-using, re-manufacturing, re-purposing (disassembly is needed), and recycling, depending on the status of each module.

Then, the main barriers related to the practical implementation of de-manufacturing and possible actions to overcome are identified from the literature and clustered according to the factors of the proposed CREDIT analysis. By acting on design, supported by valuable and integrated tools, OEMs, together with researchers, can reach for something greater, such as i) foreseeing and getting prepared for tighter regulations, ii) involving customers in a sustainable close loop, iii) introducing 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 in the reached achievements, methods to standardize the gained condition are needed and iv) I4.0 KETs application and de-manufacturing should be raised to the manufacturing level. The second topic focuses on the criticalities encountered by the industrial and academic

worlds when approaching the transition from linear to CE. In particular, how a BM can impact a de-manufacturing system was investigated: a BM may be the leading facilitator or opponent of de-manufacturing. For example, some authors favor OEMs becoming re-manufacturers or outsourcing post-use activities while maintaining control because they own the design and production information of the product, concerning all protected by IP. On the other hand, OEMs often develop their in-house methods and tools for after-use-phase activities and may be reluctant to share knowledge of these with the outside world for competitive reasons. Concerning the de-manufacturing process, the main obstacles are time and quality process and product uncertainty, balancing returned cores with demand, cores disassemblability, recovery rate uncertainty, RL, and difficulty of material matching.

According to the abovementioned findings, the literature urges for methodologies and tools to support the design phase and improve the product lifecycle.

Starting from the existent ones, studies should focus on achieving reliable and faithful LCA results while maintaining a micro-systemic approach and not falling into complexities. The wide success that LCA has been facing should be exploited to evaluate secondary results, then the punctual environmental impacts; for example, sustainability of durability, recyclability or other product environmental indices, and several strategies products can undergo.

The design phase, both as first stage of the lifecycle or in a late re-design, can boost the promotion and implementation of multi life cycle approach: products' lifecycles can be extended, goods can maintain their initial shapes and characteristics or enter a new life, in different guises, as new secondary raw material. Design methods and tools should enable the valorization of waste and scrap; particular attention should be given to circular strategies applied to composite materials. The integration between commercial/existent tools should be spurred to harmonize workflow and encourage the dissemination of lifecycle information. The goal is to increase awareness of environmental sustainability and the choices made yet in the first design phase; moreover, to support industries and increase their competencies in developing products with a life cycle perspective and optimized in environmental terms. Ultimately, research is needed to couple technical success with the overall company success, with consequences on the business mode of doing business.

3 Methodology

The CREDIT analysis proposed in the SoA revealed that several are the lacks in the literature of methodology and/or tools that may significantly act on each CREDIT factor and enable the implementation and success of de-manufacturing and consequently CE.

The methodology proposed in Figure 3.1 encompasses the primary identified needs and outlines a potential strategy to valorize the information deriving from the PLC and improve its critical aspects.

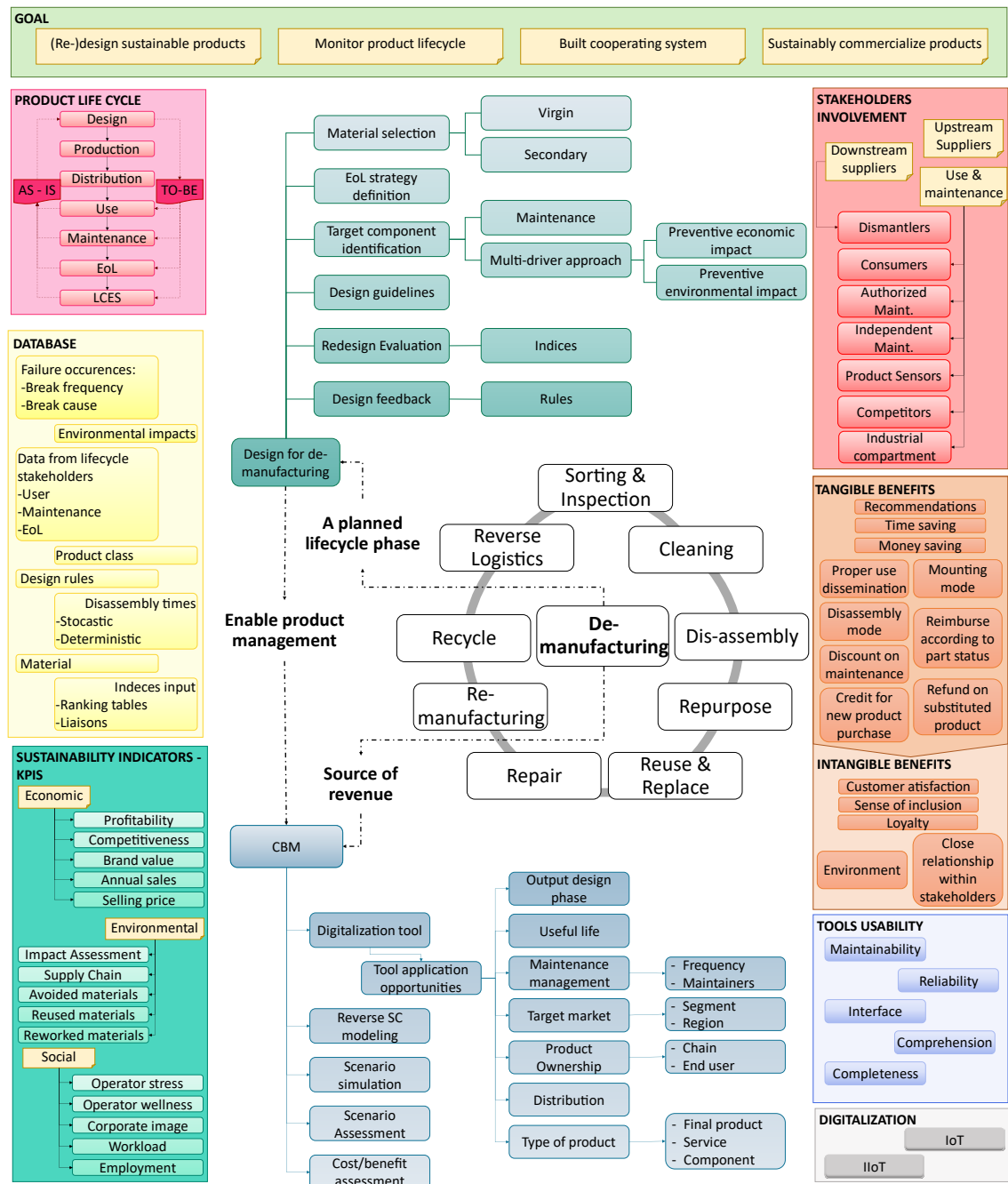


Figure 3.1 Methodology

Methodology

The methodology's core is the concept of de-manufacturing, as explained in paragraph 2.3. It is a valuable resource for a product's lifecycle's first and successive phases: design for de-manufacturing and commercialization (CBM). The methodology should be followed when designing products and/or developing tools to support that phase, spotlighting the three pillars of sustainability (economic, environmental, and social) and integrating innovative solutions. The picture perimeter contains secondary topics that contribute to the construction of solid LCT, to establish a system whose elements cooperate with each other's, exchanging resources, materials and information.

Product lifecycle awareness is essential to understand how the product functionalities should be proposed to consumers and to adapt the product design so that subsequent activities are enabled/eased. The continuous evolution of the lifecycle should be monitored and registered, so that that information can be usefully elaborated to improve new products. Feedback and information coming from the lifecycle must return to the designers so that the product can be improved release by release; for example, dismantlers retain a significant amount of information about product and components status when it reaches the EoL. Data can be collected by exploiting the smart function of products and processes or establishing synergies with upstream and downstream suppliers of the product lifecycle (stakeholder involvement). Structured DB can store failure occurrence, unitary values of impacts, product classification, rules to be suggested under given conditions. Multiple repositories may be expected according to the type of information stored. Those would build the lower layer of the developed tools.

The designers are provided with a bundle of tools. When providing a new one, this must be smoothly involved together with the existing ones: usability, maintainability, reliability and completeness must lead the main feature development. On the right tangible (that directly affects physical assets) and intangible (not directly related to the company core activity) benefits are listed; through a proper selection of Key Performance Indicators (KPIs) trends, improvements and/or worsening can be objectively monitored.

Each box enveloped around the de-manufacturing should unavoidably interact with the CBM or design tool development. However, this is not always the case. As the SD has recently appeared in technical industrial departments, some factors may be lacking when dealing with product lifecycle improvement (lifetime extension) of products already on the market. Therefore, classification is needed: the methodology proposed can be addressed through a proactive or a reactive approach (Figure 3.2).

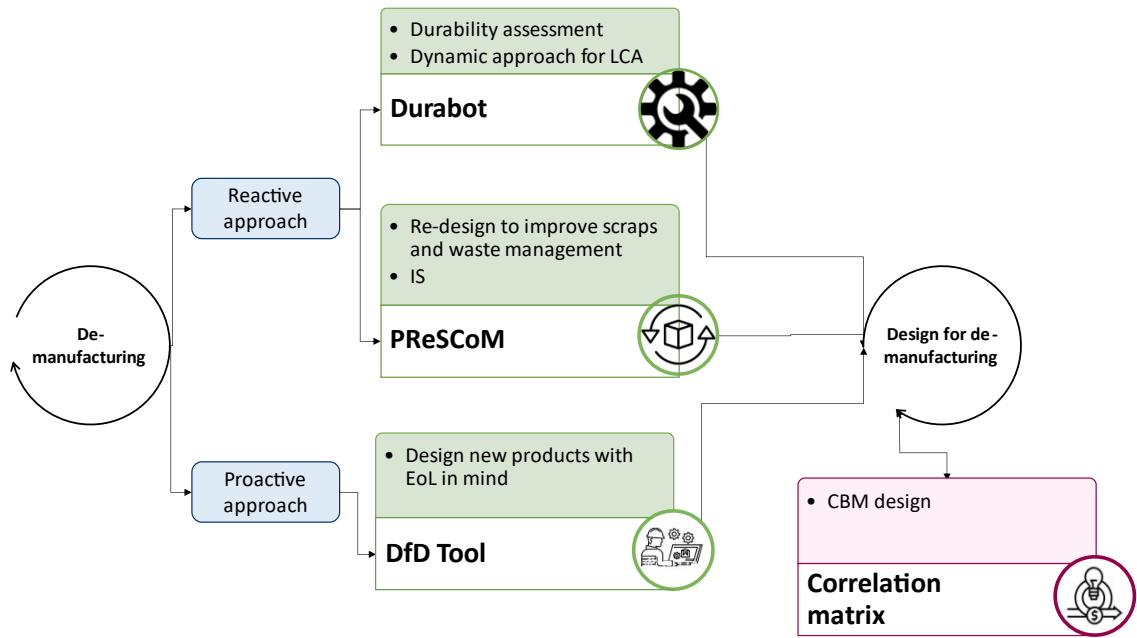


Figure 3.2 Reactive and proactive approach when tackling de-manufacturing.

Figure 3.3 shows how the four framework implementations fill the main gaps identified by the CREDIT analysis.

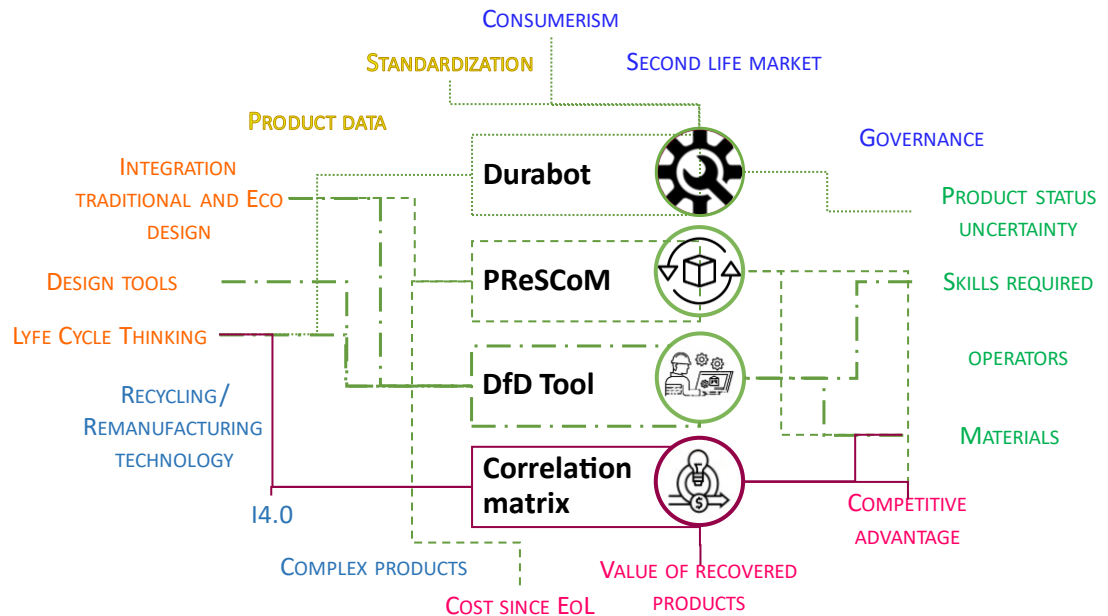


Figure 3.3 Credit analysis factors addressed through the proactive and reactive proposed approaches.

Each methodology implementation is depicted through a two levels box: on the upper side, the main objective is reported; in the lower part, the main outcome. The following paragraphs explain in more detail how each case has been explored. The reactive

approach refers to actions taken to products and processes that are already commercialized without a systematic approach toward sustainability. For these, their lifecycle, at different stages, is willing to be improved. In the proactive approach, actions are taken before the good production, so criticalities are detected in advance and tackled. The design of CBM can address both the reactive and proactive approach, as a CBM can be introduced next to a traditional BM, as its substitution, or designed from scratch.

3.1 Dynamic approach for LCA

The first reactive approach concerns the durability assessment, the convenience of the re-use strategy and a dynamic strategy to increase the quality of the main LCA outcomes. The approach arises from more assertive role acquired by the LCA in the decision-making processes and governmental regulations and the consequent high grade of objectivity and reliability that results must reach. A combination of the linearity of the ALCA and a high level of detail is proposed so that it is possible to faithfully describe the entire lifecycle, including the effects of time over it. Rather than describing a future, not-yet-established equilibrium (typical of the CLCA) the goal of the further described approach is to provide the effects of the upcoming changes that directly influence the flows included in the analysis of a given FU. The variable quantities flowing to and from the product system can either concern the evolution of the analyzed system (i.e., product aging) or due to external factors (i.e., the evolution of the energy grid mix). Plain speaking, LCA is at the basis of a durability assessment and enables:

- The comparison of different methods to describe how the product performances vary;
- To assess and investigate the correlation between durability and environmental sustainability by introducing different aspects and appropriately including evolution scenarios in product performance.

The research question answered is formulated: once a product (Pr A) is used for a certain amount of time (T) and a component breaks, is it more sustainable to substitute the component and preserve Pr A (Component Substitution, CS) using it for additional X years, or to replace Pr A with a new product (Pr B, Product Substitution, PS)? Is using a good for a long time more sustainable than replacing it with a new one? A method and related tool intended to evaluate the environmental sustainability of durable products are presented by answering to the research question. The tool supports the design phase as it preventively allows the assessment of environmental consequences of durability under

different circumstances and it is helpful in identifying which components have the highest priority to be reachable to be substituted, as their aging may affect the whole product's environmental performance. The tool allows the comparison of scenarios regarding the product lifecycle phases. It also enables the assessment of environmental consequences of durability and how it varies when specific parts of the product are substituted. The main literature gaps are filled because:

- The environmental consequences of durability are evaluated considering product evolving performances in time (i.e., worsening functionalities).
- External factors (i.e., the evolution of the energy grid mix) that partially mitigate the increase in environmental impact due to wear and aging are introduced.
- The tool enables the measurement and prediction of environmental consequences of durable products in different lifecycle scenarios during the design phase.

The approach aims to exploit commercial datasets' potentialities, making it applicable to a broader range of stakeholders and designers who apply lifecycle thinking. In Figure 3.4 is shown how the proposed framework places between the CLCA and the traditional ALCA. The inner box represents the product system under analysis, as it is conceived in the ALCA: it includes all the potential inputs and outputs from the system. The input can derive from the Technosphere (i.e., electricity, semi-finished products) or nature (i.e., raw materials, water); the output of the FU lifecycle can be different kinds of emission, by-products or waste flows.

In the static approach the quantities flowing from the input through and out of the lifecycle are fixed over time. When their values are measured or estimated and then modeled in the LCA, who carries on the analysis takes a picture of a certain instant. As it is common to carry out LCA being supported by commercial tools and DBs [229], [231] the resulting LCA shows a fixed picture: even though the lifetime extends over multiple years, the environmental impacts consider the information collected and elaborating watching a single moment in the present or relative past.

Comparative scenarios may be discussed and analyzed; however, this does not consist in deploying the detail of the FU lifecycle. In the CLCA the perspective is much more comprehensive and considers a market equilibrium that is influenced by the market of the product system analyzed in the static approach; however, this might be different from the one of the moments when the ALCA is carried out; in fact, the CLCA can describe situations that happen far in time and also take into account factors that are far from being

directly related to the flows of the analyzed FU (i.e., the introduction of innovative technology that makes the current FU obsolete and not used anymore in a specific timeframe). The intermediate box describes how the static approach may be enlarged so that the flows that take part in the lifecycle are well described. The approach is dynamic as it considers how the flows change over the lifecycle, but the focus is still exclusively on the product. The FU is the center of the analysis, however, the change of flows throughout the lifecycle is contemplated. This may also lead to looking after the surrounding system, but only for what directly concerns the flows of the static approach. It follows that the intrinsic behavior of the product system is investigated, as external factors are. By doing so, the resulting LCA results more accurately reflect the real case, as they are not just a picture of a single moment; instead, it focuses on peculiar behavior and performances of the product and the changes in flows that may occur over the entire FU lifecycle.

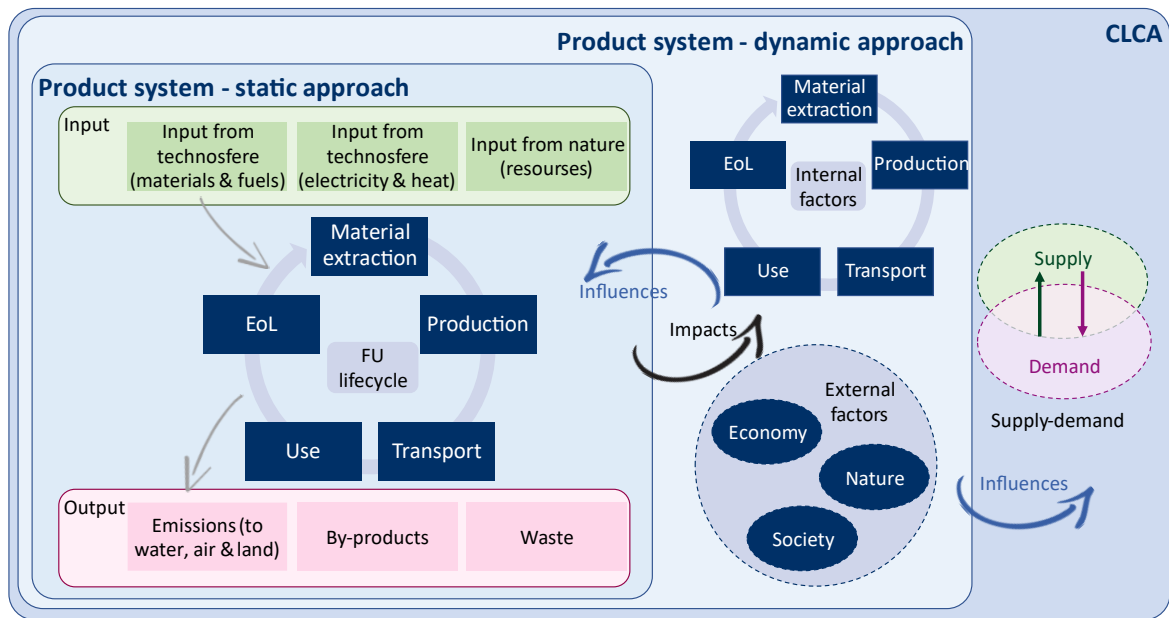


Figure 3.4 Novel dynamic approach for LCA and comparison with static and consequential framework, inspired by Hackenhaar et al. [244].

3.1.1 Durability assessment

The logic behind the durability assessment is summarized in Figure 3.5. First, collecting objective and punctual lifecycle environmental impacts for the analyzed products it is necessary. Using the results of LCA is advisable, even though alternative data can be arranged, such as EPD (Product Environmental Declaration). Finally, the environmental burdens must be described for the same impact indicators and obtained with the same methods for all the analyzed products so they are comparable.

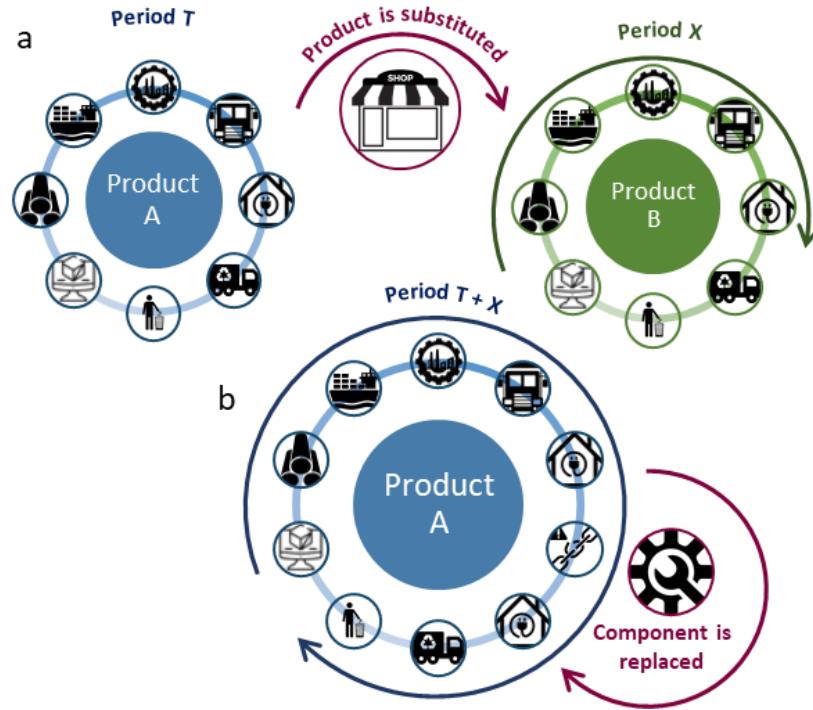


Figure 3.5 Durability assessment steps: the product substitution case, PS (a) is compared with the component substitution case, CS (b).

The evolving performances of the products may differ and vary according to the nature of the product. Therefore, the sustainability of durability can be evaluated under different circumstances by introducing of product/component aging. The approach starts from the durability index D_n suggested by Ardente et al. [267]; it is an index intended to assess the durability of ERP robustly and comprehensively. The index D_n evaluates the goodness, from the environmental point of view, of substituting a component in a product (CS) in order to extend its lifecycle or substituting the entire product and replacing it with a brand new one (PS). D_n is obtained as the ratio between the differential environmental impacts/benefits between CS and PS and the lifecycle impacts of the first product (PrA). The timeframe is delimited from the initial time 0, when the product PrA is used to the time $T_{PrA} + X$, when the product PrA with the substituted part (lifecycle extended) is disposed. Figure 3.6 shows the scenario considered to obtain the D_n . Both the simplified and the extended formulas suggested by Ardente et al. [267] can be used; nevertheless, those are re-arranged so that the external and internal factors that vary along the product lifecycle are considered. Those mainly concern the use phase: $U_{Pr*,n}$ varies and is not constant over time. The variable trend does not allow scaling the yearly label consumption for the X years by multiplying it X times; each yearly contribution $U_{Pr*,n,i}$ must be calculated.

Methodology

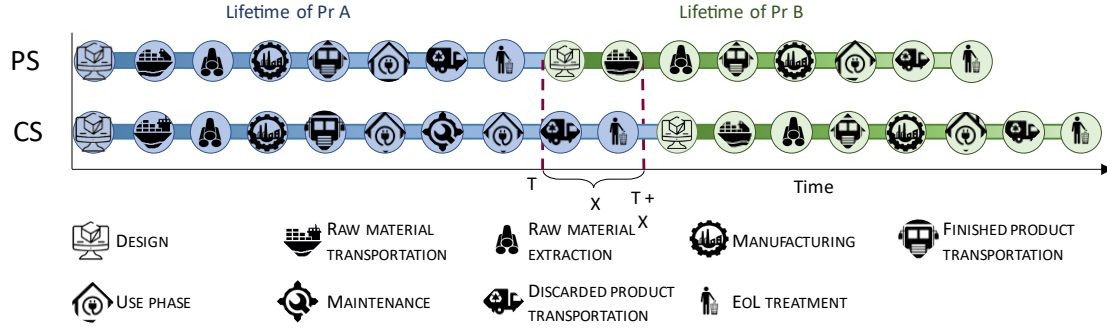


Figure 3.6 Scenarios considered in the durability index calculation, adapted from Ardenete et al. [267].

The overall consumption of the considered products is obtained by summing the contribution year by year (Eq. 3.1)

$$U_{Pr*,n,X} = \sum_{i=1}^X U_{Pr*,n,i} \quad (3.1)$$

The extended, adapted version that considers the dynamic factors of the lifecycle ($D_{n_{dyn}}$) is shown in Eq. 3.2:

$$D_{n_{dyn}} = \frac{\frac{P_{PrB,n}}{T_{PrB}} X + \frac{E_{PrB,n}}{T_{PrB}} X + (U_{PrB,n,X} - U_{PrA,n,X}) - R_{PrA,n}}{P_{PrA,n} + U_{PrA} T_{PrA} + E_{PrA}} 100 [\%] \quad (3.2)$$

Where:

- $P_{PrA,n}$ and $P_{PrB,n}$ are the environmental impact, for the n impact category, of material and manufacturing phase of PrA and PrB products respectively [unit];
- T_{PrA} and T_{PrB} are the expected lifetime of products PrA and PrB respectively [years];
- X is the time PrA product's lifetime is extended [years];
- $R_{PrA,n}$ is the environmental impact, for the n impact category, for additional treatments (e.g., repair) necessary for the extension of the lifetime of PrA [unit];
- $U_{PrA,n,X}$ and $U_{PrB,n,X}$ are the environmental impact, for the n impact category, of use phases of product PrA and PrB respectively during the X years [unit];
- U_{PrA} is the environmental impact, for the n impact category, of the use phase of product PrA for the whole lifetime [unit];
- $E_{PrA,n}$ is the environmental impact, for the n impact category, of the EoL phase of the reference product [unit].

The simplified, adapted version ($D'_{n_{dyn}}$) in Eq. 3.3.

$$D'_{n_{dyn}} = \frac{\frac{P_{PrA,n}}{T_{PrA}} X + \frac{E_{PrA,n}}{T_{PrA}} X - (1 - \delta)U_{PrA,n} - R_{PrA,n}}{P_{PrA,n} + U_{PrA}T_{PrA} + E_{PrA}} 100 [\%] \quad (3.3)$$

Where:

- $P_{PrA,n}$ is the environmental impact, for the n impact category, of material and manufacturing phase of P_{PrA} , considered equal between PrA and PrB [unit];
- T_{PrA} is the expected lifetime of P_{PrA} , considered equal between PrA and PrB [years];
- X is the time the reference PrA lifetime is extended [years];
- $R_{PrA,n}$ is the environmental impact, for the n impact category, for additional treatments (e.g., repair) necessary for the extension of the lifetime of P_{PrA} [unit];
- $U_{F,n,X}$ is the environmental impact, for the n impact category, of use phases of the reference product during the X years [unit];
- U_F is the environmental impact, for the n impact category, of the use phase of the reference product for the whole lifetime [unit];
- $E_{F,n}$ is the environmental impact, for the n impact category, of the EoL phase of the reference product [unit].

3.2 Re-design to improve scraps and waste management

The second reactive approach concerns the re-design to improve scraps and waste management. Indeed, it is proactive whenever applied when designing new products. The focus is on circular strategies, mainly applied to composite materials, i.e., materials made from two or more constituent materials with significantly different physical and/or chemical properties that, if combined, produce a material with different characteristics from the individual components [268]. The main goal is to transform scraps and off-specification products into primary materials for manufacturing different goods, also thanks to their re-design. The proposed approach, shown in Figure 3.7, aims at supporting enterprises in identifying and evaluating circular strategies for IS with a structured process and enabling them to quantify the environmental benefits of re-using scraps as raw materials. It has been named PReSCoM, as it consists of *Processes* and *Products' Re-design, Involving Scraps from Composite Materials*.

Guest products represent all the products (made of composite and non-composite materials) whose EoL is willing to be improved. Host products and processes are existing

entities whose components' virgin materials would be partially replaced by (composite) scraps.

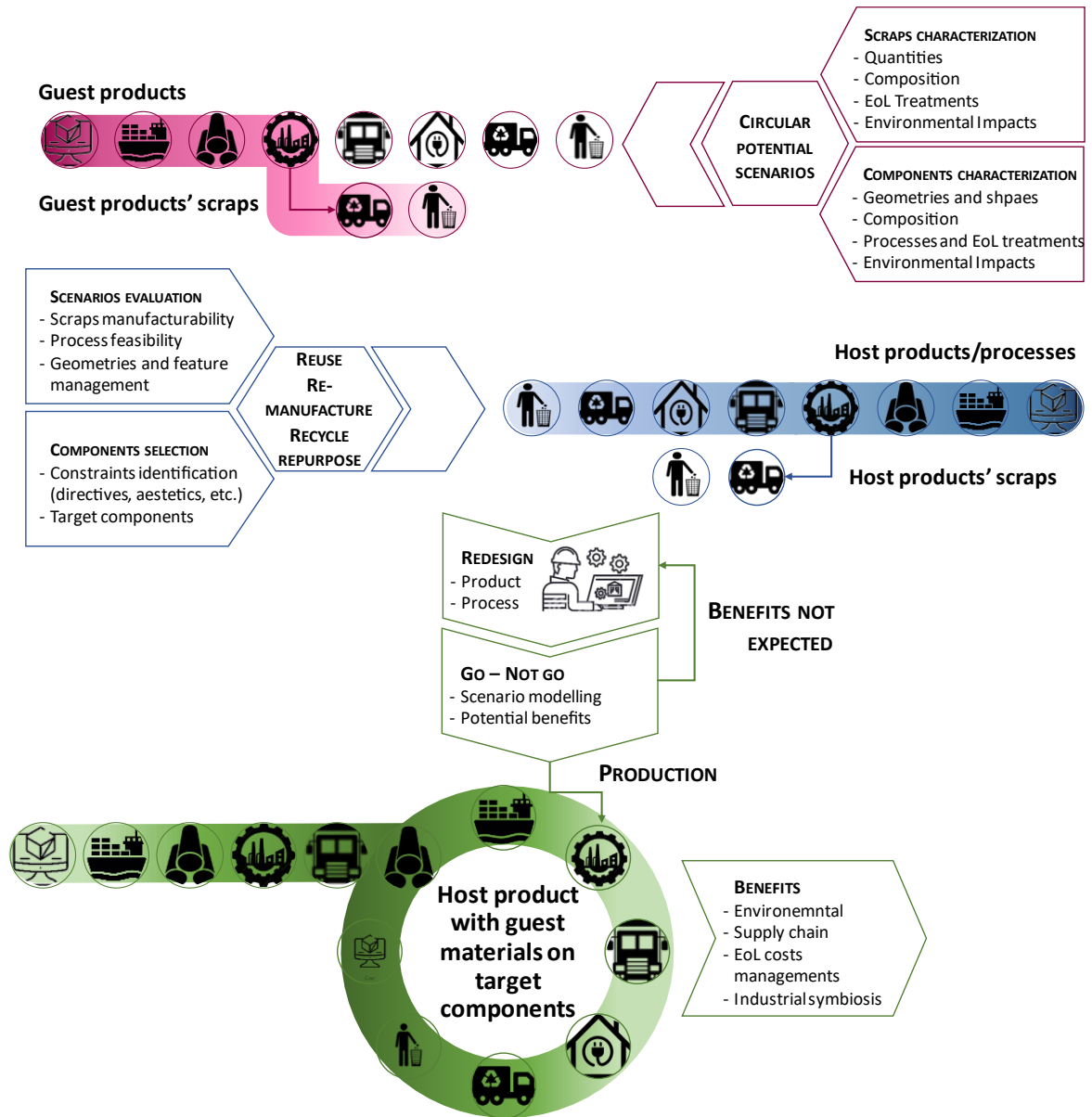


Figure 3.7 PReSCoM: Flow of valorization of industrial waste from composite materials.

Besides aiming to reduce the environmental impact, the re-design phase in the current approach seeks to extend the use of products, as well as promote a multiple life cycle approach [269]. Third entities can produce hosts product and this is the core of the establishment of IS, where scraps and waste of an organization become secondary raw materials for other industrial processes. First an assessment of the present state (As-is) should be carried out, and the characterization. As far as scraps are concerned, the following parameters need to be defined or quantified:

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- Quantity: to monitor the amount and the variability level and consequently the availability of a specific scrap on a reference target period (i.e., yearly);
- Typology and chemical composition, allowing the identification of mechanical, thermal, and physical performances and machining;
- Disposal scenario and EoL treatments for the produced scraps, including all the pre-treatments (i.e., mechanical shredding or manual separation) and intermediate transport prior to the effective treatment;
- Environmental impacts related to the involved life cycle phases, i.e., material extraction and pre-processing, transport toward dismantler and EoL treatments.

Similarly, the analysis can start for the host products, with the analysis of:

- Geometrical properties, features and shapes for components to identify parts with higher/lower-level-freedom degree and therefore suitable for material, shape, or thickness modifications (i.e., esthetical vs. functional components);
- Material properties for components and their technical, mechanical, thermal, and physical performance;
- Production processes and EoL treatments for the products' components;
- Environmental impact related to the involved life cycle phases, i.e., material extraction and pre-processing, manufacturing processes, transport toward dismantler and EoL treatments.

This step is important to obtain a clear picture of the potential flow of parts and materials to employ in innovative applications. After that, the potential target components to manufacture with alternative materials and processes are identified. The potential scenario investigation, i.e., scenario evaluation phase, should focus primarily on linking the material performance (both technical and environmental) and components function with constraints and technical feasibility. The re-design is helpful to overcome the challenges projected by the scraps feature and the characteristics to be reached by the target component. Scraps properties and their machining, the feasibility of production processes, shape and feature examination, together with environmental analysis results, guide the identification of single or multiple future (To-Be) scenarios. A To-Be scenario foresees identifying one or more circular strategies to apply to the specific situation. It is possible to choose whether the suggested solution may be convenient by quantifying the potential environmental impacts/benefits, that are the design modification of

components and their shapes, which need to allow the application of the circular scenario identified and the manufacturing operation needed to make the scraps re-usable (e.g., disassembly, finishing operations, etc.) and its application in the specific industrial context. The (prototype) production allows the quantification of the resources employed and emissions produced. Being the target products industrial process scraps allows the accomplishment of the three measures of circularity [270]: material recirculation (the use of recovered material employing re-use, re-manufacturing, or recycling instead of virgin material); utilization (the high frequency of use of a product otherwise consigned to storage) and endurance (the retention of value for as long as possible). The proposed approach praises three key strength points. First of all, it faithfully implements the CE principle of joining and bonding EoL and design phases involving a system, rather than a single organization. The second strength lies in the aim to establish symbiosis among enterprises that are active in different sectors and several materials. This offers a way out to a critical aspect that in specific sectors endangers CE, such as the cannibalization and low demand for re-manufactured products. The third distinctive element is the investigation of innovative employment for composite materials, diminishing their EoL treatment. Moreover, the method is suitable for non-composite materials too. Differently from the existing literature, the proposed approach aims to apply the scraps also with different functions they were initially conceived for.

3.3 Design new products with EoL in mind

The proactive approach aiming at open, sustainable ways for handling products at their EoL is based on a method whose goal is to support designers in optimizing the environmental sustainability aspects of their products through KBE. KBE supports the design phase by allowing the identification of design criticalities under the environmental issue and from a life cycle perspective, favoring knowledge use [238]. A knowledge DB advises the designer by identifying possible errors and/or criticalities and a calculation module, which quantifies parameters for a simplified environmental assessment. The choices made during the design phase directly prevent or ease subsequent activities (Figure 3.8). The acquisition of feedback, rather than information through the potentialities offered by smart systems (i.e., IoT), enables the formulation of new requirements for the project and thus influences design choices. The designer may be led by design rules, oriented on sustainability. Material, physical, and manufacturing features

represent the input from which design feedback and product indices are derived; feedback is automatically collected along the lifecycle phases automatically or by stakeholders (i.e. maintenance operators, dismantlers, customers, etc.).

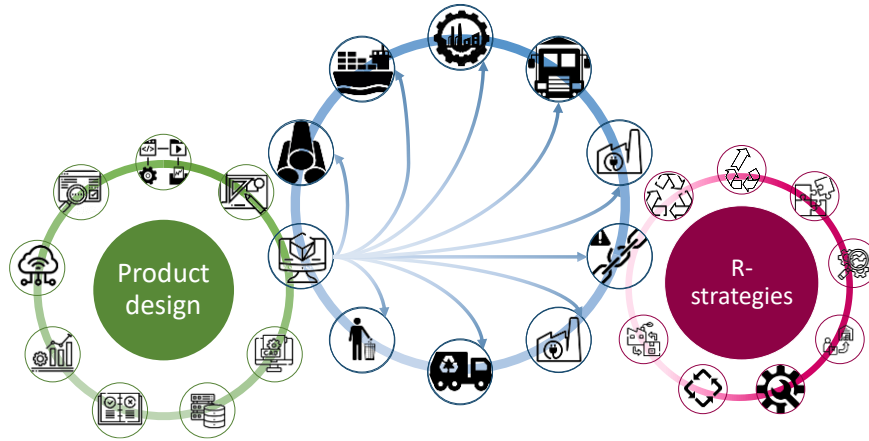


Figure 3.8 Proactive approach to work on the product structure to make informed decisions that enable sustainable actions along the product lifecycle.

The 3D CAD model can be the link between design rules and sustainability, as it makes the product information collection smoother. The geometry analysis highlights product criticalities that can hamper the subsequent lifecycle phases, EoL among them. Upon how materials are employed, located, and linked in the components of a product, certain R-strategies (repair, disassemble, upgrade, recycle, re-manufacture) can be prevented or enabled. The goal is to make designers aware of the environmental sustainability of the choices made in the first design phase, supporting them and increasing their competencies in developing products with a life cycle perspective and optimized in environmental terms. In this stands the proactivity of the proposed approach: prior to obtaining the physical product, since its virtual modeling the product is conceived as potentially suitable for circular strategies.

The system supports the designer by highlighting and explaining the root causes of the detected criticalities so that the designer knows where to act to prevent future issues.

People responsible for environmental aspects may not belong to the designers' department and may be located far from each other in the company (if there are some internal). This occurs more as the company size increases; from one side justifies why designers do not have much environmental consciousness and from the other, it is an obstacle to the mutual communication between the departments. Therefore, a proper knowledge structure will ease the passing down to designers the experience acquired in times in other departments.

Methodology

The rules should be defined with a particular interest in product EoL and disassembly strategies; they suggest to the designer improvement strategies, underlining design criticalities and possible related solutions. The structured knowledge can be provided in the form of guidelines or checklists; certain cases would demand graphical instruments that tell the information with flows and others would go for card indexes to consult when selecting materials, processes. Different phases (such as the concept phase, when there are ideas, sketches, and brainstorming or virtual modelling, where components get their shape) require additional documentation. Moreover, it can be stand-alone or integrated with other SW and documentation already used in the company. Some potential outputs the knowledge structure should provide are quantitative comparisons and evaluation of alternative scenarios from which it is easier to make reasonable choices. Besides being validated, all the information is characterized by the specific sector in which the organization acts.

The methodology introduced is based on recognizing of the characteristics of the models created in the design phase. Combining information from the features of a part, its maneuverability, or the suitability of a certain material or its accessibility is assessed. Instead, by relating the features of two different parts within the same assembly, it is possible to determine the connection mode chosen between the two components. This hides data useful to understand the assembly strategy and provide a recommended disassembly strategy. The latter will be chosen concerning the sustainability principles related to the disposal of a product, such as compatibility between recycled materials.

The proactive approach overcomes the traditional design: as the technical and functional constraints influence how the product is transported and used, the proactive approach includes consideration of the EoL phase. This is indeed often neglected, as in the traditional design there aren't constraints and/or requirements involving product disposal. The proactive approach aims to support industrial companies in constructing and capitalizing of company-specific eco-design knowledge. The construct of knowledge requires figures in charge of environmental concerns to collect data and translate them into valuable suggestions for designers.

3.4 De-manufacturing-enabled Circular Business Models

Design for de-manufacturing enables actions that highly characterize CE and do not belong to linear habits; however, to exploit at best its potentialities, the way of doing

business must also follow the innovation brought in the technical sphere. The present section, summarized in Figure 3.9, presents an approach aimed at supporting the managerial division, providing hints about innovative BMs that may be introduced in a new or running enterprise, regardless of its size.

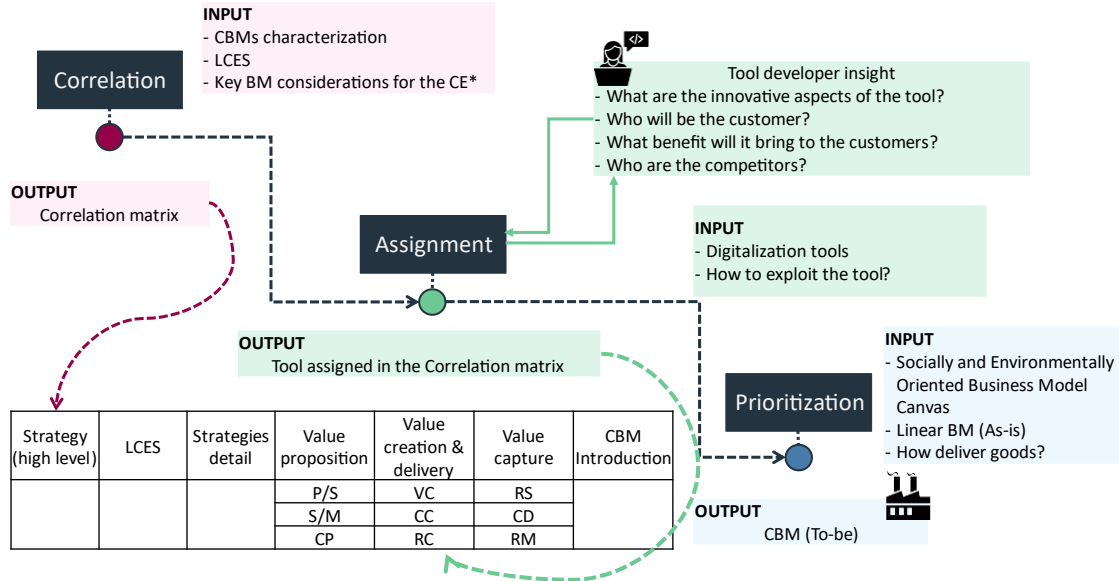


Figure 3.9 Correlation matrix definition through digitalization tools. *Key BM consideration for the CE adapted from [271] and [272]

Through the development of a toolbox Lean 4.0, Schumacher et al. [273] provide systematic support for managing the complexity in the industrial engineering proposed method; differently, the present approach aims at identifying suitable CBMs that may be implemented in the context of machinery lifecycle extension. Therefore, it is eligible for all running companies that wish to approach more sustainable ways to do business. Most importantly, implementing CBMs allows the helpful lifetime of PLC to be extended and the resources required to make, use and dispose it to be optimized. Therefore, this often paves the way to enter new markets and acquire additional market segments. Given the multiple solutions, commercial or on-site developed [274], that are flourishing into enterprises by the advent of digitalization and Industry 4.0 framework, the method rationalizes their potentialities and supports project managers in identifying how the tool may be at the basis of CBMs.

Furthermore, BM innovation capabilities can trigger a dynamic, sustainable competitive advantage for companies, increasing their importance for organizational strategy [272]. Figure 3.10 shows a characterization of CBM models. A CBM can be such either because: i) it aims as manage at best all those resources already employed in

products that reach their EoL or break and are not usable anymore, or ii) it makes flows of resources (whole products among them) circular. Alternatively, there are enterprises whose business is based on re-entering the resources into lifecycles loops.

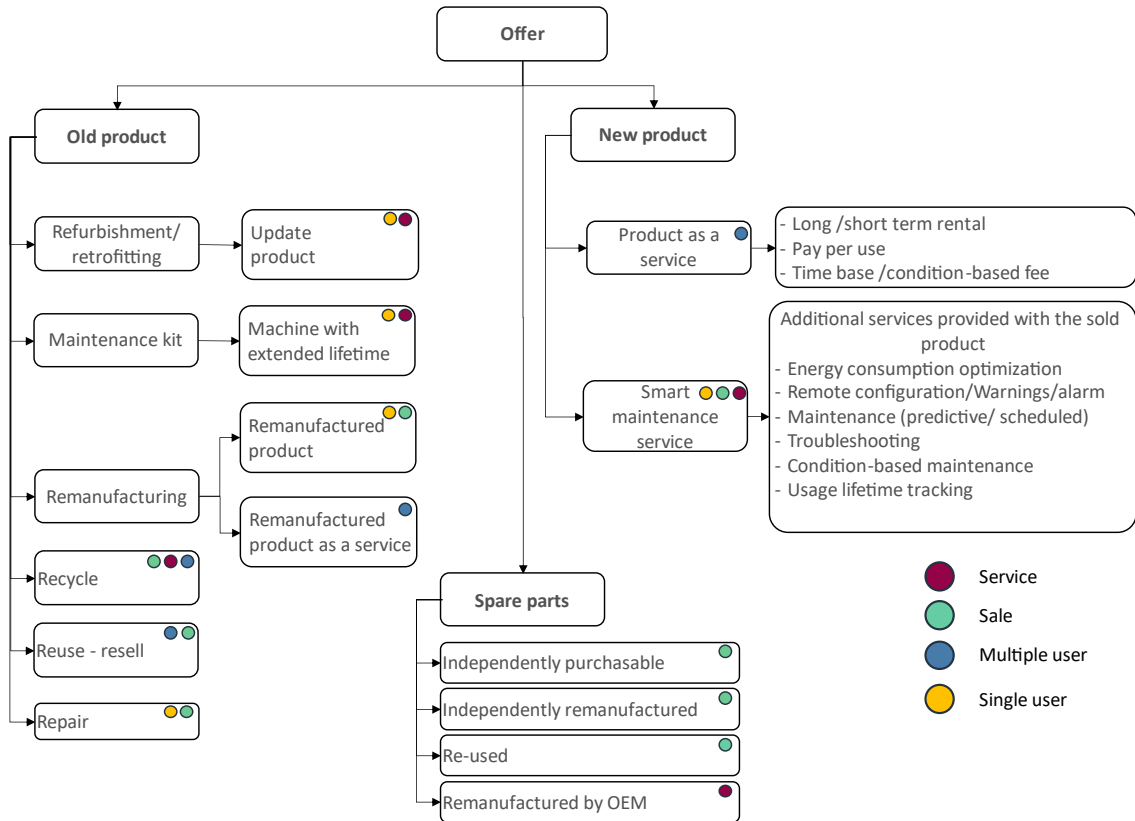


Figure 3.10 CMBs characterization; focus on the number of customers, novelty of products and offer type.

The three main proposals of CBM may offer to customers are exploded into the LCESes that are fulfilled. An example (a logo of an enterprise from the scouting section that implemented the BM) and a short explanation are given for each. Purple-filled bullets refer to a service offered to the client: this may be virtual/digital or come together with a product, whose owner does not change. Oppositely, green bullets identify the cases where a good is sold as in the traditional business model; in these circumstances, the circularity stands in the resources employed in producing the good (i.e., re-used or re-manufactured or recycled components).

Most cases see either the purple or the green dot; however, when smart maintenance is offered both dots step in. This happens because the good is sold as in the conventional selling-buying BM, but additional, optional services may come together. Those have the function to monitor the product's performance, alert the user or the OEM whenever critical parameters exceed maximum levels and thus activate the maintenance planning

in advance. Besides the benefits deriving from avoiding long downtimes, advantages also hide behind the avoided collapse of components (that makes re-manufacture feasible) and prevention of falling into high consumptions (when resources are employed in the use phase). Blue and yellow bullets outline whether the stakeholder involved in the product lifecycle is one (yellow) or multiple players use the good (blue). Green bullets are often associated with servitization and unvaried ownership, except for the re-use and resell case, where the numerosity of users is done by lifecycle loops (how many times the good is sold).

In the first step the literature has been reviewed so that the validated approaches can be associated to LCES. The literature examined academic results and success stories from enterprises that have already approached and introduced CBMs in their realities. As multiple BMs are appearing with the advent of CE, the scouting aims at identifying possible examples to follow and strategies to exploit. The connection between sustainability, manufacturing process and digital innovation is strictly linked to disruptive business reconfiguration [275]. Therefore, circularity often couples with servitization, and attention must be paid to strategies that appeal to servitization and digitalization to pursue the goal of making a profit sustainably.

3.4.1 Correlation

The correlation phase is partially based on the framework proposed by Geissdoerfer et al. [272]. It has been expanded and the LCESes introduced, as a lower level of the BM previously proposed (cycling, extended, intensifying, materializing). For example, predictive maintenance is a strategy that extends the product's useful time; by doing so, it is encompassed as a sub-group of the extension strategy. The additional information about the types of innovation has been located next to the information regarding the value proposition, the value creation and delivery, and the value capture. According to the literature research results, potential CBMs are described within the table; multiple BMs may refer to a single strategy.

At the end of this phase the correlation matrix is structured. To get all the cells filled, the guidelines are provided. As the Value proposition is concerned, it may be as a physical product or a service (P/S); the customers and the market segment they belong to should be defined (S/M) and similarly the problem the value proposition addresses (customer pains). This is the core point of the value proposition, because firstly the customer detects the benefit that would perceive from what is proposed, and only subsequently, further

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evaluations are made. The further hints are related to value creation and delivery, which sums up the steps, for example value and supply chain (VC), human resources (HR) and capabilities employed in building the P/S (RC). Being the correlation referred to the LCESes, and general BMs, the data entered may have higher validity; however, multiple may be the differences arising from the correlation of the BM available. Ultimately, the Value capture section investigates the potential cash flows (both expenditures – CD - and incomes – RS) associated with the current BM. What often distinguishes CBM from traditional BM is the revenue model (RM), as it may introduce additional strategies for the P/S provider to be paid. It is crucial to define whether the proposed value, for which the customer would pay through an (innovative) RM, transforms the business as usual or opens new paths to acquire customers. The main outcome is the correlation matrix. In Figure 3.9 only the headings are provided; Section 4.6 provides more details.

3.4.2 Assignment

In this second phase, the potentialities of available digitalization tools are exploited. The considered tool may be a single multiple, both commercial and developed in a specific industrial context. Therefore, the methodology may be integrated into the decision process when developing a specific tool with higher priority than others. In this case it is important to consider each tool's main functionalities and features of each tool. Those may not be strictly related to the LCES and the tools can be initially thought for different purposes (i.e., process monitoring, quality control, defect detection, human error avoidance). However, they can turn useful in extending the product lifecycle. For each analyzed tool, this must be allocated to the correct LCES, according to its features and functionalities. A single tool may be allocated to more than a single strategy. The tools, being crucial to implement the strategy, are part of the core resources and capabilities of the CBM. The OEM may play different roles when it comes to the use of tools. For example, an enterprise may be the one developing a digitalizing tool but can also be the one who uses it; for this reason, the assignment phase may be supported by the organizations who develop the tool, and to verify or suggest the OEM expectations. Workshops, interviews, questionnaires are useful to support the tools investigation and allocation.

3.4.3 Prioritization

The last point is about selecting which strategy best fits the company. There might be multiple chances to employ a single or a bundle of tools and make it the core of an

innovative, eco-friendly way to commercialize goods or offer services. Nevertheless, is it necessary to schedule and prioritize the introduction of innovative aspects. Thus, a sorting of strategies is needed. This first consists of selecting the best that fits the OEM case, then evaluating the urgency and feasibility of the implementation. In doing so a comparison between the initial BM with the upcoming CBM is needed.

Most importantly, the BM canvas that also assess the environmental and social benefits/impacts should be used; this enables a broader overview of the starting state [276]. The introduction of a CBM has consequences not only on the revenue streams and customer relationship aspect; it instead may influence multiple factors, such as key partners, key resources, channels. Not ultimately, the actors of the supply chain and/or their role. For example, when a pay per use system is introduced, all players responsible for the RL acquire a proper, official role, confirmed and/or managed by the OEM; without the pay per use this was a nonexistent role, because in the trade model a product is discarded by the user and then treated as waste.

As a single tool may pave the way to CBMs that are very different from the current BM, the comparison between those can lead to an implementation roadmap, where little by little, the BM is transformed or the innovative CBM introduced. The introduction of KPIs may be help evaluate when a certain step of the roadmap is successfully exploited, and the organization is ready to step forward to the next one.

The proposed reactive and proactive approaches find application to industrial cases that exploit their potentialities at best, and so happens introducing of CBMs through de-manufacturing strategies.

The dynamic approach for LCA will be supported by the newly developed Durabot tool (Section 4.1); first, the environmental impact assessment of two refrigerators is carried out, through the static LCA methodology; secondly, the durability and changing performances of the products are investigated and quantified through the Durabot tool. Finally, methodologies to analytically describe the effect of foam aging and introduce the effect of energy mix evolution over time are studied (Section 4.2).

Scraps made of composite materials are re-designed and then are processed; the case study involves four industries from the Marche region (Section 4.3). The application of the methodology paves the way to the establishment of solid IS aimed at finding a second life for materials with highly critical EoL management.

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The design of an electrospindle is supported by the DfD tool developed to introduce environmental sustainability issues in the design process, with special reference to their EoL management (Section 4.4). The context of the European project Reclaim, where multiple digitizing tools are developed with the purpose of extending the PLC, offers the best conditions to plan the innovation of the traditional BM (Section 4.6).

4 Results

The present chapter presents the tools developed from the proposed methodology and shows how they were applied to industrial case studies. The functionalities of the proposed tools aim at filling the main gaps claimed by the literature. The development of the tools digs into the main reasons lying behind the main literature lacks. Figure 4.1 shows the most significant. They are retrieved from the criticalities' reasons summarized in Table 2.2. despite; their different nature, the tools present also common challenges to tackle.

The Durabot tool supports the design phase by preventively assessing the environmental consequences of durability for different scenarios. It thus contributes to providing feedback about the product lifecycle, which is one of the main criticalities detected in the literature. The output of the analysis of the tool is helpful to identify which components should first be reached and substituted. The durability index, next to the economic evaluation, quantifies the longevity effects and replacement rates.

The second tool faces challenges due to the EoL treatment of critical materials and finds alternative solutions to the threat of cannibalization of re-manufactured products. In fact, PreSCoM analyses pre-consumption process scraps and through re-design identifies products that potentially use the re-manufactured scraps. The cannibalization finds escaping alternatives and the hamper of low re-use of re-manufactured parts decreases. Not secondary, the chances launched for enterprises to find collaborative innovation partners among new supply chains. PreSCoM is an example of a DfX approach for circular design.

The DfD tool similarly attempts this task. From the information retrieved from the CAD environmental it provides feedbacks to the user for the sake of CE. The use of the tool is an exercise of eco-design. The selection of indexes was led by the need to consider the product complexity and the relative complexity of disassembly during the design phase. Ultimately, the correlation matrix merges the goals of the tool and encompasses them into a wider perspective, conscious that the shift from the traditional sale framework to servitization requires rethinking the product and making it suitable for further de-manufacturing. The journey is split into simpler steps, where enterprises acquire little by little the know-how, expertise, and market segment for a circular system.

Results

The industrial case studies were chosen to exploit the strengths of the approaches and tools at best.

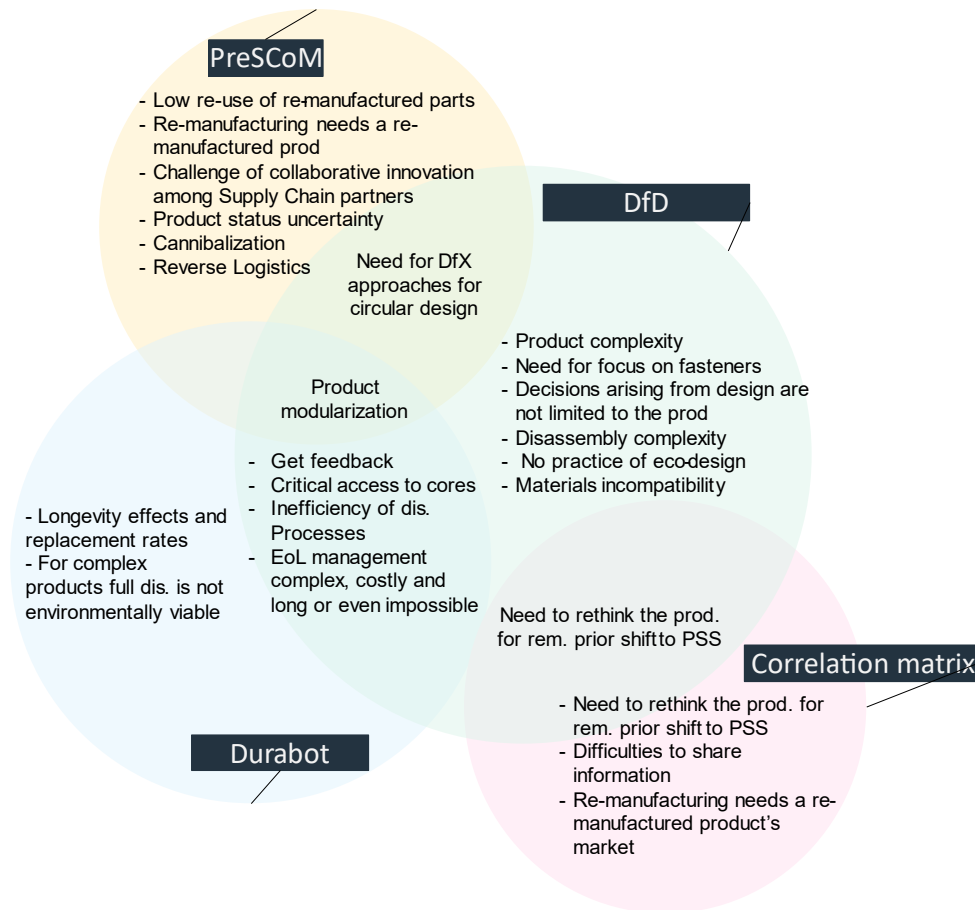


Figure 4.1 Venn diagram of main literature gaps' causes tackled by the tool's functionalities.

4.1 Durabot

The approach proposed in Section 3.1 has been the basis of developing a tool to evaluate the environmental sustainability of durable products. The tool supports the design phase as it preventively allows the assessment of environmental consequences of durability under different circumstances and it is helpful identify which components have the highest priority to be reachable to be substituted, as their aging may affect the whole product's environmental performance (Figure 4.5). In doing so, the tool Durabot supports the main principles of the dynamic approach to carry out an LCA. The tool allows the comparison of scenarios regarding the product lifecycle phases and enables the assessment of environmental consequences of durability and how it varies when specific parts of the product are substituted. Concerning existing products, the tool supports the

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go/no-go decision when a part or module of the good breaks and it is necessary to evaluate the best strategy (repair to extend lifecycle).

The tool is based on the durability index proposed by Ardente et al. [267] and edited to work with a more realistic index. In light of the limitations outlined, the external factor of the energy mix evolution is also introduced.

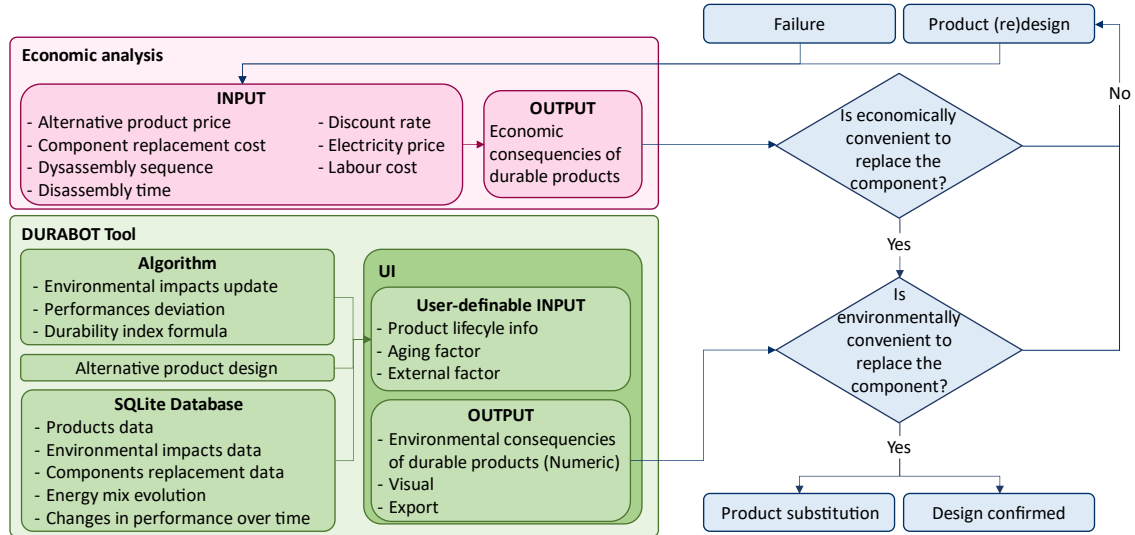


Figure 4.2 Workflow and Durabot use.

The Durabot tool is a handy and easy-to-use SW that allows users to quickly assess the convenience, from the environmental point of view, of product substitution over the repairing process. Its simple yet immediate interface guides the process by suggesting the requested inputs and providing graphs that mirror the outputs. Furthermore, the calculation is executed in real-time so that it is possible to quickly test with several different input values and impact types to achieve a better result.

The tool's main interface is divided into three areas, as shown in Figure 4.3

- The first area (top left, yellow) contains the inputs: some are direct, some are chosen from lists and others are calculated according to the inserted inputs.
- The second area (bottom left, orange) shows the main output, D_n being the durability index, and some intermediate outputs, such as $U_{A,n,X}$, $U_{B,n,X}$, $E_{A,n}$, etc.
- The third area (right, green) is dedicated to the graphs: they show the trend of the durability index as the differential initial energy efficiency between product A and product B decreases and as the overall product lifetime (T) increases.

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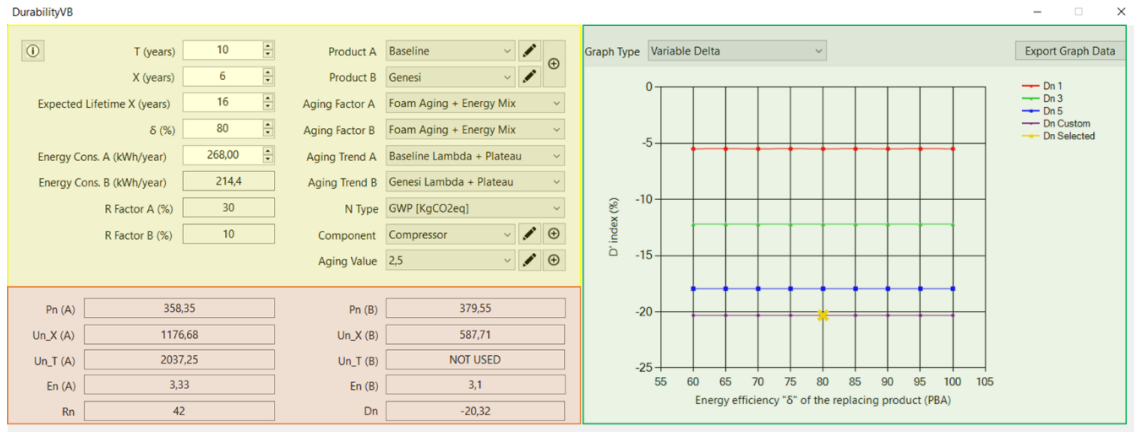


Figure 4.3 Main Durabot interface

4.1.1 Input area

The input area is composed of two columns: the left is used for numeric inputs while the right one allows users to choose the products on which the analysis should be conducted. The numeric inputs on the left column include the product's lifetime and energy consumption ratio. The tool is intended to be used for multiple products: the user can retrieve information from previously analyzed products or insert and modify additional ones. The multiple-choice inputs on the right column allow the selection of the products themselves, the impact category, the component to replace and the aging factors. Finally, the three boxes on the bottom of the left column are automatically calculated or read from the DB based on other inputs provided by the user:

- R Factor A and B are read from the DB based on the chosen.
- Energy Consumption B is obtained can be retrieved as a function of Energy Consumption A (Eq. 4.1):

$$\text{Energy Consumption B} = \text{Energy Consumption A} * \delta \quad (4.1)$$

For greater support to the user, every input box has been provided with a tooltip that suggests the required information just by dragging the mouse cursor. However, the description provided in the tooltip is quite brief, so a more detailed one could be needed. By clicking on the info button (on the top-left of the input area), a new panel will open with two links to documents that explain the whole process thoroughly.

4.1.2 Intermediate and final output area

This area contains either the input for the durability index, that are product- and case-dependent, and the main output. This area comprises of two parts: one contains the

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environmental impacts related to the lifecycle phases and the specific timeframes X and T related to product A, while the second is related to product B. As previously mentioned, the outputs are calculated as soon as all the input boxes have been filled in. New outputs are immediately calculated and shown every time any of them is modified. The output boxes also have the same suggestion feature in the input fields.

The intermediate outputs, which are further employed as input for the durability index, are obtained through the algorithms and reading of the data stored in the SQLite DB. This contains basic information about the products, their impacts, and replaceable components. It is read at the beginning of the execution and every time a new product or component is added or modified via SW. The DB stores default data and user-inserted data (Figure 4.4). The unitary environmental impacts of energy consumption belong to the first group.

Following the future trends of the European energy grid mix [277] the energy mix is supposed to increase the use of renewable energy resources; a discretization time of 5 years is considered. When the user creates or edits products (that means that environmental impacts for all the lifecycle phases are inserted for the CC [kgCO₂eq], Water Use (WU) [m³] and Mineral Resource Scarcity (MRS) [kgC_Ueq]) this information is also stored in the DB. The dependent inputs are retrieved, according to with the values inserted in the input area.

Ultimately, the D_n is calculated and shown, for the single case, related to the input parameters inserted.

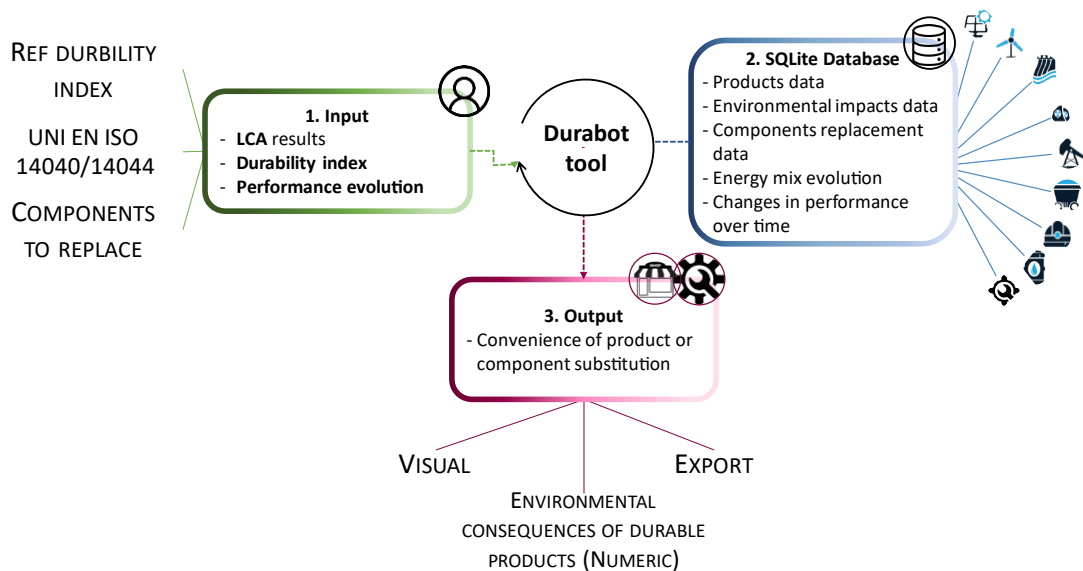


Figure 4.4 Durabot tool main functionalities and architecture

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4.1.3 Graphs area

The graphs area is in the main space, next to the menu to select the graph to show and an export button. The selectable graphs are:

- "Variable Delta", which shows how D_n changes by changing δ . Durabot shows multiple lines per each case: each dotted line represents the trend of D_n as X value increases (1, 3 and 5 years are shown by default and one, for the X value selected by the user).
- "Variable T", which shows how D_n changes by changing T. Also in this case, the dotted lines represent the trend of D_n as X value increases (1, 3 and 5 years are shown by default and an additional one, for the X value selected by the user).

A yellow cross also considers the user-defined δ value in the first graph and T value in the second graph, thus showing the actual D_n result which can also be read in the related output field. The graphs should thus be interpreted as extensions of the executed calculation. The importance for the graphs to show multiple X-scenarios consists in presenting an exhaustive overview of the possible cases. In fact, regardless of the punctual D_n value that describes a specific case, the trends for a set X (varying δ) or between different X may have high variability. For example, in the first type graph all the lines are monotonous increasing function. For certain products, their slope is high: this means that also slight differences in energy efficiency may determine the convenience of substituting the product or the component. When the lines have a slope close to zero, the dependency on energy efficiency is lower. Moreover, the differential value between different X values may lead to having very close lines (when the use phase is much higher than the remaining phases) or lines spread over a wide area of the graph (when the lifecycle phases' impacts are comparable). The export button can be used to save a complete version of an executed calculation. Not only it exports the graph axes values but also every input and output in an open source and easily manageable file format (.csv).

4.2 Refrigerator durability assessment supported by Durabot

The Durabot tool has been applied to dynamically assessment of the environmental sustainability of durable refrigerators, whose composition, divided per material classes, is shown in Figure 4.5. The static ALCA outputs of the two refrigerators constitute the starting point to assess the sustainability/durability analysis. The work was conducted in collaboration with an international company, which plays an important role as a

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manufacturer and distributor of household appliances at European and global levels. The case study involves two single-door freestanding refrigerators produced in Italy and used in the European contexts.

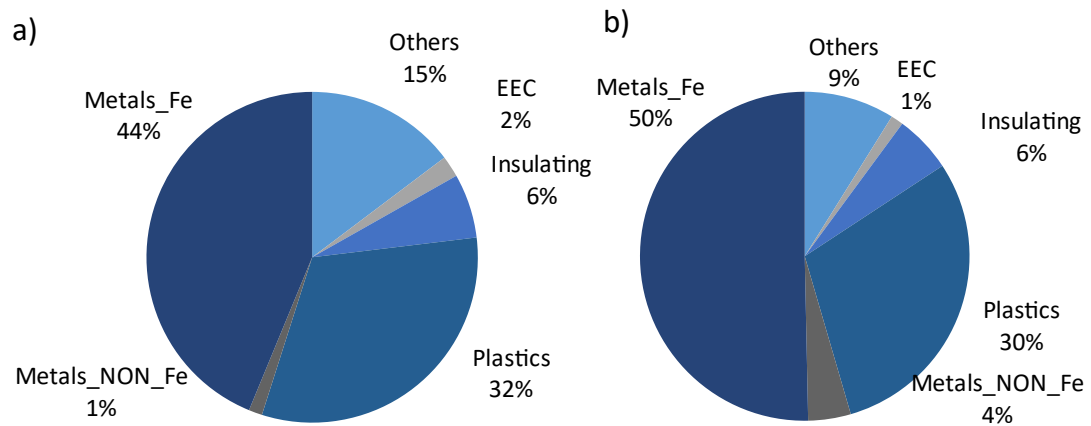


Figure 4.5 Compared to PrB (a), PrA (b) contains a higher quantity of ferrous materials and less electronic components.

These machines are equipped with an Energy label⁴⁰: the first product, called in the following PrA, is energy class F, and the latter, called in the following PrB, is class E. The energy classes refer to the European Framework on Ecodesign and Energy Labelling, Regulation (EU) 2021/340⁴¹. PrA weighs 60 kg, PrB 63kg. Both are single-door freestanding refrigerators, with a refrigerator volume equal to 193 l and a freezer volume equal to 62 l. They are characterized by an external structure in aluminum and steel, while inside the walls are covered with propylene to ensure excellent thermal insulation performances. The two products present few differences both in their composition and the technology implemented.

4.2.1 Energy mix evolution

The energy transition, especially in European countries, is already underway. The implementation of various policies and instruments, together with modern technologies, has strongly promoted the use of renewable energy [278]. Traditional energy includes dirtier and inefficient energy sources, such as wood, charcoal, and agricultural waste. By contrast modern renewable energy includes cleaner and more efficient energy sources, like hydro, solar, and wind. Therefore, shifting from traditional to modern renewable energy sources is crucial for sustainable development and environmental quality [279].

⁴⁰ EU, Commission Delegated Regulation 2021/340, 2020 <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32021R0340&from=EN>

⁴¹ http://data.europa.eu/eli/reg_del/2021/340/oj

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As international agreements and policies may set very challenging goals, several are the available estimations on how the energy mix will vary, whether the objectives are reached or not^{42,43}. Gutowski et al. [280] conducted an energy analysis of the change in consumption of refrigerators introduced to the market considering a considerable period, concluding that improvements in the efficiency of the use phase favor the purchase of new ones, showing clearly how small the materials and energy of production are compared to the energy of the use phase. This supports the intention to study the importance of the impact of the evolution of the energy grid mix. The refrigerators are commercialized in Europe; the average European energy mix has been considered to obtain the results shown in Table 4.1. However, due to the long useful time of the considered products and the changes Europe is facing to reduce the environmental burden related to the use of electricity, it is necessary to consider how the mix evolves in time as external factors influence the dynamic approach. This evolution is modeled in a simplified way and it is assumed to change every 5 years between 2020 and 2040. The evolution of energy sources is according to the EU reference scenario 2016⁴⁴. The initial LCA used the Electricity, low voltage {RER}| market group for | Cut-off, U dataset. The evolution of those energy mixes is not available in commercial DBs, thus the European DB was modified.

Table 4.1. Evolution of energy mix composition according to

Source	2020	2025	2030	2035	2040
Renewable	36,5%	40,3%	44,0%	50,0%	56,0%
Eolic	14,0%	16,0%	18,0%	21,5%	25,0%
Solar	5,0%	6,0%	7,0%	9,0%	11,0%
Bioenergy	5,5%	6,8%	8,0%	8,5%	9,0%
Hydro	12,0%	11,5%	11,0%	11,0%	11,0%
Gaseous fuels	18,0%	18,5%	19,0%	20,0%	21,0%
Hard coal and lignite	21,5%	18,0%	14,5%	9,8%	5,0%
Oil	1,0%	0,8%	0,5%	0,3%	0,0%
Nuclear	23,0%	22,5%	22,0%	20,0%	18,0%

⁴² Agora Energiewende, The European Power Sector in 2020: Up-to-Date Analysis on the Electricity Transition. 2021. https://static.agora-energiewende.de/fileadmin/Projekte/2021/2020_01_EU-Annual-Review_2020/A-EW_202_Report_European-Power-Sector-2020.pdf

⁴³ Capros P, De Vita A, Tasios N, Siskos P, Kannavaou M, Petropoulos A, Evangelopoulou A, Zampara M, Papadopoulos D, Nakos Ch et al. EU Energy, Transport And Ghg Emissions - Trends to 2050, European Commission Directorate-General for Energy, Directorate-General for Climate Action and Directorate-General for Mobility and Transport 2016 https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf

⁴⁴ CAN Europe/EEB technical summary of key elements, Building a Paris Agreement Compatible (PAC) energy scenario, 2020. https://www.pac-scenarios.eu/fileadmin/user_upload/PAC_scenario_technical_summary_29jun20.pdf

4.2.2 Performance evolution

For the current case of refrigerators, the aging of the insulating materials, namely foam aging, is investigated as the first cause of altering the nominal energy consumption of the refrigerators. Multiple studies aim at analytically describing how the foam performs year by year; although the behavior of gases is well accepted (infiltration of exterior air first and diffusion of blowing agent gasses then), few relations describe the overall refrigerator characteristics in time. Different foam aging descriptions are further employed in a double version of the durability index, and further comparisons are carried out and analyzed: the more the analysis is accurate, the more it urges to pay attention to the simplifications. The following sections will go further in detail and exploit the method steps.

Hossieny et al. [281] evaluate potential energy savings by applying two types of liners to the foam insulation for refrigerators; they prove that applying certain types of a liner with low gas permeability on the exterior surfaces of the foam insulation can retard or stop the diffusion of air and blowing agents. Verma et al. [282] review studies comparing the insulation made via Vacuum Insulating Panels (VIPs) and foams, employing different materials for their constructions and assessing the reduction of energy consumption. Empirical investigations are available in the literature and focus on analyzing the aging of polyurethane foam employed in refrigerator insulation. Some provide more qualitative results [283], while others focus on timeframes that are much shorter than a refrigerator lifecycle [284]; some researchers relate the foam behavior to the temperature of the refrigerator [285]. Recently Paul et al. [286] developed an aging model, derived from a solid DB of 100 electrical energy consumption values from a total of 32 appliances that were run under real operating conditions. The authors claim that it is the first function of its kind that was developed based on accurate electrical energy consumption data. The annual efficiency deterioration function, published by Johnson [287] and based on empirical analysis, is frequently used to describe the annual increase rate of energy consumption of household refrigerating appliances [288], [289].

The refrigerator performance changes over time due to components aging; foam aging deterioration is among the main factors. The foam deterioration impacts the thermal conductivity (λ), which is a measure of ability to conduct heat, through conduction, convection and/or irradiation [W/mK]. One of the most impactful aging effects on thermal conductivity is the diffusion of the highly insulating blowing agents and the infusion of air from the environment. These two effects begin to occur immediately after

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the manufacturing process, but the rate at which the gas movement occurs is much faster for the infusion of outside air than for the diffusion of blowing agent gasses. It is suggested that the infiltration of exterior air takes place over the first 1 - 2 years of the material life cycle, while the diffusion of blowing agent gasses takes place over 10 - 20 years [285], [290]. Initially, the conductivity of a foam material increases rapidly (the effect of air infiltration), and then slowly plateaus (the effect of blowing agent gasses diffusing expires); the higher the temperature, the faster the aging. In the present work, methods to estimate the effect on refrigerator annual energy consumption have been considered:

- An empirical formulation provided by the OEM of the refrigerators; is a polynomial function whose coefficient has been derived from empirical measurements; this scenario is further addressed as EM; for discretion, the formula will not be explicated;
- The formula provided by Johnson [287], with known aging rates for PrA and PrB (Eq. 4.2); this scenario is further addressed as JC;
- The formula provided by Johnson [287], with known aging rates for PrA and PrB (Eq. 4.2), with a plateau: the energy consumption is supposed to increase only in the first 5 years (when the energy consumption trend is steep and increases rapidly) and subsequently remain stable; this scenario is further addressed as JP.

In Eq. 4.2 ΔE is the increase/reduction of energy consumption in one year; r is the initial aging rate; a is the year of use and c is a factor related to the blowing agent (2,5 for all blowing agents except for HFC-245fa).

$$\Delta E = r \left(\frac{20 - a}{20} \right)^c \quad (4.2)$$

Table 4.2 shows the value of energy consumption, aging rate and initial thermal conductivity (λ_i) for the two refrigerators examined.

Table 4.2. Energy consumption and aging parameters

Parameter	PrA	PrB
Label energy consumption [KWh/y]	268	214
r [%]	30	10
λ_i [mW/K m]	20	19

Figure 4.6 shows the energy consumption curves obtained based on the three abovementioned methods for PrA and PrB.

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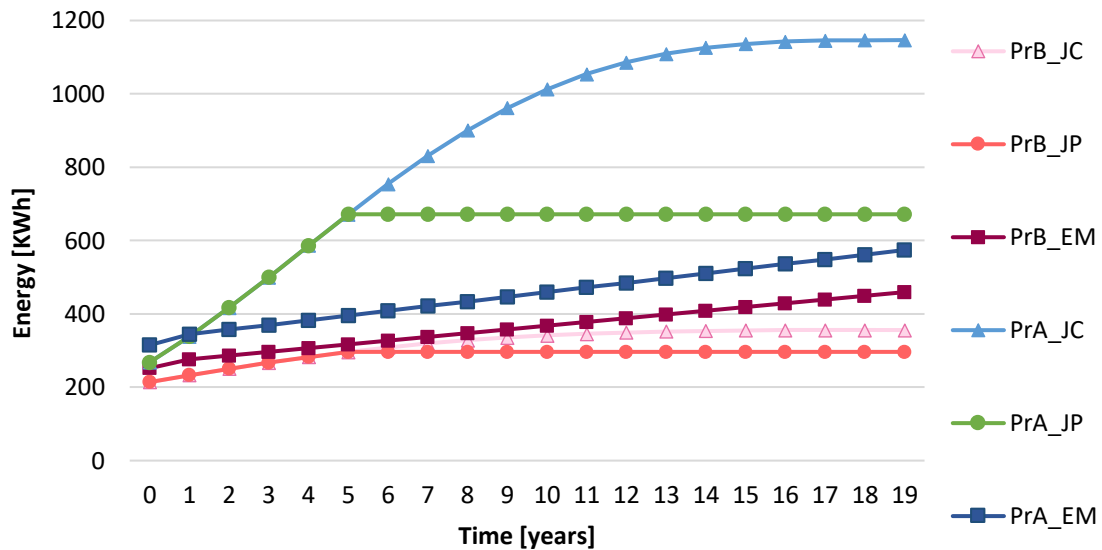


Figure 4.6 Energy consumption increase scenarios.

4.2.3 LCA

The FU of the static LCA is “to store and maintain fresh food in a household’s context, for a lifetime of 16 years; food is stored in a refrigerator of 193 l of volume at +4°C and a freezer of 62 l of volume at -18° C.” The analysis covers the phases in Figure 4.7:

- Materials and Manufacturing: it includes the extraction, pre-processing, and supply of the raw materials constituting the product and its packaging; in addition, it is the consumption (water, electricity, heat, waste, etc) related to the production of the fridges in the factory. Transport of raw materials to the manufacturing site and the final product to a distributor is also included.
- Use phase: it includes electricity consumption of the fridge during its useful life.
- EoL: it includes the transport of the refrigerator to a recycling/waste disposal site and treatments after the product disposal (i.e., landfill, recycling or incineration processes according to material classes).

During the product lifetime (16 years), the maintenance phase falls outside the system boundaries, assuming that fridges are free of maintenance during the considered lifespan. Additionally, direct emissions due to coolant leakage during useful life fall outside the system boundary [291].

LCI data derives from both the BOMs provided by the manufacturer and direct contacts with manufacturer departments. Then, the collected data were modeled to calculate their relative environmental impacts. The commercial SW Simapro version 9.1 was used for this modeling, with the Ecoinvent v3.6 commercial DB installed. The flows

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involved in the products were modelled using the ‘Allocation, cut-off by classification’ System Model. Product modelling involved the use of primary and secondary data: the first for the use phase (energy consumption) and all in-house processes, derived by direct measurement of the resources and waste involved; the latter, retrieved from secondary sources, such as scientific literature, LCI DBs and other sector-specific publications and documentation, was used to model commercial components, i.e, electronic components, and outsourced processes.

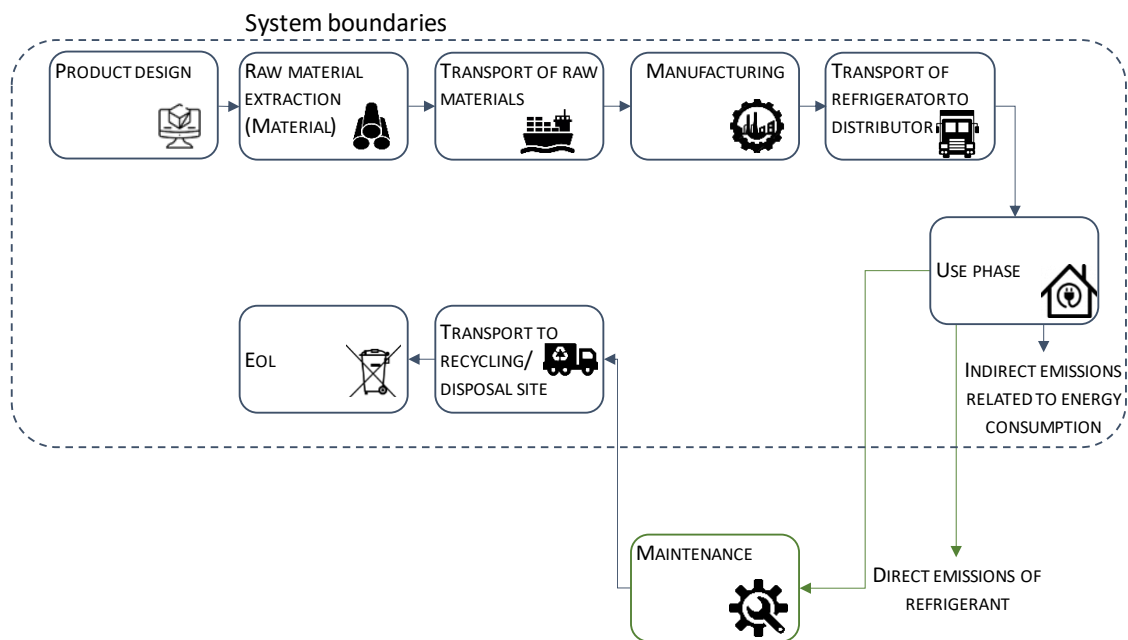


Figure 4.7 System boundaries

Regarding the material and manufacturing phase, the company supplied the BOM of the two fridges, in which the packaging is also included. The company provided all data related to internal manufacturing processes and are the same for the two products. All in-house processes were modeled using Italian datasets (IT) as the factory where the fridges are produced is located in Italy, while for outsourced processes global datasets (GLO) were used. This phase also includes the transport of raw materials and semi-finished products and the transport of the fridges to the retailer. Transports were determined based on the following region-specific assumptions:

- Electric and Electronic Components from China, distance of 6000 km;
- Other components from Europe, a distance of 150 km;
- Transport of fridges to retailers in Europe, a distance of 150 km.

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Data related to the energy consumption of the products (indirect emissions) are included in the use phase. For this data, reference was made to the energy label and a useful life of 16 years was assumed for both fridges. The expected life was thus chosen following European data on the average life of the household appliance⁴⁵. The inventory data collection for the EoL phase was performed following guidelines provided by a leading company in the recycling sector. All components were modeled with the 'Allocation, recycled content'. This model does not give credits to producers for product recycling at their EoL but allocates these benefits to secondary materials.

The methods used for this LCA study are the ReCiPe 2016 Midpoint (H) V1.04 / World (2010) method and the Aware method. Going more in detail, the chosen impact categories are CC [kg CO₂ eq]⁴⁶ and MRS [kg Cu eq], calculated via the ReCiPe 2016 Midpoint (H) method, and WU [m³] [292], calculated via AWARE V1.03 method. For the three impact categories the results obtained are shown in Figure 4.8 and Table 4.3. PrB has a lower environmental footprint than PrA in all the impact categories (about 16% for CC, 7% for MRS and about 17% for WU); however, the material and manufacturing phase of PrA is higher than PrB; this is due to the increase in mass of PrB refrigerator of 6%. For both refrigerators in CC and WU categories the phase that weighs the most over the entire life cycle is the use phase; while for the MRS, it turns out to be the materials and manufacturing phase.

Although PrB has lower annual energy consumption, this phase weighs about 78% (CC) and 64% (WU) on the total environmental impact. The structure of the products is similar, although, in PrB there is a higher percentage of EEC, which acquires a considerable percentage of impacts, especially for the MRS indicator; this is related to the rare elements contained in the electronic components. Manufacturing and transports are negligible if compared with the entire life cycle impact. A focus on the individual phases of the life cycle for the three impact categories is proposed in the following.

The use phase makes the most significant contribution, covering 78% of the total PrB impacts for the CC impact category. Comparing the two fridges, PrB is more sustainable

⁴⁵ EC, Commission Regulation (EC) No. 643/2009 with regard to ecodesign requirements for household refrigeration appliances and Commission Delegated Regulation (EU) No. 1060/2010 with regard to energy labelling of household refrigeration appliances Final Report, 2016 <https://ecodesign-fridges.eu/documents.html>

⁴⁶ ReCiPe 2016 v1.1. A harmonised life cycle impact assessment method at midpoint and endpoint level Report I: Characterisation. RIVM Report 2016-0104a M.A.J. Huijbregts et al. http://www.rivm.nl/en/Topics/L/Life_Cycle_Assessment_LCA/Downloads/Documents_ReCiPe2017/Report_ReCiPe_Update_2017

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from the environmental point of view, with an overall reduction in life cycle impact of 16%. Considering only the use phase, PrB shows an impact reduction of 20% compared to PrA, being more efficient.

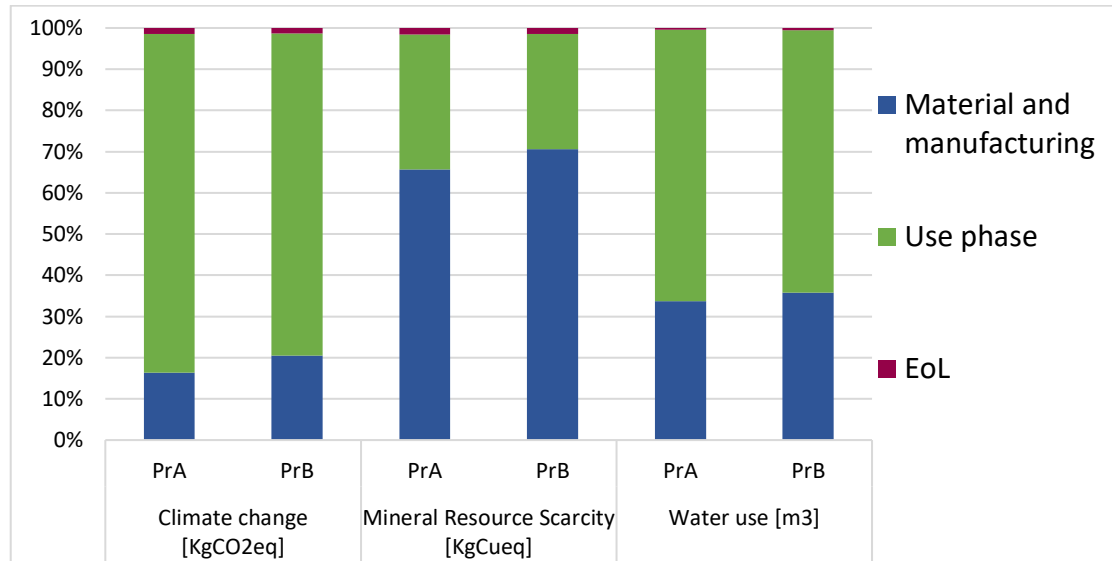


Figure 4.8 Lifecycle environmental impact for PrA and PrB

The EoL phase is negligible and for each impact category, it is at least an order of magnitude lower than the use phase. Table 4.3 shows that for CC and WU, the Use Phase is the most responsible for the environmental burden of the product life cycle.

Table 4.3 Lifecycle environmental impacts for PrA and PrB

Lifecycle phase	CC [KgCo2eq]		MRS [KgCueq]		WU [m3]	
	PrA	PrB	PrA	PrB	PrA	PrB
Materials & Manufacturing	3,63E+02	3,84E+02	7,62E+00	7,65E+00	2,11E+02	1,85E+02
Use phase	1,83E+03	1,46E+03	3,80E+00	3,03E+00	4,12E+02	3,29E+02
EoL	3,12E+01	2,54E+01	1,81E-01	1,54E-01	2,60E+00	2,57E+00

Considering only the material and manufacturing phase, the main contributors of impact are Materials, Compressor and Electric and Electronic Components (EEC).

The compressor is the single component with a higher impact due to its weight and the metals it contains. Considering only the Compressor, it has a relative impact reduction of 36.79%. In PrB, it can be noted a greater impact of the EEC than PrA due to higher weight components (Table 4.4). The EoL contributes 1.4% to the overall impact in PrB; considering only the EoL, PrB shows an impact reduction of 13.91% compared to PrA.

For the MRS impact category, the most critical phase is the material and manufacturing; the main contributors of impact are EEC (29.64%), Materials (34.42%) and Compressor (6.28%), which together cover more than 70% of total impacts. The Use

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phase makes up 28 % of the impacts. Also, for this impact indicator, PrB counts a reduction of the impact of the total life cycle of 7%. Analyzing the WU category, the use phase is the most impactful (64%), followed by materials, compressor and EEC. PrB turns out less impactful than PrA, with an impact reduction of 17%.

Table 4.4 Material & Manufacturing phases' environmental impacts

Module	CC [kgCo2eq]		MRS [kgCueq]		WU [m3]	
	PrA	PrB	PrA	PrB	PrA	PrB
Compressor	4,20E+01	2,66E+01	1,92E+00	6,77E-01	9,92E+01	5,95E+01
EEC	3,27E+01	7,49E+01	1,59E+00	3,20E+00	9,71E+00	1,89E+01
Packaging	7,56E+00	5,23E+00	6,72E-03	5,44E-03	4,15E+00	2,78E+00
Materials	2,71E+02	2,68E+02	4,04E+00	3,71E+00	9,69E+01	1,03E+02
Manufacturing	3,00E-01	3,00E-01	1,65E-04	1,65E-04	2,80E-01	2,80E-01
Transports	9,64E+00	9,14E+00	5,90E-02	6,23E-02	4,90E-01	5,20E-01
M&M Total	3,63E+02	3,84E+02	7,62E+00	7,65E+00	2,11E+02	1,85E+02

4.2.4 Durability index

Two are the target components chosen for the durability analysis of refrigerator and to see how the convenience (from the environmental point of view) of product/part substitution changes according to the nature of the component and the impact indicator. The compressor and the main board were selected because they are critical components whose damage prevents the full refrigerator functionality and because they are different: the compressor is heavy and contains high quantities of ferrous materials (alone, it has comparable impacts to the transport phase and higher than the manufacturing phase for the CC indicator). The main board is much lighter; nevertheless, it contains critical raw materials and contributes one-third of the impacts for the MRS indicator. Table 4.5 shows the environmental impacts related to the production of the target components; those will be used as R_{PrA_n} value and will stand as the environmental burden caused by the substitution of the spare part; the logistics related to the maintenance is neglected.

Table 4.5 Spare parts production's environmental impacts

Parts to replace	CC [kgCo2eq]	MRS [kgCueq]	WU [m3]
Compressor	4,20E+01	1,92E+00	1,92E+00
Main board	1,57E+01	6,62E-01	1,48E-01

The durability index returns a single value that describes a specific circumstance (substitution point); however, Figure 4.11 shows two durability index values for several scenarios and enlarges the view and eases interpretation. In Durabot only the extended version of the durability index has been developed ($D'_{n_{dyn}}$) because the simplified version

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in the dynamic approach is not able to describe the trend of the environmental impacts faithfully. For example, assuming the same lifetime conditions ($T_{PrA}, T_{PrB}, P_{PrB,n}, P_{PrA,n}, E_{PrA}, U_{PrA}, R_{PrA,n}$), $D_{n_{dyn}}$ and $D'_{n_{dyn}}$ are very different. Taking data for the two refrigerators considered in the present work, $D'_{n_{dyn}}$ and $D_{n_{dyn}}$ differs for 7 points (0,172 and -7,89 respectively) when EM and varying energy mix case is analyzed, and for 18 points (-2,52 and -20,37 respectively) when JP aging factor and varying energy mix is considered. This happens for two main reasons. First, PrA and PrB's foam has different aging trends; moreover, even though the aging trend was the same, the use of PrA would occur after T years, and during X years PrA would face the first behavior of foam aging, namely the infusion of air from the environment, while PrB would be much older and may have reached the diffusion of blowing agent gasses stabilization. Assuming the simplified formula a constant gap between PrA and PrB yearly energy consumption, it neglects that after the replacement, PrA's foam has already started deteriorating, while PrB's foam would perform at its best (Figure 4.9). In case of a lack of lifecycle information on one product (i.e., design phase), a revised simplified durability index can be used, by selecting the same product both for PrA and PrB (Eq. 4.3).

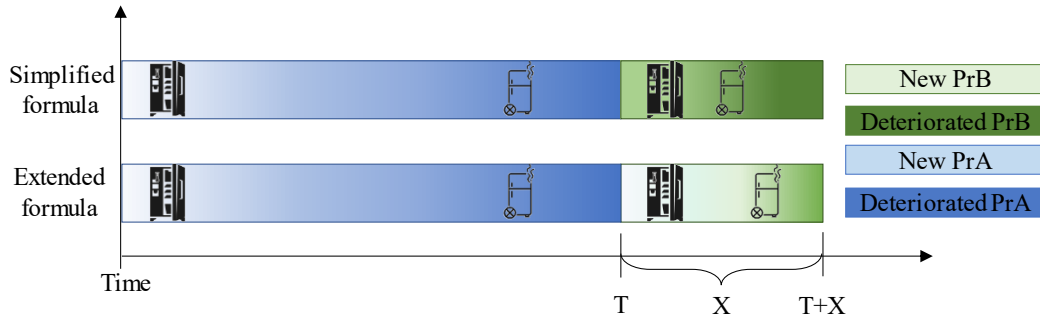


Figure 4.9 The simplified formula considers PrB as already deteriorated at its first year of use; the extended formula describes the real aging process.

$$D''_{n_{dyn}} = \frac{\frac{P_{PrA,n}}{T_{PrA}} X + \frac{E_{PrA,n}}{T_{PrA}} X - (U_{PrA,n,X} - U_{PrB,n,X}) - R_{PrA,n}}{P_{PrA,n} + U_{PrA} T_{PrA} + E_{PrA}} 100 [\%] \quad (4.3)$$

$D''_{n_{dyn}}$ allows to level off the environmental impacts related to the production and disposal of the products ($P_{PrB,n}$ and $E_{PrB,n}$) to the value of PrA, that is the product for which the environmental impacts are known, but keep aside the environmental impact related to the Use phase ($U_{PrA,n,X}$ and $U_{PrB,n,X}$). The simplified, revised version of the

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durability index formula still allows to assess the environmental sustainability of durability also when not all information regarding the more efficient product lifecycle is available. Nevertheless, it more accurately estimates the environmental burdens due to the use phase and the refrigerators decreased energy performances.

Figure 4.10 and Figure 4.11 show two examples of the outcoming Durabot graphs.

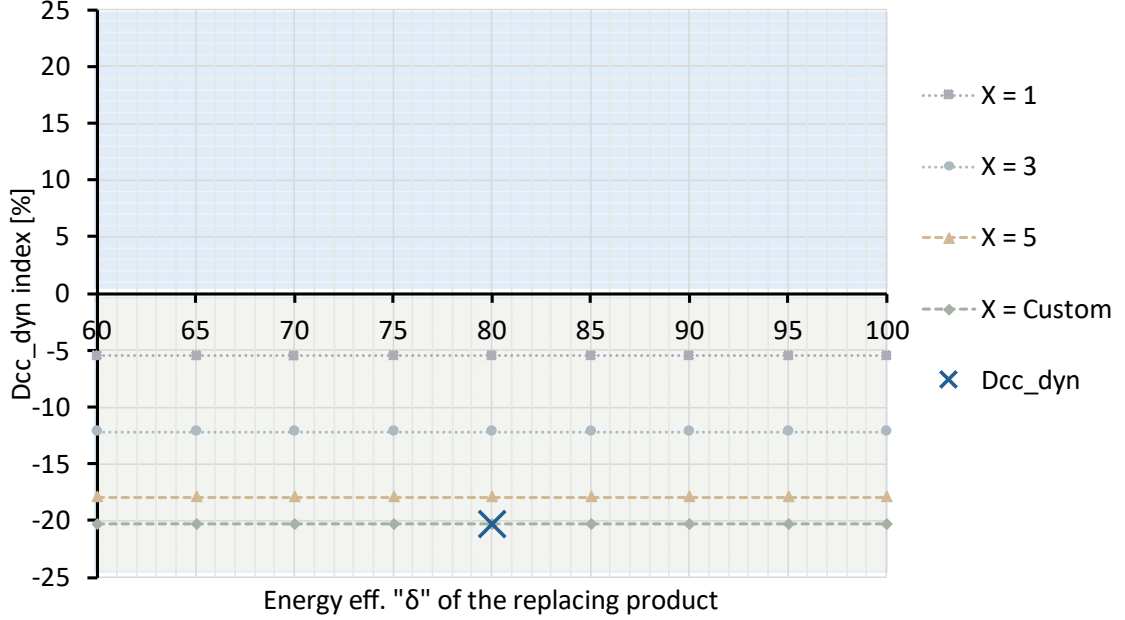


Figure 4.10 Durabot output graph 1, δ variable.

The first graph (Figure 4.10) is obtained by calculating the $D_{n_{dyn}}$ varying the higher efficiency of the new product compared to the first (δ) and the years (X) of the extended use of the product after the part replacement. The graph in Figure 4.11 is obtained for a fix δ , by varying the useful lifetime of product A and the time the replaced part or product is used. The dynamic factors considered are the evolving energy grid mix and the foam performance, according to JP analytical description and relates to CC indicator. A positive value of $D_{n_{dyn}}$ (blue filling) means that the substitution of the component is more convenient, from the environmental point of view, while a negative value (green background) means that the whole product substitution is advisable. In fact, a negative $D_{n_{dyn}}$ means that the environmental impacts due to the energy consumption of PrA ($U_{PrA,n,X}$) together with the production of the spare part ($R_{PrA,n}$) are higher than the environmental impacts due to the life cycle impacts of PrB, appropriately related to the X years. In Figure 4.11 the convenience of substituting the component or the product

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varies with time. The more PrB is efficient and the higher the environmental burden of the spare part production, the higher the negative contribution for $D_{n_{dyn}}$ and the product substitution is advisable. Instead, when the alternative product's energy efficiency is comparable with the first one, and the spare part production does not have a high environmental footprint, the replacement of the single part is recommended. However, in all scenarios, regardless of X and δ , is always advisable to substitute PrA with PrB. This is due to the high discrepancy in energy consumption of the two refrigerators and the steeper aging that PrB faces: the yearly consumption of PrB in year 11 is about 70% higher than the consumption of PrA in year 1, according to JC. Even being PrA consumption stable and PrB consumption rising, after 6 years (X), PrB requires almost double the electricity as PrB. From the geometrical point of view, following Eq. 3.3., the slope of the lines (always positive when the second product is more energy efficient than the first) depends on the energy consumption of the products: the higher the disparity the higher the slope.

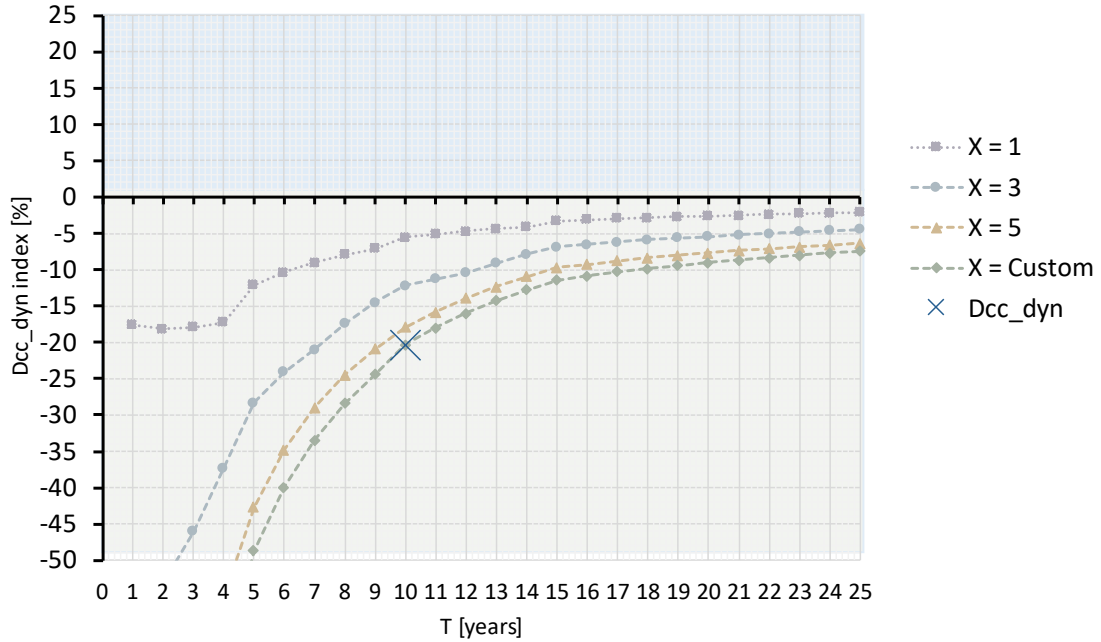


Figure 4.11 Durabot output graph 2, T variable.

The substitution point in the graphs is calculated considering the following hypothesis: $T=10$, $\delta= 80\%$ and $X=6$. Table 4.6 shows $D_{n_{dyn}}$ values for the same assumption under several circumstances: foam aging trends, environmental indicators and spare parts to be replaced are progressively considered.

Table 4.6 Durability index results for compressor and main board spare parts

External factor	Aging	Indicator	$D_{n_{dyn}}$	
			Compressor	Main board
Energy mix evolution	-	CC	7,44	9,46
	EM		-7,82	-6,29
	JC		-45,15	-44,2
	JP		-20,32	-19,23
	-	MRS	6,07	18,74
	EM		-2,03	9,44
	JC		-26,64	-17,44
	JP		-10,1	-0,2
	-	WU	31,7	32,11
	EM		30,85	31,25
	JC		27,57	27,97
	JP		29,56	29,96
Legend	Part	substitution	Component	substitution

Green cells contain negative values (PS is recommended), while blue cells advise substituting the component. The main board is more likely to be replaced, while the compressor, counts lower $D_{n_{dyn}}$ values. Regardless of the initial assumptions, the conventional case (no foam aging considered) always assumes the higher value of $D_{n_{dyn}}$ while JC the lowest. This is easily explained: if foam aging is neglected the decreasing impacting trend of energy consumption partially or fully offsets the lower energy consumption of PrB and its production and disposal impacts allocated to the X years.

The higher the number of years after the product/part replacement, the higher the convenience of replacing the component instead of the refrigerator. Instead, as foam aging is considered too, the whole product replacement is advised, due to the high increase in energy consumption faced by PrA because of the higher initial yearly consumption and faster aging rate. However, a very high variance is registered between one analytical description and another: therefore, a more faithful representation of foam aging is needed. The nature of the spare part influences $D_{n_{dyn}}$: the compressor environmental impact is higher than the environmental burden of the main board; this is reflected in higher values of $D_{n_{dyn}}$ for the main board case: the higher the environmental impact to substitute the broken part, the less likely its substitution is environmentally convenient. Consequently, the lower environmental impact is retained by the production of the spare part, the more it contributes to having the component substituted instead of the product. In addition to that, also the impact category indicator plays an important role: concerning the MRS

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R_{MRS} , both for compressor and the main board have a considerable weight if compared with the environmental impact due to the yearly energy consumption, while the impacts of the two spare parts are much lower than the impacts due to the energy consumption in CC.

4.3 PReSCoM

4.3.1 Scraps characterization

The PReSCoM approach proposed in Section 3.2 was applied by four companies from the Marche region in the center of Italy. Three of them (labeled as G1, G2 and G3 in Figure 4.12) made their scraps available to be worked and employed as secondary raw materials in different production processes (guests). G3 turned out to be a host (H3); H1, H2 and H3 refer to different products of the same company, that produces espresso coffee machines and grinders.

The scraps of company G1 come from marble (natural material) and porcelain stoneware (composite) manufacturing; company G2 produces sinks for domestic kitchens. Company G3 designs and produces wind blades.

The scraps are off-quality products (that cannot be commercialized because they do not satisfy the customer quality standards and requirements) or process scraps (i.e., dust or pieces from Computerized Numerical Control - CNC - machining). In addition, their dimensions are unstable and unpredictable due to process inaccuracy. The As-Is analysis evaluates the environmental burdens through LCA) methodology and tool, deriving from the extraction, production, and disposal of the annual quantity of scraps produced by the three guest companies.

Table 4.7 summarizes LCI data and results for the environmental assessment of the scraps deriving from processes of G1, G2 and G3. For each waste type the percentages in weight of annual scraps are indicated, together with the material and respective composition, when multiple materials are part of the same waste typology. By employing composite materials, enterprises can accomplish the high efficiency of working conditions and durability of products. After being discarded, the scraps of G1 fill an old quarry; although smart and sustainable (as far as marble is concerned), this solution does not valorize the potentialities of the scraps. Sink scraps are fully incinerated after being pre-treated in dismantling centers.

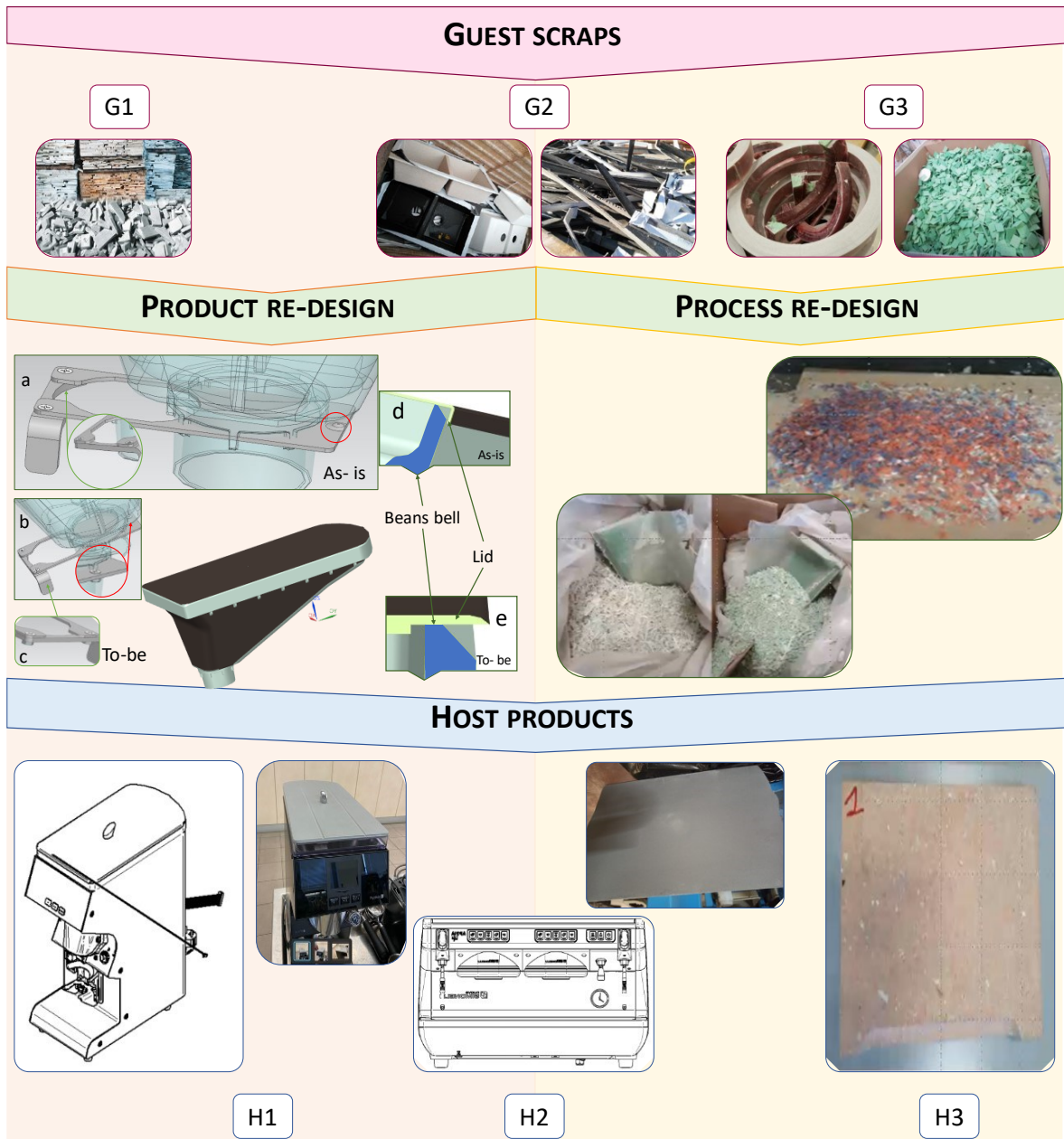


Figure 4.12 Product and process re-design to optimize the EoL of scraps of guest companies 1, 2 and 3. Scraps from G1 and G2 are introduced in the H1 product, thanks to the components' re-design. Scraps from G2 are also used in H2, after a process re-design. Scraps from G3 are introduced as secondary raw materials for consumables in the H3 process. Orange-filled areas concern the product re-design; areas colored in yellow, the process re-design.

In Table 4.7 the current disposal scenario is reported, with details of the means of transportation used to move the scraps. G2 and G3 produce goods made of composite materials; the blades' scraps are partially incinerated with heat recovery; the remaining is sent to disposal; prior to that, the waste is shredded and compressed in both cases to lower its volume.

Table 4.7 LCI scraps and Environmental impacts distribution

#	SCRAPS/COMPONENTS				Current disposal scenario	Transport
	Category	Quantity*	Material	Composition		
G1	Slime	18%	Dust - mixed		Quarry re-development	Road, truck
	Pieces	35%	Marble		Quarry re-development	Road, truck
		40%	Silica sand	6%		
			Clay	48%		
			Feldspar	46%		
			Granite			
		10%	Quartz granulates	93%		
			Polyester	7%		
			Epoxy resin	20%		
G2	Sink scraps	87%	Mineral	70%	Incineration	Road, truck
			PMMA**	25%		
			Additives	5%		
	Sink dust	13%	Mineral	70%	Incineration	Road, truck
			PMMA**	25%		
			Additives	5%		
G3	Glass fiber scraps	0,32	Glass fiber		Landfill (33%)	Road, truck
					Incineration (66%)	
	Plastic waste	4%	PVC***		Landfill (75%)	Road, truck
		5%	Polyamide			
		3%	Synthetic rubber	70%		
			Buthacrylate	30%		
		3%	PET****			
		34%	Catalyzed Epoxy Resin		Incineration (25%)	
		30%	Epoxy adhesive ^a			
			Glass fiber ^a			
			Epoxy Resin ^a			
		5%	Epoxy Resin ^b	40%		
			Glass fiber	42%		
			Carbon fire ^b	30%		
		Coating waste dust	6%	Epoxy Resin	80%	
Insulating	20%					

*per year **PMMA= Polymethyl methacrylate ***PVC= Polyvinylchloride

****PET= Polyethylene Terephthalate

^a Blade trimming ^b Blade root trim

0-10%	11-20%	21-30%	31-40%	41-50%
51-60%	61-70%	71-80%	81-90%	91-100%

Similarly happens for the sink scraps that are fully incinerated. Waste is always pre-treated in at least two dismantling centers before being incinerated or conferred to a landfill (Figure 4.13). Unless specific projects or strategies are launched, enterprises are unaware of what happens to their scraps (or their product) once discarded. In Figure 4.13 it is clear that G1 knows how its scraps are confined; G1 took part in a project aimed at

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re-filling an old quarry close to the manufacturing plant. What G2 and G3 expect for their scraps (pink-filled boxes) is different from what happens (green-filled boxes), not only for intermediate steps (i.e., sorting) but also for the final disposal (incineration/landfill). The ultimate information was retrieved by interviewing the direct supplier the companies have contact with. The sorting and mixing phase refers to sorting the scraps collected by the supplier and the mix with scraps of the same nature that come from other industrial realities.

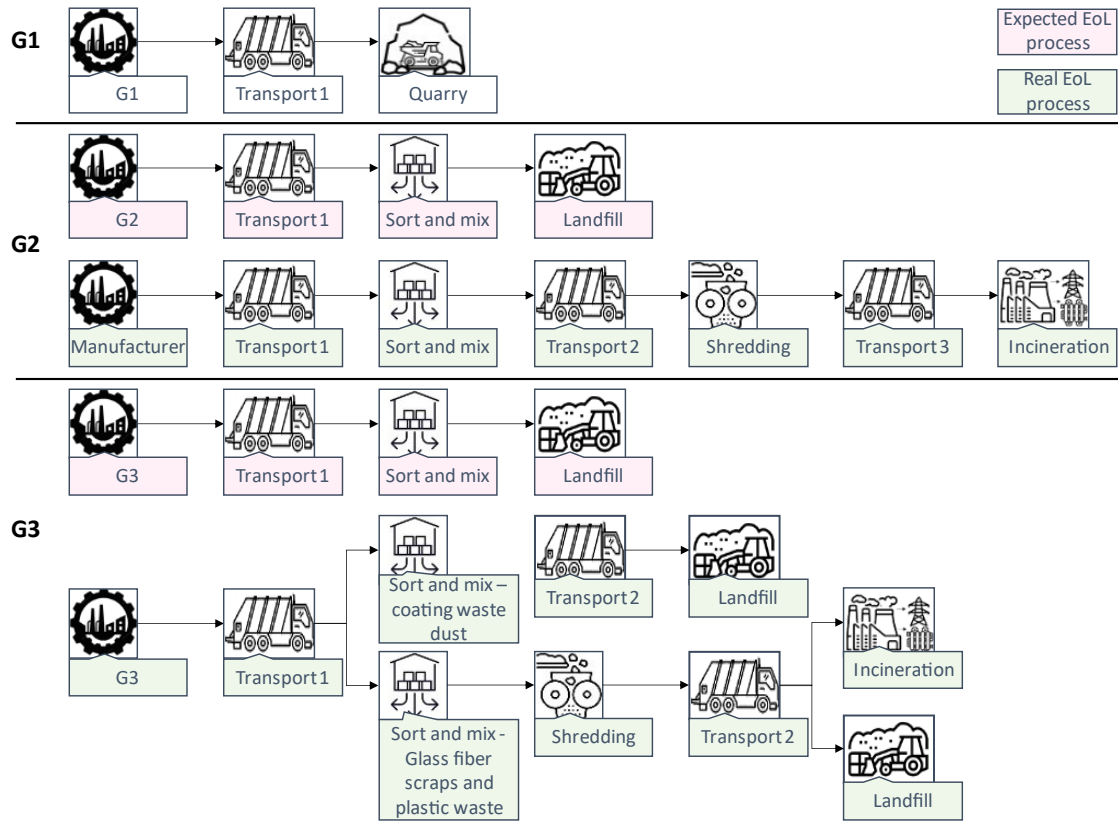


Figure 4.13 EoL Life cycle inventory. Enterprises are not aware of what happens to their scraps. Pink-filled boxes depict what organizations think their scraps undergo. Green-filled boxes show the actual processes and travels.

The colors of the cells in Table 4.7 quantify the percentage of environmental burden accounted for each lifecycle phase for the CC indicator. The material and EoL phases were considered. The analysis was carried out with the support of SW the SimaPro 8.0, EcoInvent v3.6 DB, and results were calculated by the Recipe MidPoint (H) method. The material phase is the most impacting (more than 85%, with a peak of 91% for G3), followed by the EoL phase. Wind blades and sink scraps disposal is responsible for about 10% and 15%, respectively. Transportation and treatments prior to the final disposal are

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negligible. G3 waste pre-treatment impacts, such as grinding, compacting and transportation, is lower than 1%.

4.3.2 Components' characterization

The components characterization requires first a ranking of the most impacting components of the host products. Therefore, the environmental impact of the product lifecycle is assessed. Two products are considered: a professional coffee grinder (H1) and a professional coffee machine (H2). The FU for the first's product LCA was the product's production, use and disposal; and so was the FU for the H2.

Figure 4.14 shows the LCA analysis results for the GWP indicator (H1). The EoL phase was modelled considering the same assumption: most of the product's weights come from components made of metals; those are recycled up to 70%; the remaining is shredded and sorted as Waste from Electric and Electronic Equipment (WEEE). According to the design parameters, it is assumed that the coffee grinder and the coffee machine are used daily in Italy for 5 years and produce 36 coffees per hour on average. The same tools that supported the quantification of the scraps' environmental burden were also employed in this phase (SW SimaPro 8.0, equipped with EcoInvent v3.6 DB, results calculated by the Recipe MidPoint (H) method).

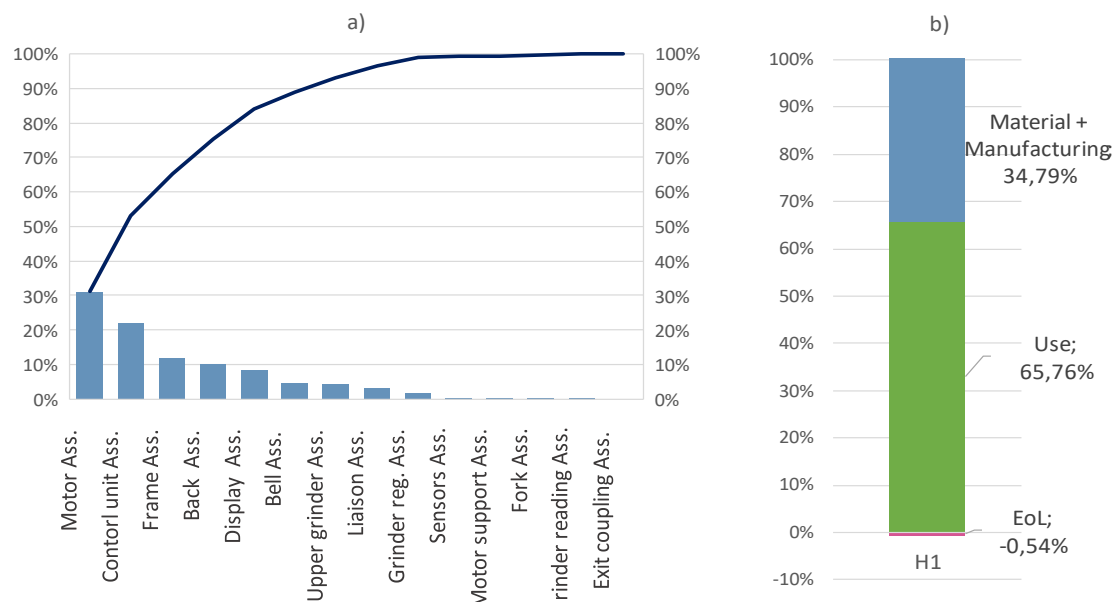


Figure 4.14 As-is environmental impacts of professional coffee grinder (H1), for GWP indicator [KgCO₂eq]. On the left (a), a detail of environmental impact distribution for the Material and Manufacturing phase; on the right (b) lifecycle impact assessment.

Over the whole lifecycle, the first counts impact about 5,0 E+2 KgCO₂eq. The production of the coffee grinder impacts more than 30%. Regarding the EoL phase,

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materials recovery allows for obtaining low credits from the EoL treatment. H2 major impacts are retained mainly by the use phase (more than 90% of the overall impacts, Figure 4.15). The Back Assembly for H2 is the second most impacting assembly.

The results of environmental analyses, both for scraps and coffee grinder, show several potential improvements; first, introducing the composite scraps into alternative value chains would nullify their environmental burden deriving from the actual EoL scenario (Table 4.7). Secondly, their use in different goods would lower their material phase impacts.

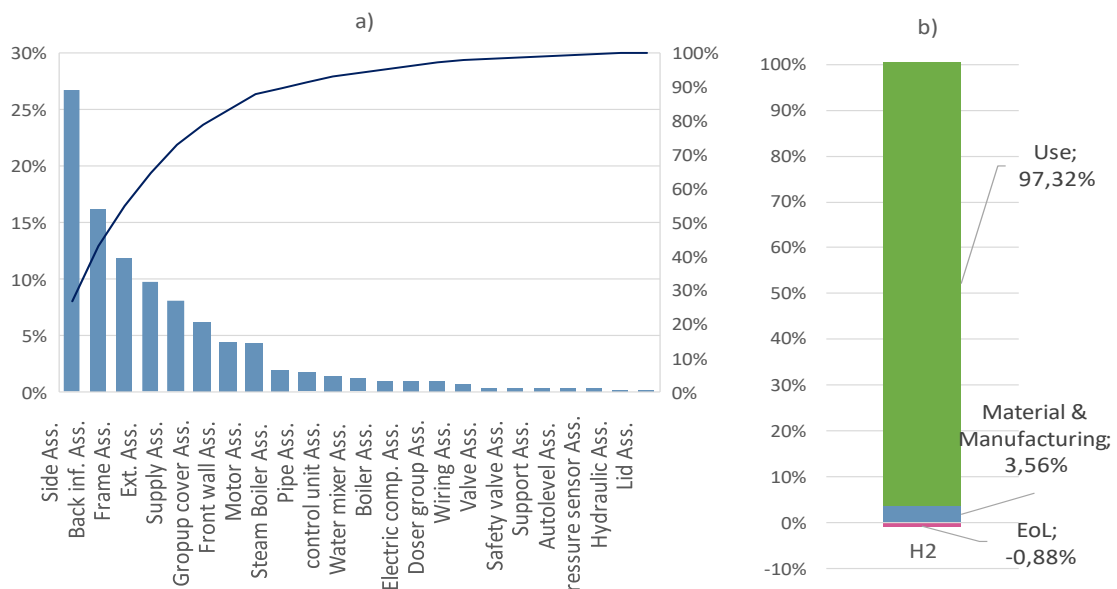


Figure 4.15 As-is environmental impacts of professional espresso coffee machine (H2), for GWP indicator [KgCO₂eq]. On the left (a), a detail of environmental impact distribution for the Material and Manufacturing phase; on the right (b) lifecycle impact assessment.

4.3.3 Product re-design

Circular scenarios' feasibility is strictly related to technological and functional constraints. For example, although the scraps of guest companies have simple geometries, their peculiar manufacturability lowers the chances of being re-used in differentiated scenarios: they cannot be heated, or their properties alter; they cannot be extruded nor threaded, nor welded, but can be milled. These are strong constraints that must be considered when identifying the potential target component of the host products.

The scraps deriving from sink off-specification have vast flat areas, holes (i.e., for water draining) and their thickness is limited to a few millimeters (less than 1cm). G1 provides flat sheets of scraps, different in thickness and dimensions (from a few mm to 1

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m wide). The scraps deriving from wind blades are either high in one dimension and curve (trimmed part of the blades) or made of materials that do not accomplish the strength, resistance and corrosion parameters for the coffee grinder, nor of the coffee machine (i.e., PVC scraps or glass fiber patches).

According to scraps characteristics, host products' components were classified according to their shape. Five components were identified, one for H2 (back cover) and three for the coffee grinder: i) the buttons plate, ii) the company logo, iii) the guillotine kit and iv) the lid. As far as the back cover is concerned, its high environmental burden and simple shape made it one of the best candidates to re-use scraps; however, its aesthetic constraints, which overlap with its function, prevent its re-design; in the current state, any scrap ensures the right shape and dimension; for this reason, its process re-design has been evaluated. More details will be provided in the next paragraph. The analysis of the potential circular scenarios that would value the scraps deriving from the production of the wind blades did not identify any processes that would implement those wastes in H1 nor H2. A possible shredding or grinding of the blades may obtain very few pieces of blades that may be compressed to obtain insulating panels or shaped to be melded to produce new products. These alternatives are investigated in the next paragraph.

The button plate has holes where the buttons to switch to working/off mode the grinder fit; it is also provided with pins and tiny wings to attach it to the frame; the logo is meant to be attached to the back of the grinder, it is similar to a “v” geometry and presents a simple, curved shape; the function of the guillotine kit is to stop or allow the coffee beans to pass through it when it slides to the right or left respectively. The kit comprises two screws that link the guillotine and the support used by the barman to activate the locking system. The main technological complication is the unfeasibility of modifying the shape of the scraps, except for the cutting/milling processes. Therefore, the buttons plate was discarded among the target components and similarly the logo because their re-manufacture would require bending the sheet, or the aesthetic constraint would not be accomplished. The guillotine kit and the lid were set as targets. The first belongs to the bell group, and it is located at the bottom of the assembly. The lid shape instead is intended to link it with the bell and have the part stable over it.

4.3.3.1 *Guillotine kit*

The original design of the guillotine kit expects it to be made of stainless steel; its production accounts for 3,5% of the environmental burden of the bell group. The current

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design of the guillotine (Figure 4.11a) expects the part to have a camber (red circle) to allow the component to stop and position in the right place relative to the bell group (light blue part). Therefore, a re-design was needed to overcome this obstacle. Starting from the current design, the re-design hypotheses consider using scraps to obtain the guillotine and the support and link them with a bolt (Figure 4.11b). The green profile areas show the guillotine's different link between As-is (Figure 4.11a) and re-design (Figure 4.11c): the latter requires a bolt instead of a simple screw. The bolt is necessary because neither the PMMA nor the porcelain stoneware can be threaded. Nevertheless, considering disassembly, the support and the guillotine are easily detachable. In the case of re-using the scraps of G2, the bent part of the sink enables the support to be made of scraps, too; this is not possible with the porcelain stoneware or marble; thus, the support material remains the same (stainless steel), nevertheless disassemble. Table 4.8 summarizes the main composition changes. The resources employed in the re-manufacturing process (milling) have been considered and their impacts have been evaluated through the Recipe MidPoint (H) method in SimaPro 8.0, EcoInvent v3.6 DB.

Table 4.8. Product and process re-design. Guest products are the scraps used as new raw materials in host products. The material composition and main production processes are shown for As-is and To-be cases. The EoL refers to the hypothesis assumed when modeling the product it refers to.

Part	Guest Host		As-is			To-be		
	prod.	prod.	Material	Manufacturing	EoL	Material	Manufacturing	EoL
Product re-design								
Guillotine	$\frac{G1}{G2}$	H1	Stainless steel	Deep drawing + CNC milling	H1	$\frac{\text{Stainless steel} + G1 \text{ scraps}}{\text{Stainless steel} + G2 \text{ scraps}}$	CNC milling	$\frac{G1}{G2}$
Lid	G2	H1	steel, low alloyed	Deep drawing	H1	G2 scraps	CNC milling	G2
Process re-design								
Panels	G3	H3	Eulithe, Ureol, MDF*	Milling	G3	G3 scraps	Shredding + cold cure + milling	G3
Back cover	G2	H2	Aluminum	Milling and coating	H2	G2 scraps	Shredding + cold cure + coating	G2
*MDF = Medium-density fiberboard								

Results show great sustainable potentialities of the implementation of the redesign, as summarized in Figure 4.16. The graph shows the environmental impacts of the products manufactured with traditional materials and techniques (blue scale bars) and with scraps

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(purple scale bars). The green line explicates the percentage of reduction of impacts due to the product/process re-design.

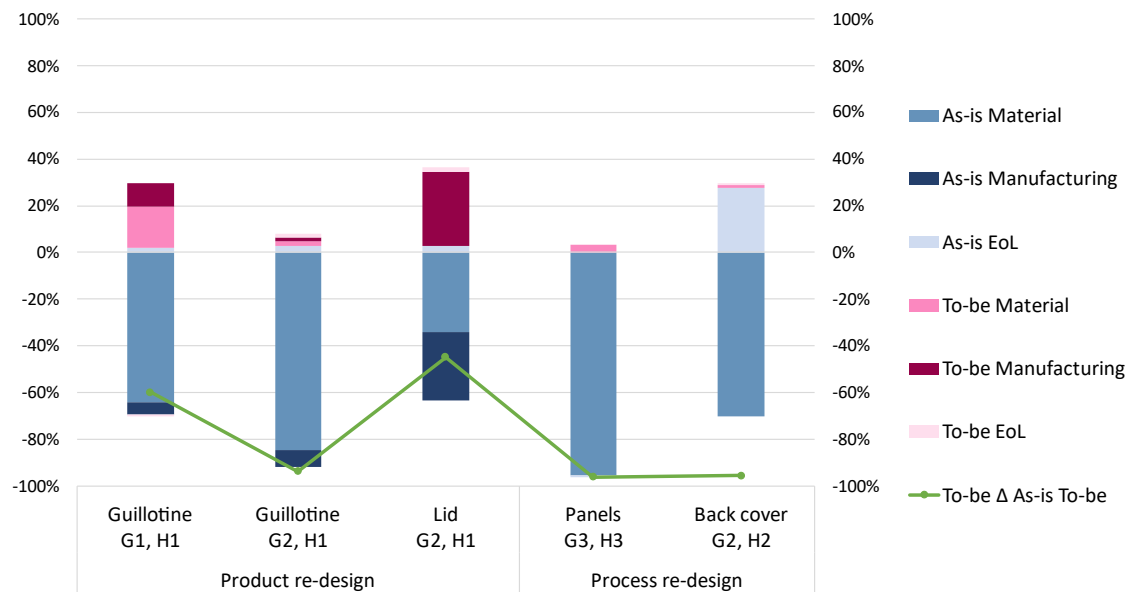


Figure 4.16 Environmental impact comparison between initial new design.

The changes from low alloyed steel to plastic composites (Mineral + PMMA + Additives) and the re-design lead to a reduction of more than -90% (G2, H1) of overall impacts related to the production of the guillotine (Figure 4.16). Although lower, the introduction of the waste from the G1 process also ensures lower environmental impacts related to the production of the guillotine (-60%).

4.3.3.2 Bell assembly lid

Figure 4.12 shows how the lid of the bell of the coffee grinder has been re-designed (Figure 4.12 e), so the re-manufacturing of the off-quality sinks is feasible. The picture does not show the knob, which is useful to handle the lid, because it is also maintained in the new configuration; it is bonded by a screwed inserted in a hole on the lid. The lid is the component in dark; the gray part in the details (Figure 4.12 d and e) is the beans bell. Light green and blue sectors are the planes crossed by the section plane: the first for the lid, the blue for the wall of the bell. In the initial configuration, the bend sides that ran over three sides of the lid made introducing the sink unfeasible. Re-design actions modified its geometry so that bending and material-adding processes are avoided: the bent parts were eliminated and substituted with a thickness reduction around the perimeter of the lid. This ensures the correct positioning of the lid over the beans bell. Table 4.8 summarizes the main changes, while Figure 4.16 assesses how the new scenario allows

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the companies to achieve lower environmental burdens. There are benefits from the environmental point of view in introducing sink scraps as secondary raw material in the coffee grinder. The re-design determined a reduction of volume of -10%; additionally, a reduction higher than 45% of impacts due to the lid production is obtained.

4.3.4 Process re-design

4.3.4.1 *Wind blades*

The geometric features and the manufacturability constraints of the wind blade process scraps did not find any placement in H1 or H2. Therefore, alternative treatments have been investigated. The scraps cannot undergo any chemical process; otherwise, their properties change. However, mechanical treatments are allowed. The core material, the blade trim (that comes from the blade finishing process) and the blade root trim (what is left from the finishing of the base of the blade) were shredded so that they were used to obtain new panels as their dimension dropped. Those are introduced in the same process but with a new function: the panels are employed to make models or mold to be milled; subsequently, prototypes are obtained from them. The panels with secondary raw materials replace sheets of polyurethane polymer (i.e., Eulithe, Ureol) or MDF. Table 4.8 summarizes the main differences in material composition between the traditional process and the new one, whose disposables are made of secondary raw materials. Figure 4.16 compares the environmental burden caused by traditional and innovative processes. The panels' milling for mold production is neglected, as it is a phase common to both processes. Regarding the new panels, both the resources employed in shredding and curing are considered.

4.3.4.2 *Back cover*

An innovation similar to the panels' production for the wind sector (H3) has been introduced in the coffee machine's back cover production (H2). The back cover is a part that presents big dimensions, and its function is primarily aesthetic, as it consists of hiding (from the bartender and the coffee shop customer) and protecting (from dust and other undesired substances) internal components. G2 scraps, especially those of lower dimensions, deriving from the trim of the safety and drain holes and the sink profile, have been shredded and subsequently the back cover obtained from them, through cold cure. The main material composition and environmental impacts are compared in Table 4.8 and Figure 4.16, respectively. The prototype of the back cover is shown in Figure 4.12 (H2). All the investigated situations account for a reduction of CO₂ emissions and line up as

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promising measures aimed both at combating CC and achieving a successful application of the CE principles: what is produced from an industrial process is employed as raw material for a different product, attesting a reduction of natural resources exploiting.

4.4 Dfd tool

The proactive approach finds application in the development of a DfD tool. Figure 4.17 shows the workflow expected for the DfD tool and its architecture. It provides a procedure to effectively use eco-design knowledge during the first phases of the design process. For the SW prototype development, 3 sub-projects have been defined. All 3 components have chosen the C# programming language and the .NET Framework 4.6.2, while their functionality is divided as follows:

- Tool Gui (View + Controller) is a Windows Application type Windows Forms, represents the graphic component of the SW, and contains the structure of the interfaces and the essential components of their operation;
- Tool Lib (Model) is a Class Library and is the component that manages imported data and internal SW components, such as index calculations and analyses;
- Solid Edge Interface (Model) is a Class Library and is the component that communicates with Solid Edge to integrate CAD models and make them immediately importable.

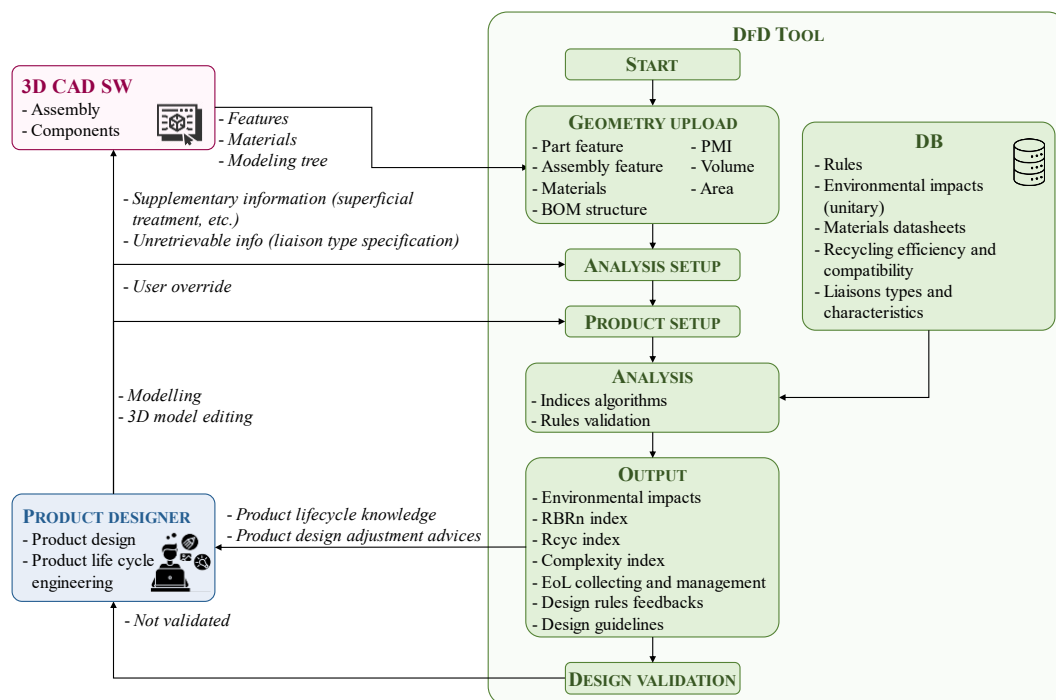


Figure 4.17 Workflow and DfD structure

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The SW is equipped with an SQLite relational DB, which stores the "fixed" data to be used in the analysis. It preserves, for example, information related to materials, EoL strategies, environmental impact indicators, and iterations data related to the function that the components perform within the document (links and fasteners). Figure 4.18 shows the Entity–Relation diagram (ER) that visually summarizes the entities in the DB and their main relationship.

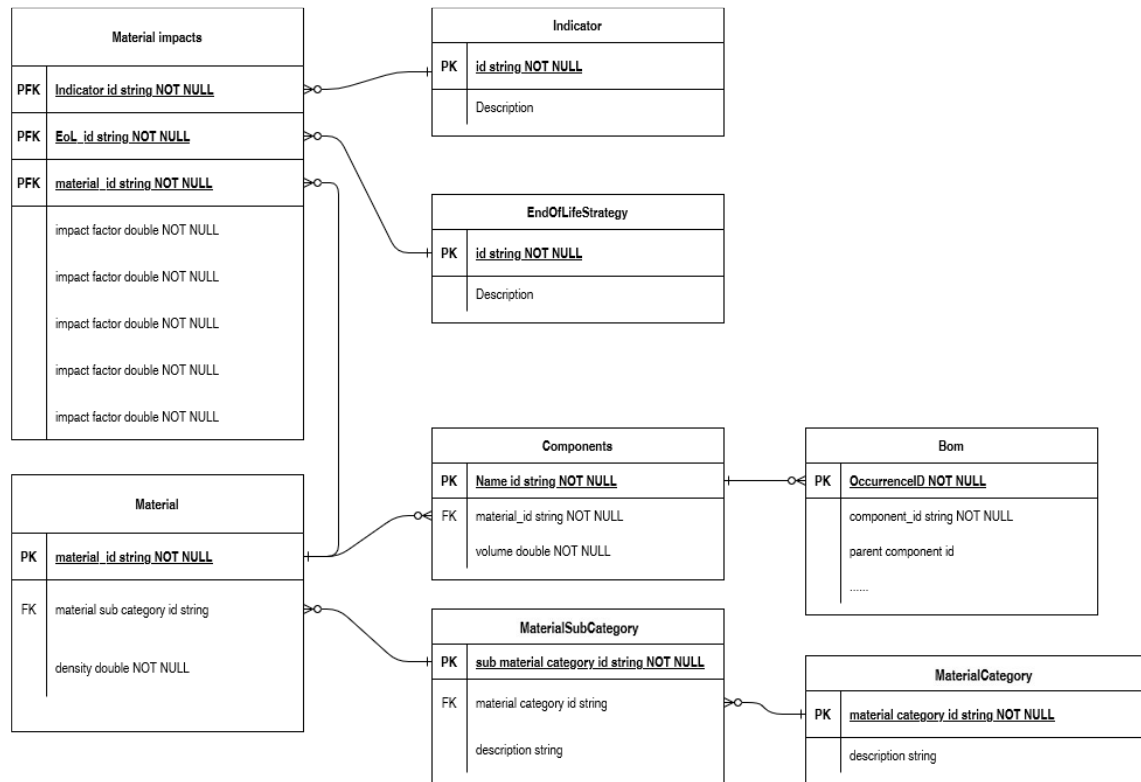


Figure 4.18 ER diagram of the DfD tool DB

Figure 4.19 shows the main interface presented to the user as the tool is launched. The Given a material, a name (string), density and a sub-category are attributed to it. Multiple sub-categories can belong to a single category. The subcategory and category attributes are Primary Keys (PK), as they distinctively identify the entity they belong to. For each material unitary environmental impacts are defined. It is necessary to state the indicator, the lifecycle phase and specific strategy for the lifecycle phase (if present) they refer, to define environmental impacts. Consequently, the indicator id, the EoL id and the material id are Primary Foreign Keys (PFK) as they act as PK in more than one table, which occurs in tables with an identifying relationship (i.e., material impacts, indicator, EoL strategy). tabs the user can navigate mirror the SW's main functionalities. They are:

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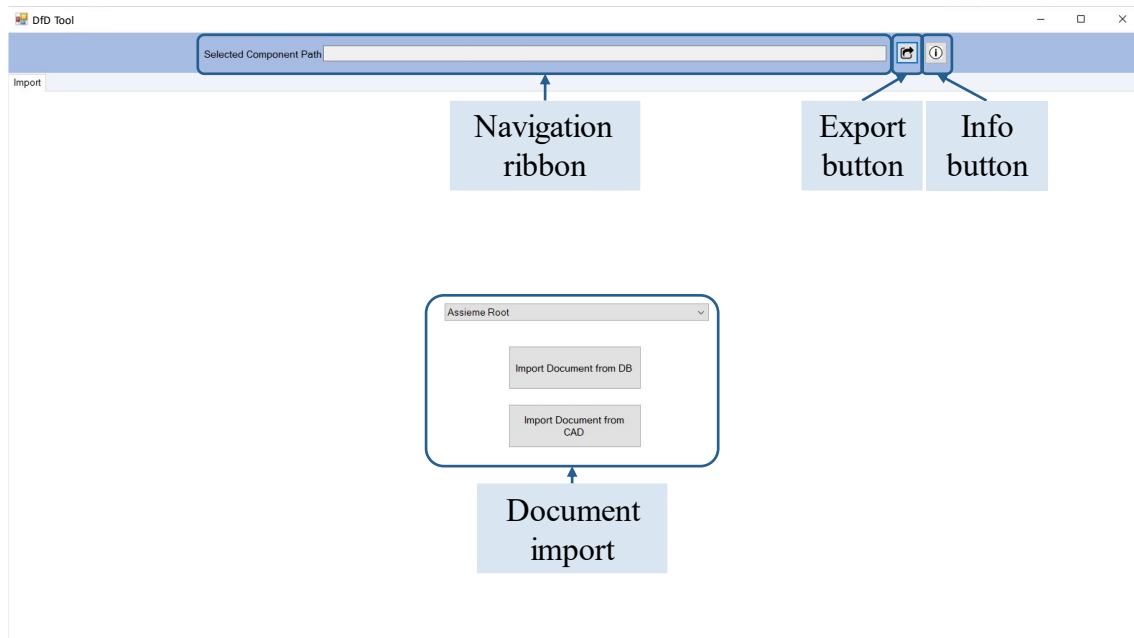


Figure 4.19 DfD tool home interface

- Component Structure: displays the internal structure of the component and allows you to switch from one assembly to another in order to evaluate the individual parts which make up the document in the analysis (an exemplification image is provided in Figure 4.20);
- Environmental Impacts: performs and shows the calculation of environmental impacts (Section 4.4.1);

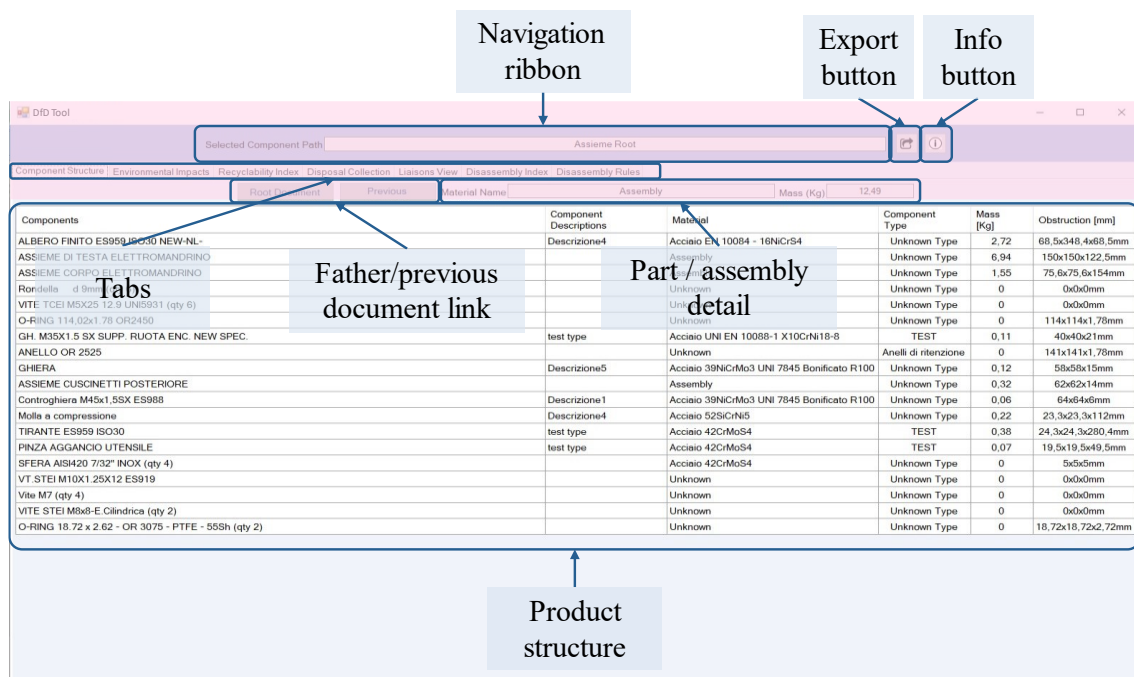


Figure 4.20 DfD tool, example of interface.

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- Recyclability Index: performs and shows the calculation of recyclability indexes;
- Disassembly Index: performs and shows the calculation of the disassembly index;
- Disposal Collection: performs and shows disposal analysis;
- Design Rules: exploit the main product criticalities and guide the product re-design.

Figure 4.20 shows an example of the operating interface: the bar on the top, highlighted in pink, is fixed and allows the user to move between functionalities (tabs). The part path (navigation ribbon) and the part/assembly detail bars update as the analyzed part is selected.

4.4.1 Environmental impacts

The DB contains information about the unitary environmental impacts related to the pre and production of materials. If scaled adequately, this allows to evaluate in advance the environmental impact of the components, proportional to the volume and weight of the components examined; in addition, the variation of impacts for different EoL strategies. The environmental impacts are retrieved through the EF Method^{47,48} which allows quantifying of environmental impacts according to different categories and related indicators. Therefore, the output is therefore quantifying potential impacts according to different categories of damage (for example, CC, Ozone Depletion, Resource use-mineral and metals, Resource use-energy carriers). Furthermore, the impacts will be shown divided by phases of the life cycle (e.g., impacts related to the raw material, processing impacts, and disposal impacts). The unitary impacts of material production and eol processes have been retrieved with SimaPro 9.1, provided with EcoInvent 3 DB. The user sets the analysis by choosing the impact category (Figure 4.21); drop-down menus list the impact categories and the imported parts and sub-assemblies, from which the one to be analyzed is selected. Regardless of the indicator chosen, all the results are quantified, but only the chosen impact category is displayed.

An overall picture is obtained if data are exported. The analysis set up is completed after the output is chosen: bar chart, 100% bar chart, or pie chart are available. The selection influences the right part of the window. Regardless of the tab considered, one graph per time can be displayed in a tab. On the bottom, a table summarizes the

⁴⁷ European Platform on Life Cycle Assessment, 2020, <https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml>

⁴⁸ Simapro, 2020, SimaPro database manual – Methods library, <https://simapro.com/wp-content/uploads/2020/10/DatabaseManualMethods.pdf>

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information, listing the parts and assemblies involved in the analysis, the father group they belong to and explicating the environmental impacts for each. Percentages on the left side of the window distinguish the percentage of environmental impacts deriving from the analyzed phases, i.e., material and EoL.

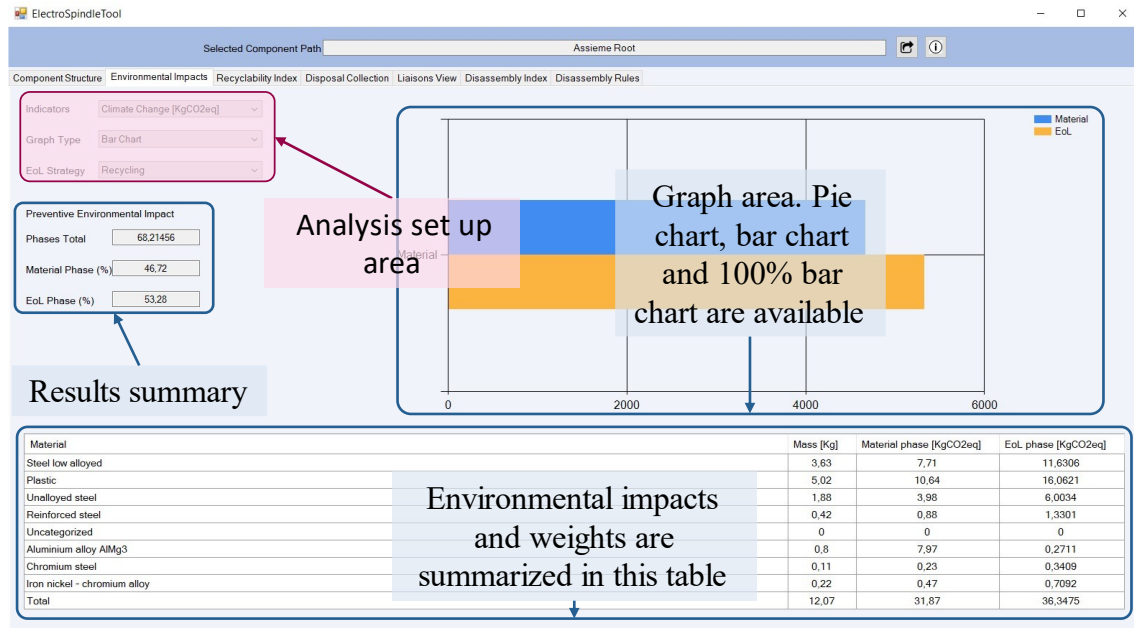


Figure 4.21 Environmental Impacts tab interface

4.4.2 Recyclability index

The recyclability modules provide feedback to the designer regarding how much the product is recyclable. Numerous indexes are proposed in the literature; some follow quantitative approaches or are the result of qualitative methods, analytical tools, indicators based on specific values or the result of the composition of indicators to assess circularity. There is a general lack of uniqueness and uniformity in the calculation of indices. The lack of standardization of definition, measurement criteria and tools leaves a great deal of freedom in choosing indicators, depending on the context of use. Talens et al.⁴⁹ defined the EoL-RIR (End Of Life Recycling Input Rate); although it can be traced back from the general case in Europe to the specific case of the individual company, this index has not been considered because it requires a large amount of EoL's supply chain information, which turns in complication and is subject to high variability. The recyclability index by Villalba et al. [293] uses the material recyclability index to

⁴⁹ European Commission, Joint Research Centre, Talens Peiró, L., Blengini, G., Mathieux, F., et al., Towards recycling indicators based on EU flows and raw materials system analysis data : supporting the EU-28 raw materials and circular economy policies through RMIS, Publications Office, 2018, <https://data.europa.eu/doi/10.2760/092885>

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determine whether it is economically feasible to disassemble a product. First, the percentage by weight of the product composed of materials with a high recyclability ratio is calculated. This estimates how much the product can be recycled, theoretically. Then, a profit-loss margin for recycling is calculated to determine whether it is economically feasible to recover that percentage of materials with a high recyclability ratio previously calculated. If the margin is positive, then it is economically possible to recycle that product, and if it is negative, some actions could be taken to achieve a positive margin. This index was not selected because it is mainly focused on the economic aspect rather than the environmental one and does not introduce variables on which a manufacturer (OEM) can directly act, except in the reduction of materials used in the same product. In the DfD tool, two different indexes are provided: the RBR suggested by Huysman et al. [250] (RBR_n , where n is the unit of measure of the selected impact category) and R_{cyc} , provided in the recently released standards CEN CENELEC - UNI CEI EN 45555:2020⁵⁰. Two indexes are proposed, so the DfD tool has broad applicability: from one side the RBR_n is a complete index; however, it requires specific environmental information; indeed, the R_{cyc} index accomplishes European standards and is much simpler; however, it is intended for ERPs. The RBR assesses the rate of the recyclability benefit, i.e., the ratio between the environmental potential saved that obtainable by recycling the product in environmental charges of virgin production followed by disposal (4.4).

$$RBR_n = \frac{\sum_{j=1}^P \sum_{i=1}^N m_{recyc,i,j} RCR_{i,j} (V_{n,i,j} + D_{n,i,j} - R_{n,i,j})}{\sum_{j=1}^P \sum_{i=1}^N m_{i,j} V_{n,i,j} + M_n + U_n + \sum_{j=1}^P \sum_{i=1}^N m_{i,j} D_{n,i,j}} \quad (4.4)$$

Where:

- P is the number of parts in the product;
- N is the number of materials contained in the j_{th} part of the analyzed product;
- U_n is the environmental impact due to the use phase of the product [n];
- $m_{i,j}$ is the mass of i_{th} material of j_{th} part of the analyzed product [kg];
- $m_{recyc,i,j}$ is the recyclable mass of i_{th} material of j_{th} part of the product [kg];
- $D_{n,i,j}$ is the environmental impact due to the final disposal of 1 kg of the i_{th} material of j_{th} part of the analyzed product [$\frac{n}{kg}$]; as the index expresses the ratio between recycling and alternative EoL disposal strategies, $D_{n,i,j}$ can refer to landfilling, incineration w/o energy and heat recovery;

⁵⁰ <https://store.uni.com/uni-cei-en-45555-2020>

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- $V_{n,i,j}$ is the environmental impact due to the production of 1 [kg] of the i_{th} virgin material of j_{th} part of the analyzed product [$\frac{n}{kg}$];
- $R_{n,i,j}$ is the environmental impact due to the production of 1 [kg] of the i_{th} recycled material of j_{th} part of the analyzed product [$\frac{n}{kg}$];
- M_n is the environmental impact due to the manufacturing process of the product [n];
- $RCR_{i,j}$ is the recycling rate⁵¹ of the i_{th} material of j_{th} part of the analyzed product.

$RBRn$ is an indicator defined as the ratio between the potential environmental savings that can derive from the recycling of a product compared to the environmental impacts of the production of virgin material, then sent to landfill or incineration. In other words, it indicates how many fewer emissions (if positive) are emitted if the product is recycled, sent to incineration, or landfilled.

The $RBRn$ has high values if all parts of a product are recyclable ($m_{recycl} = m_{tot}$); the amount of material leaving the recycling process is equal to the amount of material introduced into the recycling process ($RCR=1$); the impact of the recycling process is low ($R \sim 0$). $RBRn$ can take low values or be negative. This happens when little material in the analyzed product is recyclable (low m_{recycl}), or there are many losses in the recycling process ($RCR \sim 0$) or the recycling process is very impactful (high $R_{n,i,j}$). If the $RBRn$ is high, the recycling process brings many benefits; indeed, if the index is small or less than zero, recycling is inefficient and impactful. The $RBRn$ therefore represents an index of comparisons between recycling and other EoL strategies. Due to its simplicity, the calculation of R_{cyc} is immediate, but minor changes and relative improvements/worsening (i.e., replacement of recyclable materials with other recyclable materials) may be omitted. R_{cyc} is calculated as follows:

$$R_{cyc} = \frac{\sum_{k=1}^n m_k R_{cyc_k}}{m_{tot}} 100\% \quad (4.5)$$

Where:

- m_k is the mass of the k_{th} material;
- m_{tot} is the total mass of the analyzed product;
- R_{cyc_k} is the recyclability factor of the k_{th} material.

⁵¹ RCR= Recycling Rate. Is the quantity of recycled material produced (output) per kg of waste in input if losses are considered during the recycling process.

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In the DfD tool the table at the bottom of the interface reports the intermediate calculation of the index (i.e., $D_{n,i,j}$, $R_{n,i,j}$, $V_{n,i,j}$ and so on); the recyclability indices results are on the left side of the window. The delta, on the other hand, represents the ratio between the two recyclability indices in percentage. Finally, an additional box contains an account of the recyclable, and non-recyclable materials and their masses: this information is also reflected in the pie chart, which shows the individual materials and differentiates them based on their recyclability (recyclable materials are colored in blue scale, those not recyclable are red scale).

4.4.3 Disassembly complexity index

In disassembly, complexity is the extent to which individual parts or subassemblies have geometric/physical attributes that can cause difficulties or problems when handling and removing components. The methodology proposed in this research integrates the evaluation of the manipulation complexity with the quantitative evaluation model of the complexity of disassembly. In the DfD tool the complexity index proposed by Soh et al. [111] and Das et al. [294] (Eq. 4.7) is assessed:

$$I_{com} = \frac{C_h + C_r}{2} \quad (4.6)$$

Where C_h is the average index of handling complexity and C_r is the average removal complexity index. The result is an average of the two, so the same weight is given to the two aspects considered. The central aspect is that the calculation is not done considering only the link between the part/subset.

4.4.3.1 Average handling complexity index C_h

The average manipulation complexity index is defined as in Eq. 4.7, while the complexity of handling is defined in Eq. 4.8

$$C_h = \frac{\sum C_{h,f}}{3} \quad (4.7)$$

$$\sum C_{h,f} = Rating_{Size} + Rating_{Thickness} + Rating_{Mass} \quad (4.8)$$

The three addends depend on the weight and dimension of the considered part or assembly. The linear dimensions refer to the dimensions of the bounding box of the considered object, with the three dimensions laying parallel to the axis of the cartesian reference system of the CAD 3D model. Defined the $Operation_{type}$, $Rating_{Thickness}$ is calculated through Table 4.9. The $Operation_{type}$ considers the maximum size that can be handle with one or two hands or with the support of tools if the dimensions require it.

Table 4.9 Rating thickness

Operation Type	Thickness min [mm]	Thickness max [mm]	Rating
One Hand	0	0,25	1
One Hand	0,25	2	0,5
One Hand	2	38	0,27
One Hand	38	70	0,5
One Hand	70		1
Two Hand	70	300	0,27
Two Hand	300	400	0,5
Two Hand	400	600	1
Automation	600		1

The *Thickness* is the minimum dimension along X, Y and Z directions. The range of values defined in Table 4.9 consider the tables relating to the gripping measures for a hand and the rating values agree with the study by Soh et al. (Figure 4.22) [111].

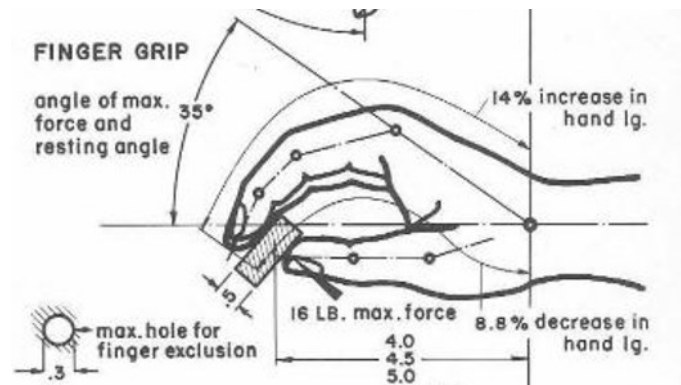


Figure 4.22 Thickness dimensions maneuverable with one hand

$Rating_{Size}$ is calculated through Table 4.10: in accordance with the $Operation_{type}$.

Table 4.10 Rating size

Operation Type	Size min [mm]	Size max [mm]	Rating
One Hand	0	6	1
One Hand	6	15	0,81
One Hand	15	38	0,75
One Hand	38	70	0,81
One Hand	70		1
Two Hand	70	460	0,75
Two Hand	460	610	0,81
Two Hand	610	910	1
Automation	910		1

The size refers to the diagonal dimension between the maximum and average dimensions along X, Y and Z, according to Eq. 4.9.

$$Size = \sqrt{(\max(x, y, z))^2 + (\text{somma}(x, y, z) - \max(x, y, z) - \min(x, y, z))^2} \quad (4.9)$$

Ranges consider the tables relating to gripping measurements (Figure 4.23)

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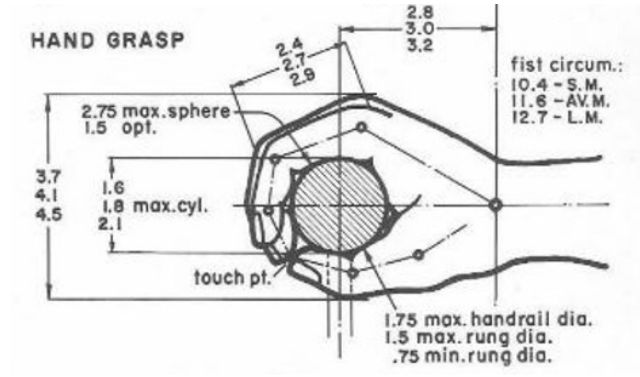


Figure 4.23 Dimensions graspable with one hand

$Rating_{Mass}$ is calculated according to mass value; ranges are in line with the study of Soh and al. [111].

Table 4.11 Rating Mass

Mass min [kg]	Mass max [kg]	Rating
0	1,125	0,2
1,125	2,25	0,4
2,25	3,375	0,6
3,375	4,5	0,8
4,5		1

4.4.3.2 Average removal complexity index C_r

The removal complexity index is calculated for the single link between parts. If one part is linked several times, the calculation is repeated n times, where n is the number of liaisons (links). The removal complexity index is obtained as the sum (Eq. 4.10) of the single complexity indexes:

$$C_r = \sum_{i=1}^N C_{r,i} \quad (4.10)$$

Each single removal complexity index is calculated as in Eq. 4.11:

$$C_{r,i} = U_{Effort} * 0.4 + (R_{NumT} + R_{TR} + R_{OT}) * 0.2 \quad (4.11)$$

Where:

- U_{Effort} is the effort required to move the part;
- R_{NumT} is the rating attributed according to the number of required tools;
- R_{TR} is the rating attributed according to the type of required tools;
- R_{OT} is the rating attributed according to the type of operation.

R_{NumT} is calculated according to Table 4.12, where values from the study of Soh et al. [111] have been partially retrieved, revised and normalized.

Table 4.12 Rating number of required tools

Number of Tools	Rating
0 tools	0
1 tool	0,3
2-3 tools	0,6
>4 tools	1

R_{TR} is calculated according to Table 4.13, where values from the study of Das et al. [294] have been partially retrieved and normalized.

Table 4.13 Rating type of required tools

Tools Required	Rating
None	0
Mechanic	0,5
Special	1

R_{OT} is calculated according to Table 4.14, where values from the study of Das et al. [294] have been partially retrieved and normalized.

Table 4.14 Rating operation type

Operation Type	Rating
None	0
One-hand	0,3
Two-hand	0,6
Automation	1

It is calculated automatically evaluating the mass and the maximum dimensions along X, Y and Z (Table 4.15).

Table 4.15 Dimensions – mass relationship to derive the operation type

Dimension	Mass [kg]					
	< 1,125	< 2,25	<3,375	< 4,5	<20	>20
< 38	one hand	one hand	one hand	one hand	two hands	automation
< 70	one hand	one hand	two hands	two hands	two hands	automation
> 70	two hands	two hands	two hands	two hands	two hands	automation

U_{Effort} (Figure 4.24) values depend on the connection type: fastener (presence of a connecting element) and non-fastener (the link is derived from the part itself). Values are shown in Table 4.16. The number of liaisons indicates the number of connections, that is, how many links are present on that specific part or assembly; instead the number of fasteners (Num_F) indicates how many times that specific link is repeated for the analyzed coupling. An example is provided: a part is linked with three different parts (Number of Liaison = 3); each liaison can be made of more than one fastener, such as:

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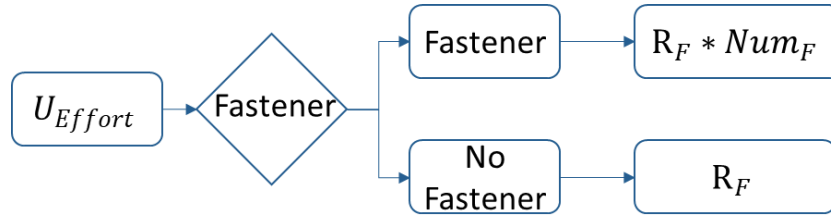


Figure 4.24 U_{Effort} rating schema

- Coupling 1 = Connection with screws
 - o Number of screws = 3 ($Num_F = 3$)
- Coupling 2 = Interference
- Coupling 3 = Connection with screws
 - o Number of screws = 6 ($Num_F = 6$)

Table 4.16 U_{effort} for link w/o fasteners

Fastener	Rating	No Fastener	Rating
Retaining Rings/Circlips	0,83	Interference Fit	1,00
Screw/Bolt special head	0,73	Integrally Threaded Part	0,73
Nut e Bolt	0,70	Cylindrical Snap fit	0,53
Adhesive	0,70	Seam/Crimp Joint	0,53
Rivets/Staples	0,67	Cantilever Snap fit	0,43
Nail w/o head or Pin	0,60	Socket and Plug	0,40
Releasable Clips	0,60	Free Part	0
Tape	0,57		
Nail with Head	0,50		
Screw/Bolt standard head	0,47		
Velcro/Zipper	0,33		
Free Part	0		

The user interface requires the user to define whether the complexity index should be obtained on absolute terms or, rather, compared to the average I_{com} of all the parts analyzed (only for assemblies); the second choice is about the different types of graphs that can be shown. Regardless of the choice of the user, a table and a summary are provided: the first contains the analyzed components' list and $C_h, C_r, I_{com}, I_{com}[\%]$ for each part. The summary reports the total I_{com} , the medium, maximum, minimum and fashion.

4.4.4 Disassembly and compatibility

This function identifies why certain parts are not recycled once they reach their EoL. The criticality here stands in joining components of different materials that are not recyclable anymore when assembled in a more extensive assembly. This is because the

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recycling process requires homogeneous flows. The tab is structured as follows: the user can set the analysis by choosing the analysis sensibility and the output type (graphical or table). The sensibility relates to the materials' recyclability classes. For example, the value of recycled materials can derive from a good sorting of input materials; however, for a material, sub-categories may be identified, as for stainless steels, where more homogeneous flows allow higher alloy control. The greater detail enwidens the user view on optimized recycling processes. Output data are structured as follows:

- A table on the bottom lists the material classes and the components that are allocated to each class;
- On the right, the materials detected from the model are grouped according to the category they belong to (pie chart); alternatively, the product structure is proposed, highlighting whether the components and/or sub-assembly can be recycled together or should be disassembled. Each line contains the sub-assembly name and is colored: green if all the materials in the sub-assembly belong to the same class and red if not.
- The tables on the left (one is the analysis only refers to the first level of analysis) summarize the information by materials category and sub-category, also indicating the percentage of mass;

The information provided by this function highlights all the parts that should be disassembled to ensure a high level and great output from the recycling process. When recycling a product, the fewer parts dissembled, the lower the time and costs needed. On the contrary, when sub-categories are considered, the user can evaluate whether it is convenient to disassemble certain parts to ensure better recycling performance. The remaining DfD functionalities support the designer in this sense.

Figure 4.25 shows an example of an interface for the current function. The red line on the right outlines that that assembly contains sub-assemblies that do not belong to the same sub-category.

The green lines below highlight sub-assemblies made of materials that can be recycled indistinctly together without disassembling, nether hampering the recycling process performances. Their materials are reported. The user can navigate the product structure: each sub-assembly can be entered (i.e., for the assembly highlighted in red). Differently from the product structure presented in the first tab, the navigation in this tab does not alter the analysis in the remaining tabs.

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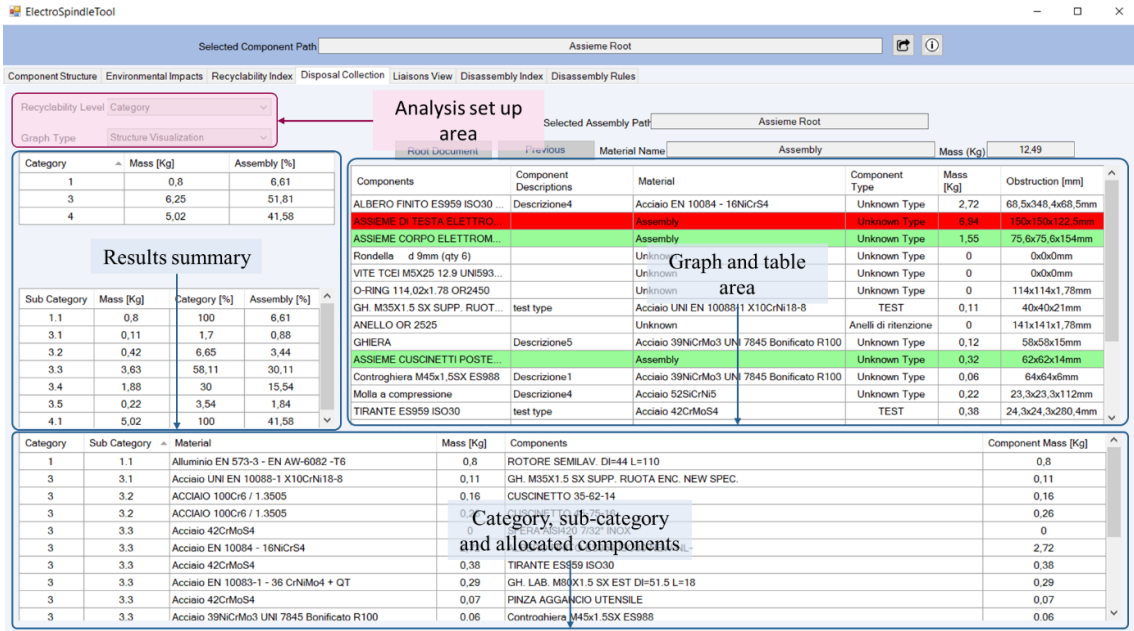


Figure 4.25 Disassembly and compatibility tab interface

4.4.5 Guidelines

This functionality aims at correlating and interpreting the results of the previous functions and thus should be addressed afterward. The main goal is to exploit the previously obtained results to understand the leading causes of the highlighted criticalities. For the time being, only the focus on the complexity of disassembly is addressed. The algorithm is reported in Figure 4.26. A threshold (S) is defined or the automatically suggested is chosen.

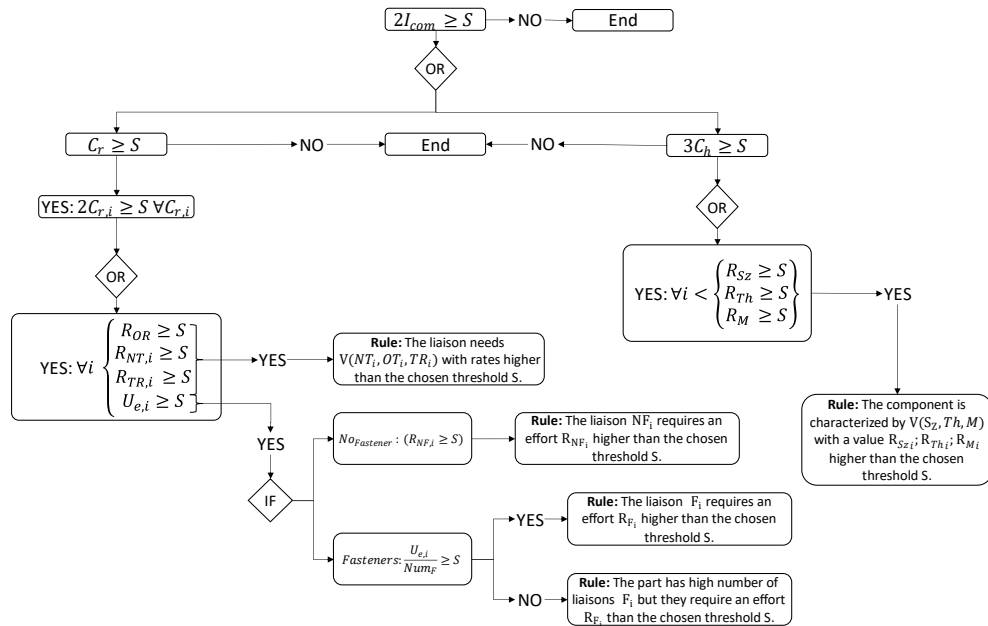


Figure 4.26 I_{com} exploitation algorithm for every j component

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As all the factors that contribute to obtain I_{Com} are normalized and assume values between 0 and 1, it is possible to check criticalities, by comparing them and S . The proposed algorithm should be applied to every component (j). The criticalities' causes arise through the algorithm; for example, whether the component is too small or big, if it is linked to many components and/or the liaisons are difficult to detach. As soon as a criticality is obtained, a rule appears, highlighting it to the user and guiding the designer where considerations are needed. The tools' proactive nature lies in the chance to launch the analysis several times during the design process: at any point of the modeling, the designer can choose to analyze it; whenever criticalities arise, the design can be revised, and solutions proposed. By doing so, the tool is well integrated into the design process and fulfills its goal of anticipating environmental issues sufficiently in advance in the lifecycle.

4.5 Design of an electrospindle shaft tree supported by DfD tool

The first application of the DfD tool is to subassembly an electrospindle. An electrospindle is an advanced electric motor that hooks the tools to work aluminum, steel, glass, wood and is installed in CNC machines or robotic cells. It is composed of two main blocks (Figure 4.27): the shaft kit that encompasses the rotor, the pneumatic cylinder, and the hooking system and the extrude-stator that contains the electronic parts, the cooling system, and the stator. The Italian company that produces the electrospindle wishes to introduce environmental sustainability considerations in the design process. The electrospindle must not withstand any EoL regulation or eco-design directive yet. Environmental sustainability is relatively new for designers, who have very different backgrounds and almost no experience in that.

The DfD tool successfully provides pills to guide the designer, highlighting criticalities (high environmental impacts or difficulty in disassembly) never considered before. Besides the market requirements, which are still far from requiring documentation on the sustainability of electrospindles, the company wishes to act proactively so that its offer may enlarge and the business is ready when the expected requests come. Moreover, currently, the OEM of the electrospindles mainly handles only used, guaranteed electrospindles that return to the headquarters whenever a failure occurs. Knowing the precious resources employed in the product (alloyed steels, expensive components, etc.) and the high reliability that characterize the electrospindle, the company wishes to

investigate whether it can gain profit from incoming electrospindles. This means it consists of properly sorting the material flows, rather than substituting damaged modules and sending back the electrospindle to the market. The following paragraphs report the main results obtained by analyzing the shaft kit through the DfD tool.

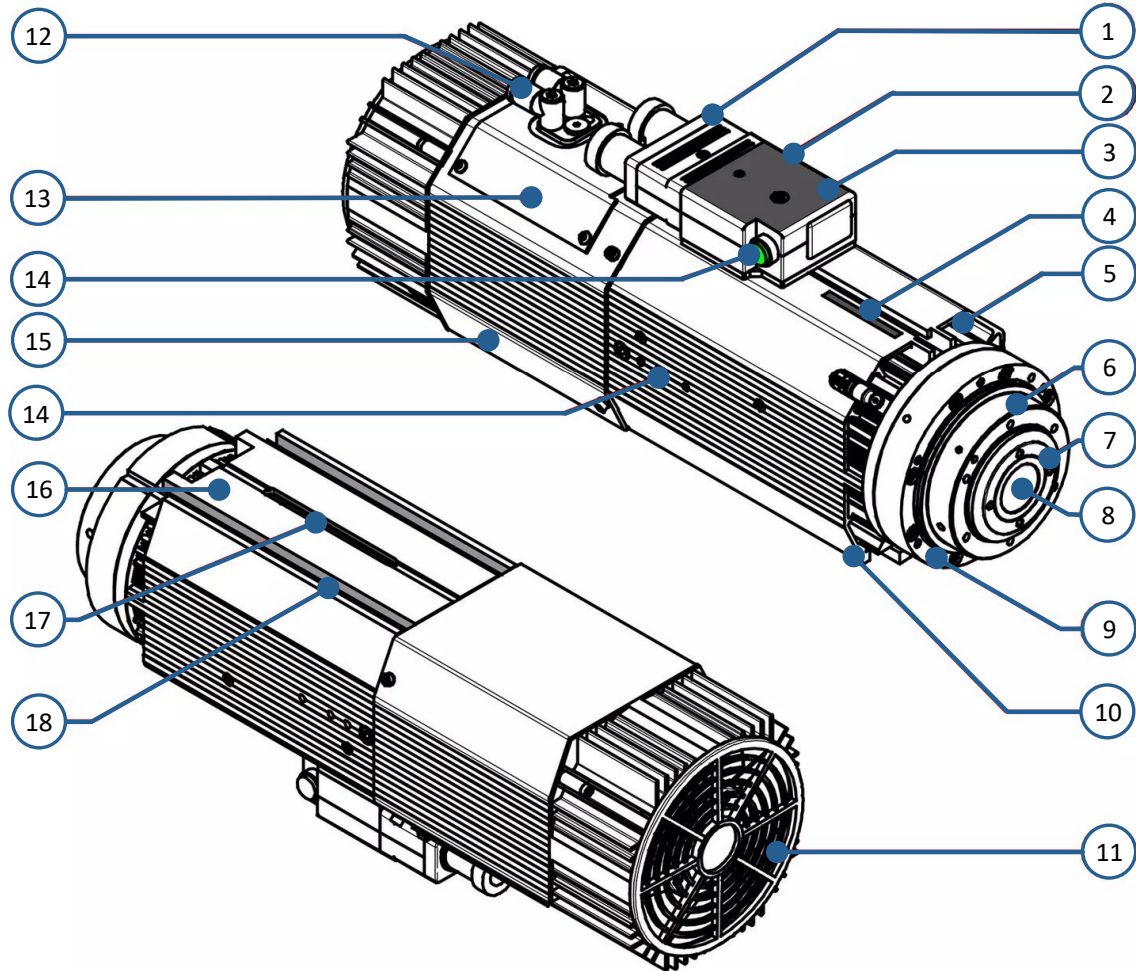


Figure 4.27 Electrospindle main parts: 1. Fixed electrical connectors; 2. EC marking plate; 3. Encoder connector; 4. Serial number; 5. Connector for sensors on accessories; 6. Fore flange; 7. Shaft; 8. Tool hooking system; 9. Threaded bores for accessories; 10. Extrude-stator; 11. Cooling fan; 12. Pneumatic connectors; 13. Cover of the sensor area; 14. Manual release of tool holder; 15. Pneumatic cylinder; 16. Rear case; 17. Lang centering; 18. Slot fixing.

Regarding the environmental impact tab, the tool highlights much higher impacts (kgCO₂eq) for the material phase rather than the EoL phase. As expected, the recyclability indexes highly differ. Considering the CC impact category, the RBR_{kgCO_2eq} registers high values, as most of the materials are recyclable. The R_{cyc} value is almost one. The spindle, especially the shaft kit, is mainly made of metals, such as aluminum, steel, cast iron, and copper in the rotor. Thus, no big criticalities arose. However, their

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assembly partially alters this equilibrium. Table 4.17 summarizes the different outcomes retrievable by choosing the category or sub-category level in the analysis: the material in the spacers belongs to the sub-category 3.2; the ferrule is made of similar material (3.1) recyclable with the previous, but should be separated to achieve better performance. The fore flange assembly is critical both at category and sub-category level: the fore flange is made of cast iron, that belong to the group 2, while the remaining materials belong to group 3.

Table 4.17 Category and sub-categories' compatibility for the electrospindle

Name	Level	Position	Type	Material	Mass [kg]	Comp. category	Comp. sub-category
Shaft kit	1	1	par	Steel EN 10084	2721		
Fore flange assembly	1	2	asm	N/D	6944	No	No
Fore flange	2	2.1	par	Cast iron UNI EN 1561	5019	2	2.1
Spacers	2	2.2	asm	N/D	1123	Yes	No
Internal ring spacer	3	2.2.1	par	Steel EN 10083-2	359	3	3.2
External ring spacer	3	2.2.2	par	Steel EN 10083-2	764	3	3.2
Ferrule	2	2.3	par	Steel EN 10083-1	289	3	3.1
Bearings assembly	2	2.4	asm	N/D	512	Yes	Yes
Bearing 45-75-16	3	2.4.1	par	Steel 100Cr6	256	3	3.1
Thread UNI 5927	2	2.5	par	Stainless steel 316	1E-3	3	3.2
Thread UNI 5927	2	2.6	par	Stainless steel 316	1E-3	3	3.3

The columns *Level* and *Position* contain information about the assembly structure: Level 0 is the full product; the successive Levels show the parts or sub-assemblies to disassemble afterward if the sub-assembly of the previous level is considered. The *Position* lists the sub-assemblies or components contained. In addition, the *Position* contains information about the potential disassembly path to follow when disassembling the considered part: for a part whose *position* is $X.Y$, it means that it is the Yth component to be disassembled of the Xth sub-assembly. Instead, from the *Level* information, it is impossible to understand the sub-assembly the considered component belongs to. For example, the bearing and the internal and external ring spacers have the same level, but belong to different sub-assembly (bearing assembly and spacers, respectively). The following function, related to the compatibility, reveals that some modules should be

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removed for high efficiency in the recycling process (i.e., fore flange, spacers' module). The disassembly complexity index supports the designer in evaluating whether the detachment of these components is feasible. Table 4.18 summarizes the primary outcomes.

Table 4.18 I_{com} results for the shaft kit assembly of the electros spindle

Level	Position	#	Description	I_{com}	%
1	1	1	Shaft ISO 30	2,202	225%
1	2	1	Fore Flange assembly	0,619	-9%
2	2.1	1	Fore Flange	1,727	155%
2	2.2	1	Spacers	0,486	-28%
3	2.2.1	1	Internal ring spacer	0,253	-63%
3	2.2.2	1	External ring spacer	0,253	-63%
2	2.3	1	Ferrule	0,695	3%
2	2.4	1	Front bearings assembly	0,486	-28%
3	2.4.1	2	Bearing 45-75-16	0,253	-63%
1	3	1	Body assembly	0,728	8%
2	3.1	1	Extrude- stator	0,287	-58%
3	3.1.1	1	Compass rotor	1,003	48%
3	3.1.2	1	Rotor	0,603	-11%
3	3.1.3	1	Compass rotor ring	0,603	-11%
1	7	1	Ferrule - wheel supporter	0,512	-24%
1	8	1	O-ring	0,537	-21%
1	9	1	Ferrule	1,370	102%
1	10	1	Rear bearing assembly	0,486	-28%
2	10.1	2	Bearing 45-75-16	0,253	-63%
1	11	1	Lockferrule	1,370	102%
1	12	1	Compression spring	0,270	-60%
1	13	1	Tie-biem	0,686	1%
1	14	1	Tool hooking	0,497	-27%
1	15	4	Sphere	0,238	-65%
1	19	2	O-RING	0,512	-24%

The shaft registers the highest complexity index (2,202), followed by the fore flange, the ferrule and the locking ferrule. The table shows the position, in the product structure, of the component, provides its description and the I_{com} ; the results from the DfD tool (medium, maximum) are used to evaluate the differential value between the I_{com} and the average I_{com} . One of the most critical components is the fore flange assembly, whose I_{com} is much higher than the average one. The algorithm behind the guidelines function supports the designer in understanding the reason behind the high complexity: Figure 4.28 provides an example. The threshold chosen is the default one, equal to 0,75. The assembly is heavy, as components as bearings, the main ferrule and the spacers are contained and increase the overall part weight over the admissible values. Moreover, the

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size (almost 200 mm) requires two hands to move the assembly. The two factors lead to high values of the handling index. The removal complexity index also presents a higher value than the threshold due to the effort required by the ferrule removal, which requires special tools. Following the project constraints and requirements, the designer can choose whether to accomplish or neglect the proposed correction.

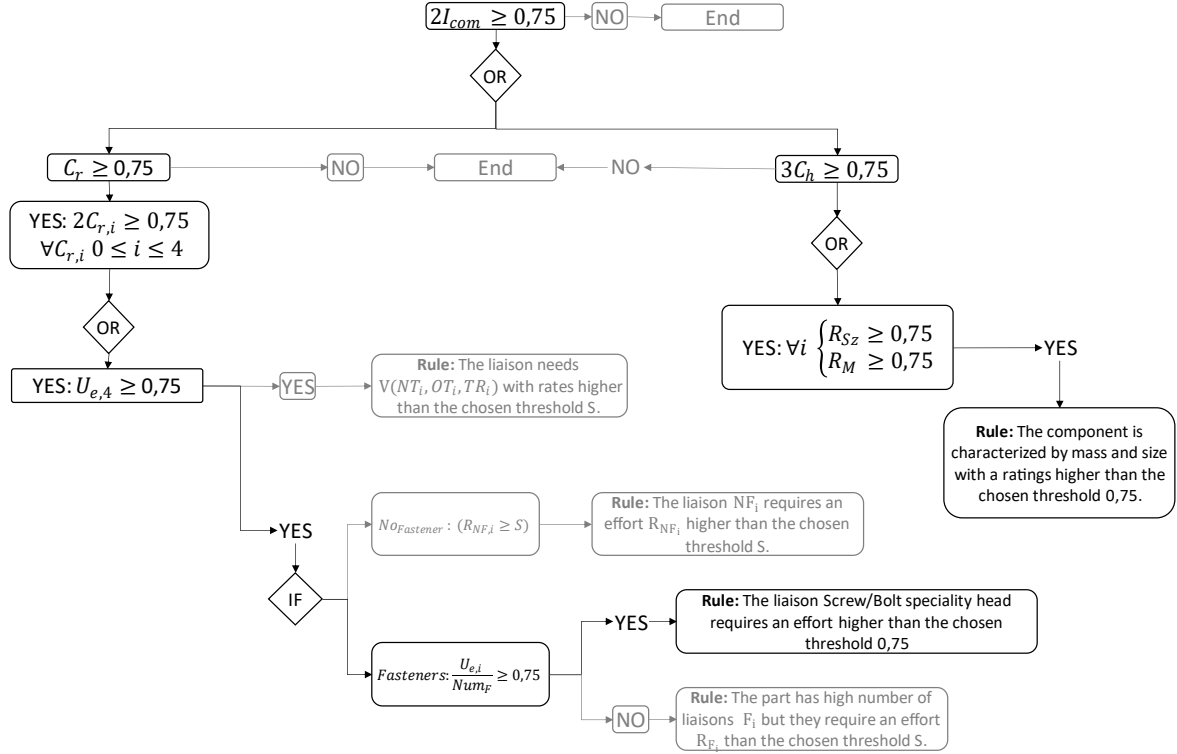


Figure 4.28 Rules highlighted for the fore flange assembly

4.6 Correlation matrix

When multiple tools are available and a rationale is needed to understand how they can be exploited for establishing CBMs, the first step is to correlate the results of the SoA that enlightened the multiple CBMs and the LCES strategies. It is important to note that a single, high-level strategy can be explicated in more than one LCES, likewise, can stand under multiple value propositions. Table 4.19 summarizes the outgoing correlation matrix, where only the value proposition for each BM is outlined. The column CBM introduction integrates information regarding how the corporation may introduce the innovative BM. The cases in Table 4.19 relate to acquisition and diversification. The first refers to innovative channels and ways to sell (additional) products or provide services that enter into the running business. Diversification instead consists in selling/offering a

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value different from the traditional selling/buying model with the traditional business remaining in place.

Table 4.19 Circular value proposition and strategies correlation

Strategy (high level)	LCES	Value proposition	CBM introduction
Cycling	Resell–re-use	Used machine take back	Acquisition
	Pay per use	Machine as a service (rent- subscription/pay per use)	
		Re-manufactured machine as a service	
	Recondition	Reconditioned machine	Diversification
	Refurbish	Machine refurbishment	
		Back in box spare parts	
	Cannibalization	Used machine take back	
Extending	Recycle	Used machine take back	Acquisition
	Re-manufacture	Re-manufactured machines	Diversification
	Repair or Corrective Maintenance	Remote/automatic troubleshooting AR maintenance	
		Spare parts/modules rent	
	Preventive M.	- Remote configuration, statistics and alarms - AR for maintenance	Diversification
	Predictive M.	- Remote configuration, statistics and alarms - AR for maintenance - Usage lifetime tracking	Diversification
	Time-based M.	Maintenance kit	Diversification

For example, the case of selling the maintenance kit falls in the case of diversification because the traditional trading system is maintained, although additional products are added to the portfolio and are provided as a service. On the contrary, when a machine is re-manufactured and provided for renting to new customers, this is the case of acquisition; in fact, the CBM is acquired and placed next to the existing one. Transformation does not appear in the table because the identified CBM may be placed next to the traditional one. The cycling strategy includes all those CBMs whose value proposition enables the establishment of (close) loops of use of resources, both as they are (resell/ re-use) and in a different state (i.e., reconditioned). The core of the value propositions is the protraction of the use of resources in a longer timeframe, especially by optimizing the maintenance, monitoring and control of the machinery.

4.6.1 Re-use - resell

The resell-re-use strategy has multiple elements in common with cannibalization, as both require a product to disassemble, parts to inspect, and their selection to re-employ, either for being re-sold or re-introduced in other products internally managed. The following tables show in detail the content of the correlation matrix. The cells were filled

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considering the existing literature and the outcome of the literature research regarding the success stories of existing companies. Table 4.20 shows the part of the customization matrix, related to the resell-re-use strategy. This strategy can be carried out by industries or private; however, in the current study only the first case is considered.

Table 4.20 Correlation matrix, re-use-resell

Value proposition		Value creation & delivery		Value capture	
P/S	Sell used full products of parts of it	VC	RSC management operations (take back)	RS	Revenues models based on used parts of product sale
S/M	Segment of existing or new customers	HR	Capacity management (demand and supply of products)	CD	- Machine disassembly/inspection/ri-assembly - Logistics costs
CP	Need machine but with lower initial investments	RC	Machine experts or specific tools able to understand the state of the part/product	RM	Sale

When attributing a piece to re-use or resell, defects must be classified since their entities determine if a piece can be re-used, re-manufactured or must be discarded or employed in different sectors. Kin et al. [190] propose to criticality rank an assessment of the defects. Now the decision is primarily up to the worker's experience: an extensive human intervention is required for feature recognition and knowledge interpretation [125]; this makes the classification costly and vulnerable to human error. In this field, AI can powerfully detect and cluster the status of components and make the process much more flexible. Similar considerations about product inspection and defect classification are valid also for other strategies, such as pay per use, re-manufacture, refurbishment, as they all expect the product to return after the user discards it and be inspected to evaluate which strategy better fits the component/ product case.

4.6.2 Pay per use

In the pay per use (Table 4.21) strategy, machine as a service and re-manufactured machine as a service were included; the two value propositions are similar, except for the state of the provided machine. For more clarity, aspects that differ between the two CBMs are highlighted in a different color (cells filled in grey refer to the re-manufactured machine as a service). In pay per use strategy, the product is designed, materials are acquired and processed to obtain the finished product. Then, multiple customers use it.

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The service may be provided under multiple revenue models, as a rent of the good, or per subscription (time-based or cycle-based fee).

Table 4.21 Correlation matrix, pay per use

Value proposition		Value creation & delivery		Value capture
P/S	Machine as a service	VC	- Services operations	RS - (Reman) machine is provided by time/activities
	Re-manufactured machine as a service		- SC/RSC management operations	
S/M	Segment of existing or new customers	HR	- Machine maintenance	CD - Maintenance
			- Capacity management	
CP	- pay only when machine is needed - lower total cost of ownership and/or lower up-front investments - have functionality or temporary availability of products, no ownership	RC	- Machine maintenance	RM - Machine disassembly/inspection/ri-assembly
			- Capacity management	
CP	- have functionality or temporary availability of products, no ownership	RC	- Machine re-manufacturing	RM - Logistics costs
			- Digital capabilities	
CP	- pay only when machine is needed - lower total cost of ownership and/or lower up-front investments - have functionality or temporary availability of products, no ownership	RC	- Service network collaboration	RM - Recurrent revenues from service temporary contracts
			- Long term customer relationship	
CP	- have functionality or temporary availability of products, no ownership	RC	- Contract and customer relationship management	RM - Pricing per unit of service (i.e. time, number of uses etc), rental or leasing rent
			- Suppliers outsourcing and collaborations to close the loop	
CP	- have functionality or temporary availability of products, no ownership	RC	- Disassembly, inspection, evaluation and assembly operations	RM

Both are PSS and so significantly foster CE; however, PSSs were not born to support CBM specifically: many organizations shift to PSS to dampen maintenance, re-manufacturing, and up-grading issues, either from an economic or legal point of view [174]. The customers interested in renting a machine, or endorsing a subscription, may either be users who already know the product or new customers. They have in common the need to pay for the machine only when needed and face a lower total cost of ownership and/or lower up-front investments; they are not interested in owning the good, rather have it functioning when needed, even just temporarily. As the product must be returned at the end of the subscription period, service and RL activities are crucial for the success of the pay per use strategy, where modules and components must be analyzed once returned: the inspection site may be the same or different from the OEM site.

Service operations include all activities related to maintenance and repair. In fact, when customers get a machine as a service instead of buying it, they implicitly expect the machine to be consistently well functioning or whenever a failure occurs, the user is not responsible for fixing it. The fee is proportional to the guarantee ensured by the OEM and

the limitations of roles and musts. Running PSS modifies the concept of delivery. The service provider must be careful when balancing the number of machines offered and the demand. In addition to that, the capacity demand does not only regard the availability of machines for upcoming customers, but also spare machines must be ready to be delivered in substitution of running machines that face stops. Differently from the sale model, when a good is acquired by pay per use systems the user and the service provider may have multiple contacts; therefore, their relationship may last longer, even just exchanging a single good. On a broad base, the EoL is a crucial phase because it requires high volumes to be optimized. The pay per use strategy gives a massive advantage in this sense. The organization that offers the machines for rent has three main strengths: it may reach the high quantities that a single user may not fulfill, even with big machinery; secondly, it can gain much experience in treating goods at the EoL; ultimately, the big volumes may raise its role towards suppliers and all who may cooperate to close the loop, as gap exploiter, collectors, retailers).

4.6.3 Repair or corrective maintenance

Table 4.22 shows the part of the correlation matrix concerning the repair or corrective maintenance strategy. This is a well-known practice, widely applied in linear economy contexts since corrective maintenance is performed after a failure or detection of a fault; however, the boost of Industrial IoT (IIoT) and innovative practices can make this strategy more sustainable.

Table 4.22 Correlation matrix, Repair or corrective maintenance

Value proposition		Value creation & delivery		Value capture	
P/S	Troubleshooting AR maintenance	VC	Support maintenance phase /service operations	RS	Revenues models based on service packages
	Spare parts/modules rent				Revenues from storing services
S/M	- Existing/new customers	HR	Knowledge of machine and failure cases	CD	Service maintenance costs
	- Segments of customers in need for expertise in certain non-core activities, convenience				Cost for warehousing and maintain spare modules in good condition
CP	Willing to accelerate/ make maintenance simpler	RC	- Digital capabilities - Service network cooperation	RM	- Recurrent revenues from customized service packages
			Suppliers' management		- Platform fees

First of all, organizations can be supported by companies that provide service of troubleshooting to release them from the burden of failure and faults. Remote

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troubleshooting may have multiple advantages because time is saved, and transportation and consequent impacts are also lowered. AR and other KETs may be helpful in easing maintenance activities. The corrective maintenance can be either adopted as an implicit service that comes together with a sold good or can also be apart from it; in this case, it is offered as an additional service, whose extensions vary following the customer preferences (customized/ differentiated service packages). In the latter case, the customers who benefit from the packages may be old or new. The size, the approach to maintenance, the location and multiple factors can influence the choice of adhering or not to the maintenance service; nevertheless, a key point is the availability of data, connection and sensors between who take care of the maintenance and the machinery. The organizations widely accept the maintenance supply, as they feel it as a non-core activity and does not wish to employ and increase expertise in secondary activities. When dealing with machines, downtimes are a sore pain. The temporary unavailability of a machine can cause significant losses. To avoid this inconvenience, enterprises recur to the stratagem of buying in advance (supposed) critical components to store in their warehouses as spare parts. Besides the costs due to this attitude, problems can arise as spare parts must be at their optimum (i.e., electric motor). Being stored and unused can cause disorder (dirt, humidity) and the missed functionality once the spare part is needed. The spare parts/module rent is a strategy that tackles precisely these circumstances: instead of being bought and stored in the customer's warehouse, the OEM can offer the service of storing the spare parts, guaranteeing both their maintenance (also during the time they are not used) and rapid delivery when the module is needed. This practice has positive impacts both on the economic and environmental perspectives. The OEM manages a higher number of parts, thus may have a convenient agreement for spare parts supply; secondly, the OEM arranges the needed number of spare parts and customers avoid buying spare parts that may never be used and get damaged without being used (resources saving).

4.6.4 Predictive maintenance

If machines include sensors, data are analyzed and information about machine and process status obtained, corrective maintenance may be anticipated, even in moments preceding failures. This is the case of predictive maintenance, whose matrix is shown in Table 4.23. The BMs behind the different kinds of maintenance are very similar, however different are their value proposition and their objectives. While in corrective maintenance the failure may occur and any effort is not put to avoid it, in the predictive maintenance

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pre-planned tasks are performed. The acquisition of data directly from the shopfloor enables a huge range of activities, tracking usage lifetime among them. The machine monitoring phase enables understanding when and if a failure is about to occur; sometimes the monitoring may also avoid the failure by anticipating the maintenance.

Table 4.23 Correlation matrix, Predictive maintenance

Value proposition		Value creation & delivery		Value capture	
P/S	- Remote configuration, statistics and alarms - AR for maintenance - Usage lifetime tracking	VC	Avoid physical interventions	RS	Revenues models based on service packages and/or tailored contracts
S/M	- Existing/new customers - Segments of customers in need for expertise in certain non-core activities, convenience	HR	Knowledge of machine and failure cases	CD	Service maintenance costs
CP	Need to avoid unexpected failures	RC	- Digital capabilities - Service network cooperation	RM	- Recurrent revenues from customized service packages - Platform fees

4.6.5 Time-based maintenance

Time-based maintenance is an additional recognized type of preventive maintenance (Table 4.24) and consists of restoring or replacing a component regardless of the product's condition.

Table 4.24 Correlation matrix, Time-based maintenance

Value proposition		Value creation & delivery		Value capture	
P/S	Maintenance kit	VC	Periodical shipment of maintenance kit to the customers	RS	Revenue models based on maintenance kit fee
S/M	- Segment of existing customers who wish to carry out maintenance autonomously - Segment of existing customers that did not buy spare parts before	HR	- Machine/customer localization - Orchestration of suppliers - Capacity management (demand and supply of products)	CD	Maintenance kit logistics
CP	Need to avoid unexpected failures	RC	- Service network cooperation - Long term customer relationship	RM	Revenue from providing maintenance kit (time based)

The scheduling and management of maintenance may result in annoying and made onto secondary activities, even though it is crucial for the machine's safety. The supply

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of a maintenance kit may support enterprises. Through a subscription, the user can receive a maintenance kit based upon a set timeframe/number of cycles to know when to do ordinary maintenance and what is necessary to substitute/repair. The waste hierarchy and CE have evolved to emphasize the design and use of a product before it turns into waste. Therefore, they share a joint philosophy, aiming to manage waste by rethinking, redesigning, re-manufacturing and repurposing to improve the resource effectiveness of a product and reduce the generation and adverse impact of waste [142]. Depending on the status of the parts employed and the operated modules, the activities of taking old machines and restoring their conditions and functionalities or making new machines out of them, there are different LCESes and depend on the type and functionality of the products; for example, mechanical and electromechanical systems have to be separated from mechatronic systems [295].

4.6.6 Re-manufacturing

The market of re-manufactured (Table 4.25) (as for the reconditioned, Table 4.26) can be tricky for an enterprise.

Table 4.25 Correlation matrix, Re-manufacture

Value proposition		Value creation & delivery		Value capture	
P/S	Re-manufactured machines	VC	- RSC management (take back) and re-manufacture operations - acquire spare parts from discarded products	RS	- Reman machine is sold - Lower cost of spare parts supply - Additional revenues from residual values of products/materials
S/M	Segment of existing or new customers	HR	- Machine re-manufacturing - Capacity management (demand and supply of products)	CD	- Maintenance during guarantee - Machine disassembly/inspection/ri-assembly
CP	- lower total cost of ownership and/or lower up-front investments - Need machine in good condition, but with lower investments	RC	- Suppliers outsourcing and collaborations to close the loop - Disassembly, inspection, evaluation and assembly	RM	Revenue from high quality products at lower prices

From the technical point of view, there are multiple barriers, firstly because the status of which products come back after the use phase is unknown and unpredictable; this directly impacts the inspection and disassembly times and costs. Disassembly automation can bring many advantages to disassembly tasks by applying the latest developments in I4.0 and cooperative and collaborative robots [125]. Some studies induced a physical

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phenomenon under controlled conditions to ease product de-manufacturing [187] or investigated eco-friendly approaches. The re-manufacturing process may employ multiple technologies; very often, a winning strategy is the combination of additive (such as electroplating [205], welding [199], [200], cold spray [199], laser cladding [210], [211]) and subtractive ones, i.e., CNC operations as boring, turning, gross grinding [296]. All those strategies that expect a partial action on the machine (i.e., re-manufacture, refurbishment, recondition) also require an inspection that enables the decision of implementing or not the strategy. In the case of re-manufacturing, the parts or modules introduced come (if possible) from previously discarded machines (additional parts that enter the lifecycle).

4.6.7 Recondition

Besides difficulties, multiple benefits come along with CBM implementation; among them, the customer faces lower initial investment, resources are used more sustainably and efficiently. In addition, the lower price paves the way to the acquisition of new market shares, in particular in the case of the recondition strategy, because the requirements of the customer may be different from the traditional one (a reconditioned machine may not fulfill the overall functions of the new machine, Table 4.26).

Table 4.26 Correlation matrix, Recondition

Value proposition		Value creation & delivery		Value capture	
P/S	Reconditioned machines	VC	RSC management (take back) and re-manufacture operations	RS	- Reconditioned machine is sold - Lower cost of spare parts supply - Additional revenues from residual values
S/M	Segment of existing or new customers	HR	- Machines recondition - Capacity management (demand and supply of products)	CD	- Maintenance during guarantee - Machine disassembly/inspection/ri-assembly
CP	- Lower total cost of ownership and/or lower up-front investments, convenience - Need machine in good condition - also not as new-, but with lower initial investments	RC	- Suppliers outsourcing and collaborations to close the loop - Disassembly, inspection, evaluation and assembly operations	RM	Revenue from reconditioned products sold at lower prices

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4.6.8 Refurbishment

Different is the case of refurbishment (Table 4.27); in this case, especially in complete machine refurbishment, the customer of the “old” and “refurbished” machine is the same. Beside the benefits deriving from the machine update, the user can also obtain a smarter machine from the refurbishment. In fact, refurbishing a machine can provide a technological upgrade; therefore, by facing little expenditure, the user gets an old machine that can be remotely monitored and switched on/off, connected to the industrial system. Refurbish presents matching contributions to the re-manufacturing case; however, the customer along the whole supply chain remains the same. The machine refurbishment may require the product to move to the specific facility of refurbishment. However, returning the spare parts in the box employs refurbished components without moving the product. It consists of substituting certain damaged parts with refurbished ones; those that are damaged are sent back to the manufacturer, instead of being thrown away, so that the OEM decides whether to refurbish or recycle it.

Table 4.27 Correlation matrix, refurbishment

Value proposition		Value creation & delivery		Value capture	
P/S	Machine refurbishment	VC	Refurbish machines as done in pilot cases	RS	Additional revenue through upgrade service
	Back in box spare parts		- Provided low-price spare parts - reimburse client for returning old part - spare parts RSC mngt		Re-manufactured spare part selling
S/M	Segment of existing customers that want their machines to be upgrade	HR	Supply chain management (if upgraded occur outside the shopfloor)	CD	Refurbishment cost + machine analysis status costs (+ reverse supply chain cost)
	Segment of existing customers that never bought original spare parts		Spare parts refurbishment		- RSC, inspection, refurbishment costs - Spare part residual value reimbursement
CP	Wish to have a keeping-up to the times machine without investing a lot	RC	- Service network - Knowledge of machines + upgrading technologies	RM	Payment of refurbishment service
	Wish to pay less for maintenance but want guaranteed of well-functioning spare parts		- Service network cooperation - Spare parts residue value estimation		Bosch Exchange - back in box

4.6.9 Recycle & cannibalization

CBM can also support and push recycling (Table 4.28). What endangers recycling is the bad design of products (focused on functionality and manufacturing, not on EoL) and

the lack of product knowledge. The machine user may not be able to properly recycle the product because optimized recycling would require a partial disassembly: time, cost and inexperience make it ineffective and economically unsustainable. To gain many conveniences, disassembling a large number of machines is necessary. Dealing with high quantities of materials ensures higher refunds from recyclers, which may bring consistent incomes. Thus, the value reported in the table expects the machines to be collected after the use phase, properly disassembled (by selective disassembly) and materials sorted in flows to optimize recycling. The potential revenues from conferring the properly differentiated materials should exceed the costs of disassembly and refund of the customers. However, this CBM may matche with others, such as those involved in re-use-resell, refurbishment, re-manufacturing strategies, because they also require the machine to be re-collected after the use phase. By doing so, the machines' parts are allocated in other machines or reworked, and the remaining are sent for recycling.

Table 4.28 Correlation matrix, recycle

Value proposition		Value creation & delivery		Value capture	
P/S	Used machine take back	VC	- RSC operation - Suppliers outsourcing and collaborations (i.e. collectors)	RS	- Additional revenues from residual values of products/materials - Savings with reduced costs for resource input
S/M	Segment of customers who bought machines years ago and are replacing/dismantling the machine	HR	- Machine/customer localization - Recycling flow management	CD	Costs related to machine taking back (RL) and preparing for recycle
CP	- Need to get rid of old machine in a sustainable way - Need turnkey solution for machine dismantling	RC	- Access to core/EoL products/ Selective disassembly - RSC	RM	Revenue model based on direct sales or trade of resources

4.6.10 Business cases

4.6.10.1 Digitalization tools

The methodology supported by the developed correlation matrix found application in two industrial cases. One organization is a small-medium German enterprise active in d designing, producing and commercializing welding machines (Company A). The second is a big Italian enterprise and design produces and commercializes machines for wood and metalworking (Company B). Both organizations count on external and in-house resources to develop digital solutions. Several tools have been exploited and developed to get information about the product's status and its components during its life cycle, the

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remaining useful lifetime, to extend it while keeping any action economically sustainable. For each tool, the main functionalities have been first investigated. This paved the way to the assignment phase: every CE-driven LCES was retrieved, and the tools were identified as core resources and capabilities of the strategies. One tool might be helpful for more than a single strategy; it may also occur that a strategy is not enabled by any tool. Figure 4.29 graphically summarizes the primary outcome of the assignment phase. Four LCESes were considered (pay per use, re-manufacturing, refurbishment, and predictive maintenance).

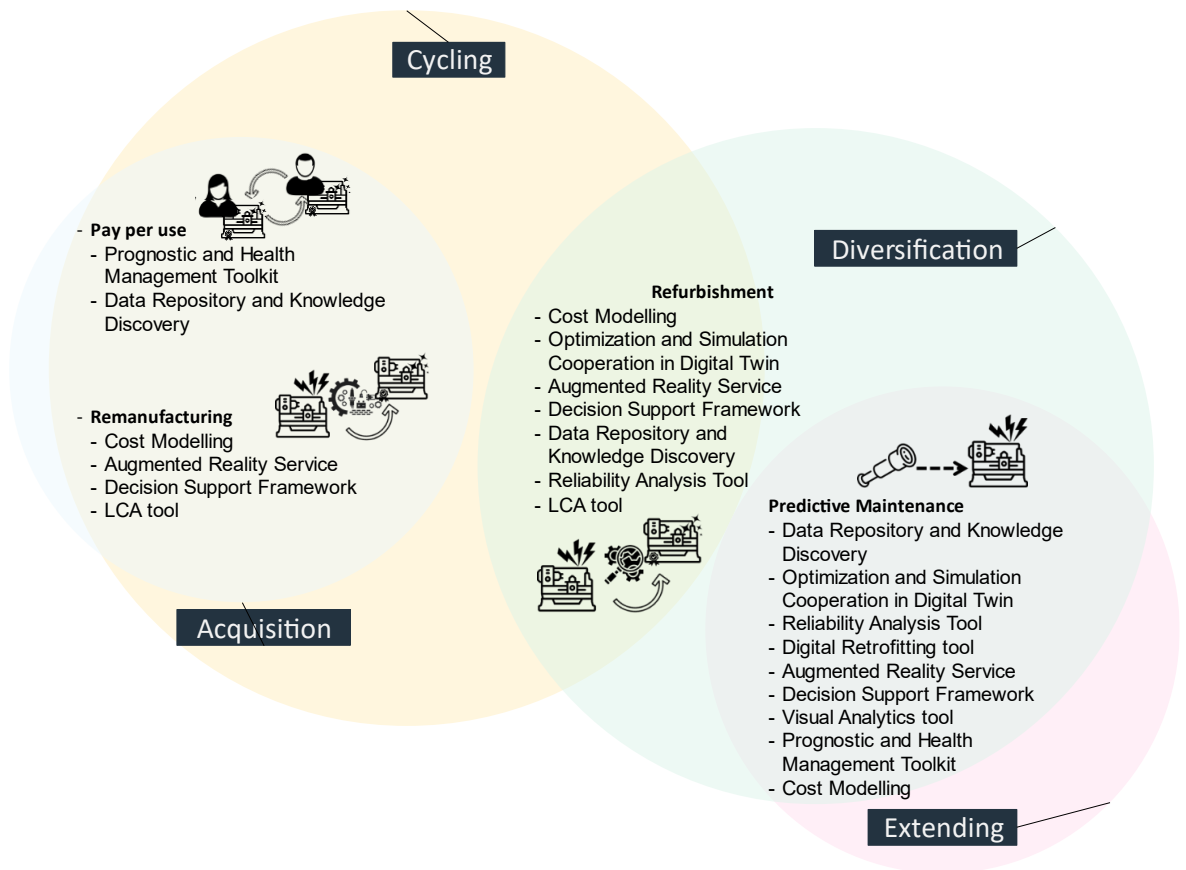


Figure 4.29 Tool assignment to the correlation matrix.

The blue and green circles mark the strategies for BM acquisition and BM diversification, respectively. Predictive maintenance is the strategy all the tools can support. The prognostic and health management toolkit and the data repository and knowledge discovery tool enable the pay per use.

Both organizations were provided with multiple tools; the analysis of the current BM revealed that the businesses are closer to the traditional BM than the circular ones. Beside some activities focused on digitalization (i.e., the machine connectivity of company B, where digital services are provided through standard platforms and add-on), maintenance,

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EoL management and value offers are still bounded to traditional schemas. Therefore, roadmaps were defined for each company, instead of a single CMB; the roadmaps are presented in Figure 4.30. Each roadmap is customized according to the current status of the company. The last strategy is the pay per use; however, several intermediate BMs were identified. The greatest potentialities of the roadmaps stand in:

- segmenting the complex metamorphosis process from linear to circular BMs
- simplifying the transformation by tackling difficulties and changes little by little.

By defining and respecting the roadmaps, innovative and new approaches and activities can be introduced progressively, without hampering the already running or new markets. In addition to that, a gradual change allows for a smoother and more seamless introduction of new roles and partners.

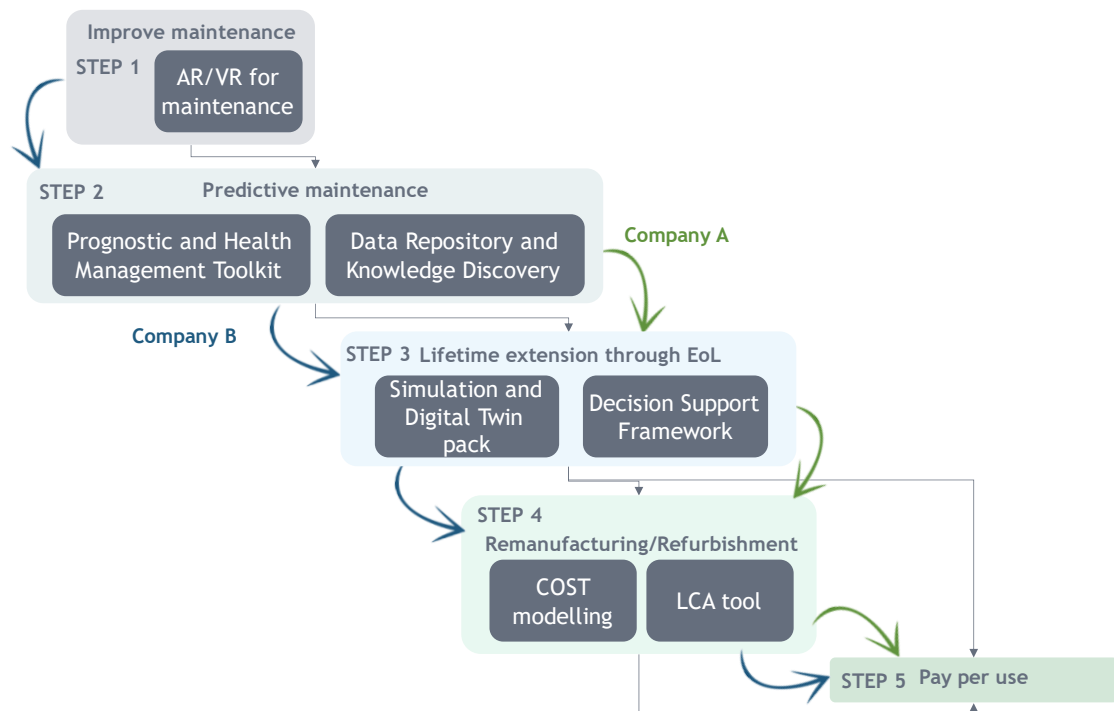


Figure 4.30 CBMs roadmap. Yellow arrows relate to Company A; blue arrows relate to Company B

The roadmap supports the enterprises introducing digitalization tools and practicing the management of the used products they sell. First the focus, through the Prognostic and Health Management toolkit (company A), the Reliability Analysis toolkit and the Digital Retrofitting tool (Company B), is on optimizing the maintenance of the running machines. This can happen in situ (where the machine was produced), or where the machine is installed and the failure occurs. The main goal is to detect in advance potential failures and monitor the machine status so that the wealth of the components and modules

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are known. This first step requires the support of roles previously unnecessary, such as services providers, Hardware (HW) suppliers, data analysts.

After well managing traditional maintenance, which can be supported by innovative tools that decouple the physic machine and the maintenance operator's actions, predictive maintenance can be investigated. In doing so, is it necessary to be provided with a classification of machine status, failure mode, and causes so that off-standards events can be detected and unexpected failures avoided. Knowing the status of the machine and being able to handle and interpret unexpected behaviors to pave the way to the modeling of a digital twin of the product, to monitor its performance; consequently, whenever the customer wants to discard it, the resources contained in the machine can be exploited at best (i.e., the best lifetime extension strategy exploited). This mastery leads to alternative models to the provided goods: a service rather than a product.

4.6.10.2 Durabot, DfD, PReSCoM

Besides the primary purpose of the correlation matrix, to exploit functionalities of the digitalization tools, its applicability can also involve *offline* tools that pave the way to CBMs implementation. Table 4.29 shows the results of following the approach proposed in Section 3.4: a summary of the correlation matrix is shown, where the above-proposed proactive and reactive methods and tools have been assigned to the LCES strategies they can support.

Table 4.29 Correlation matrix, focus on LCESes enabled by the tools and approaches proposed in this work.

Strategy	CE-driven LCES	Value creation & delivery	CBM
Extending	Repair or Corrective Maintenance	Durabot	Diversification
	Time-based maintenance	Durabot, DfD	
	Predictive maintenance	Durabot	
Cycling	Re-manufacture	Durabot, DfD, PReSCoM	Acquisition
	Recondition	Durabot, DfD, PReSCoM	
	Refurbish	DfD, Durabot	
	Recycle	DfD	

The Durabot tool can positively impact the implementation of all the maintenance strategies, as it provides feedback about the sustainability of components substitution; those encompass the repair/corrective, the time-base and the predictive maintenance. DfD tool can bring positive contributions as well, as can provide feedback on the complexity of disassembly of the parts to be substituted. Specifically for time-based maintenance, where the OEM often suggests the maintenance schedule, the design analysis through the

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DfD tool can highlight criticalities of disassembly for the components that are often to be substituted (target components). The tool's support can tackle and diminish the target components' criticalities. Similarly, it supports the advanced scheduling and easing of recycling. Beside the Durabot and DfD tools, the re-manufacture and re-condition strategies are also supported by the PReSCoM approach, which enables their technical feasibility.

5 Discussion

De-manufacturing is the milestone from which four applications of the methodology proposed in Section 3 arose. According to their main implementation, three were classified as proactive or reactive, and the fourth, related to the innovative and/or CBMs that may ease their applicability in industrial contexts, can find connections with the previous. In the following paragraphs, the discussion debates the methodologies proposed and the main results obtained from their implementation.

5.1 Durabot and the dynamic LCA

The durability assessment has been presented through a tool that includes a dynamic approach for a deep LCA, maintaining linearity in the mathematical approach. Compared to the static approach of the ALCA it considers more specifically the flows that directly enter or exit the analyzed product system. Ekvall [224] identifies 5 main criteria for methods in environmental systems analysis; the above-presented approach observes them all. The dynamic approach:

- is feasible: it can be easily applied and repeated. It uses commercial datasets, even though those are partially adjusted; however, it respects the feasibility criteria as the results and conclusions it generates can be generalized and re-used in multiple decision situations.
- is accurate, as the case study proves that it generates comprehensive and accurate results.
- generates results that are easy to communicate and understand, at least present the same level of understanding of the well-known and established static ALCA, since they and share the same way to present results.
- is inspiring because not only it is impartial and fair, as the static ALCA, but the deeper investigation of flows entity enlarges its credibility and legitimacy.
- is robust as multiple users can repeat it and the same results are retrieved.

The approach aims to exploit the potentialities of commercial datasets, making it applicable to a broader range of stakeholders, designers who apply lifecycle thinking above all. However, as it requires more investigation in certain aspects of the LCI than the static ALCA, the user must choose among robust and reliable sources when making assumptions. This aspect is not to be adducted to the robustness of the method but rather

to the user's ability to choose data with a higher quality level. The relation with the time differentiates the static ALCA and the dynamic approach, and this last and the CLCA:

- Compared to the ALCA, it has a view over the relative future. Even if a static approach is stated that the FU consists of actions carried out for a time frame (months, years), the analysis of the future flows is made as a reproduction of static photography of the present (at least present and relative past). The dynamic approach instead allocates each flow to the specific moment they occur.
- While CLCA focuses on a potential future equilibrium (that may rely on future decisions, CLCA only propagates the effects in the relative future of the decision [243]) dependent on the choices of a multitude of stakeholders, the dynamic approach relies on already taken decisions that affect the flow of the product system.

According to the results obtained from the case of a domestic refrigerator, the dynamic approach registers variable emissions, as they depend on the decreasing performances of the refrigerator (foam aging) and the lower burden due to electricity consumption. The static approach expects 16% lower environmental impacts for the use phase, while the CLCA returns half the environmental impacts than the dynamic approach. It can be stated that the dynamic approach has a definition of one year for energy consumption: its trend is calculated for each year, and the user can contemplate either effect of flows that enter the product system and derive from the surrounding environment and the changing of flows strictly related to the product. The DBs for consequential analysis currently available on the market do not differentiate between any time in the relatively far future. Moreover, they aim to estimate only the effects on a macro-scale, with validity in all fields. The comprehensive validity necessarily brings along a higher uncertainty. Table 5.1 summarizes the main innovative aspects of the dynamic approach concerning the traditional ALCA. The merged cells stand for common aspects of the static and dynamic approach. ALCA's typical features also belong to the dynamic approach; however, the last one also involves additional aspects. The main distinguishing factor is time. Multiples are the reasons why a flow may change its amount over time. In the dynamic approach, this change is considered, not only its initial or average value. The linearity is maintained, nevertheless flows are in progress. The Durabot tool presents two main innovative points if compared to the available literature because:

- The evaluation considers the effect of technology aging: the durability index is adapted to consider how the use phase's impacts change, according to worsened

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refrigerator performance. This is usually considered fixed and stable over the entire product lifetime;

- The sustainability of durability under different conditions is evaluated; for example, it is possible to know whether substituting a part of a whole product is more sustainable according to the time the refrigerator is used after the substitution.

Table 5.1 Overview of the covered aspects and how they are differently addressed by ALCA, Dynamic approach, adapted from Schaubroeck et al. [243].

Feature	ALCA	Dynamic approach
Basic concept/ Relation with the global burden	Share of the global impact linked with a product life cycle.	
Relationships and boundaries of the product system, of which the impact is assessed	All processes have interlinked relationships based on physical, energy and service flows.	
	The product system can be infinite and propagated amount as well.	<i>Internal and external factors are subjected to the time factor.</i>
The aspect of time	Absolutely: processes can be considered in past, present or future. Relatively: considers processes before product finalization, i.e., relative past consideration.	
		<i>Relatively: considers processes that directly influence the lifecycle also after the product finalization, i.e. relatively future consideration</i>
Specify product system and its impact separately or in scenarios	Separately: share of human/industrial system and its global impact.	
	Scenario: the difference between the world and a hypothetical world without a product system and its impact.	
Constraints in mathematical modeling due to a theoretical concept	Restricted by additivity (e.g., guaranteed by linearity), necessitating a validity check or consideration of the extrapolated world.	
How it deals with multifunctionality	To be done through partitioning processes, both for LCI and, in the case of environmental multi-input processes, for LCIA. An alternative is system expansion.	
Marginal versus average considerations in the assessment	Amount-specific effects are advised, but average or marginal impact effects are possible in practice and should be consistently considered.	
	Interlinked suppliers need to be considered. Average or marginal product consideration is possible.	<i>Interlinked suppliers must be considered. Average or marginal product consideration is advised</i>
Complete framing of environmental impact assessment, coupled with the product system	Environmental impact assessment is purely consequential (with exception of inventory indicators) but limited by additivity, e.g., necessitating partitioning. Due to these other rules, this necessitates a separate consideration from the product system.	

The concepts of durability and environmental sustainability are interchangeable for products whose use phase does not require high quantities of resources. The development

of Durabot tool filled the main literature gaps; first, it enables the assessment of environmental consequences of durability considering product evolving performances in time (i.e., worsening of functionalities); moreover, it introduces external factors (i.e., the evolution of energy grid mix). Ultimately, the tool enables the measurement and prediction of environmental consequences of durable products in different lifecycle scenarios during the design phase. The Durabot user can identify which components are convenient to substitute for extending the PLC and consequently acting on its design to ensure component accessibility. The maintenance man and/or product user would also apply the presented approach. The Durabot enables a complete evaluation of component substitution right when the failure occurs.

Figure 4.6 shows the high variability of refrigerators' foam performance, according to the different equations that describe foam aging. A higher initial thermal conductivity characterizes PrA. The empirical trend is the most conservative; according to the JC formula, PrA would consume more than double the electricity after 20 years than the case of EM. Oppositely, PrB absorbs more electricity after 20 years, according to the EM, while according to JC 40% less. The EM draws similar trends for PrA and PrB, although the PrA line is shifted higher than the PrB's due to the higher initial energy consumption. As far as the formula provided by Johnson [287] is employed, two different behaviors are registered: even though the shape of the line reflects that expected: first, the consumption increases, then it settles. The registered values after 20 years for PrA implausibly raise and reach more than 70% higher value than the initial energy consumption; this is respectively about 40% and 50% more than the trends of JP and EM. In the case of PrB the values do not register the same gap as in PrA: the most conservative in PrB (EM) registers the higher increase (about 50% after 20 years). Moreover, while PrB has very close values in the first years, trends are much different for PrA: already at year 5, there is more disparity between JC (equal to JP) and EM than the total gap between PrA EM and the three values of energy consumption of PrB.

The different aging trends considerably affect the evaluation of the convenience of substituting components or full products. Thus, the central claim is to align the description of refrigerators' degradation in time. Nevertheless, the present work rearranged the existing formula proposed by Johnson [287], proposed in Eq. 4.3, so that an accurate analytical description of the components' aging can be introduced and accounted for in the evaluation. The work provides a successful and essential tool and overcomes the

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existing literature. The exemplification of the extended adapted formula that considers the time factors is advantageous and applicable early in the PLC, i.e., the design phase when not all data about the new product are available. The reactive would also become a proactive approach.

Furthermore, the multiple results allow more conscious decisions during the manufacturing phase; the customer, as for the maintainer, can place environmental considerations next to the economic ones when evaluating whether to invest in substituting components or the entire product. Several focuses originate from the obtained results:

- External factors that influence the product lifecycle phases should be considered; for example, in this historical era of transition toward more sustainable energy sources, the possible evaluation of the energy mix should be considered: it would contribute to mitigating the increase of environmental impacts, even with the foam losing its initial characteristics.
- The economic evaluation should be drowned near the environmental one: as the production and disposal of a product represent a considerable plinth of the product lifecycle impacts, similarly the initial investment of buying goods may also contribute to choosing whether substituting the whole product or only certain parts.
- The rearranged formula enables the assessment of the environmental sustainability of multiple ERP products' durability; nevertheless, their variable performances with time should be known to obtain consistent results.

In conclusion, the application to the refrigerators' case enlarged the view over the awareness that foam aging is a delicate topic and there is not a comprehensive and valid consensus on how to evaluate it from a macro scale analytically. Secondly, it provides a powerful method to integrate realistic parameters in the evolution of the durability of products from the perspective of environmental sustainability, especially those goods whose use phase requires high quantities of resources.

5.2 How PReSCoM supports re-design and scraps management

The PReSCoM approach starts from the awareness that designing for the CE involves giving new meaning to the EoL of products [297] by replacing irrecoverable resources with valuable alternatives. The methodology presented enables the valorization of certain materials (composite materials in the current application) whose EoL management is

currently highly inefficient and unsustainable from the environmental perspective. The method is structured in three main phases: the first two focus on analyzing the available materials and the products that may further host them. This investigates the current emissions due to the use and dismantling and technical analysis. The main potentialities and strengths of the proposed approach lie in the support provided in giving value to scraps made of composite materials, whose disposal is very challenging. The approach is also compliant with the base principles of CE. In fact, it strictly links the EoL and first stages of product lifecycles. In addition, it expects cooperation between multiple manufacturers active in different sectors so that they can work together to find sustainable solutions and improvements. For example, without any common point of convergence, none of the grinder parts would be re-design and no scraps would find placement. Furthermore, scrap producers refer to detached sectors. Thus, they are unlikely to phase cannibalization or low demand for re-manufactured products [298]. This is often a sore point that distresses enterprises and hampers circular initiatives if not properly exploited [299]. The novelty of the proposed methodology is its purpose of finding innovative applications and employment of scraps to existing or new products instead of reintroducing them in the same loop they were first used. It lets enterprises overcome the main obstacles related to the lifecycle extension of composite materials:

- If G1, G2 and G3 are willing to use their scraps to produce new products, they would not be able to re-use them as they are, nor to recycle them. In rare cases when it is possible, the processes are expensive, energy-demanding processes.
- Despite the costs of material recovery, when they are recycled, composite materials can restore their performances [300]; if they do not, the OEM must either reject the recycled material or use it to produce a product with lower performance (risk of image jeopardization or cannibalization).

PRESCoM can be integrated with well-known and established methods and tools (i.e., LCA). The potential applicability is vast: the growing boom recorded for many industrial markets and applications in the composites industry [301] provides multiple applications; moreover, although born to find a respectable EoL for the composite material, the approach can be applied to homogeneous waste materials too.

The results show great potentialities and benefits deriving from using scraps to produce the grinder components. The benefits mainly stand into:

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- Avoided impacts related to the extraction of the raw material (the new material already exists, and any other resources must be extracted from the geosphere);
- Avoided impacts related to the EoL treatment and disposal of the scraps; becoming secondary raw material, they do not undergo any EoL processing (i.e., landfilling, incineration) in the first phase, but their lifecycle is extended;
- Avoided impacts related to the EoL treatment and disposal of stainless-steel guillotine steel and lid. As their extraction is avoided, so is their treatment.

The obtained results show that it is hugely convenient, from the environmental perspective, to launch the studied strategies. Promising effects also come from producing prototypes made from an alternative process. The panel almost nullifies its environmental impacts. As panels are employed in the process but are not part of the final product (wind blade), it is extremely convenient to investigate alternative solutions, as it is one step toward the net-zero emission aimed by organizations. The panels should withstand only technical constraints, such as hardness, and flexibility, but no commitment is needed for beauty or similar aesthetic requirements.

The case of the Back Cover (G2, H2) proves that the transition from linear to CE can happen in multiple ways. According to the availability of the scraps from G1, G2 and G3, and the first analysis results (scraps and components characterization), there was not any waste type suitable for the dimensions of the back cover. Neither a re-design may offset this lack, as the primary obstacle was the part dimensions. In this case, an alternative process has been investigated.

The panels are employed during the production process and do not require any aesthetic conditions, instead the back cover fulfills a critical aesthetic function besides protecting internal components. In the current state, the prototype has reached high finishing quality. Its production process also expects the cured part coated. However, the back cover's final appearance differs from the original one. This may hamper customer satisfaction. Therefore, the back cover made of secondary raw material would not wholly replace the traditional part; however, it would be an alternative material for the customer to choose. Now, according to the customer requirements (the style of the grinder or the machine's location, or a matter of taste) the back core alternative materials available are copper, satin or matte steel.

The choice of the guests' and hosts' components is a combination of factors: part and material features, functionalities, design constraints and environmental impacts.

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Moreover, certain parts were discarded from the potential target components because they are off-the-shelf parts and the company has little decision power on them; one example is the motor, which is the most impacting assembly of product H1.

G3 has a wide variety of scraps; some are available in a process and heterogeneous state and as virgin materials (i.e., fiberglass or PVC). The latter, rags of various dimensions (order between 1 E-2 to 7E-2 m), in the case of the wind blades, are discarded only because of their dimensions (they are too small for the whole blade) but may be re-used in other processes since they are still virgin material. The first application of the approach neglected them. Nevertheless, further investigations may involve alternative applications (i.e., processes requiring smaller fiberglass patches).

G1 is aware of what happens to the waste its industrial process produces, thanks to the partnership with a project to re-develop an old breach quarry. On the contrary, the LCI related to the EoL treatment of scraps of G2 and G3 requires multiple steps and highlights a wide unawareness of the waste treatment. Organizations have direct contact with the EoL supplier responsible for collecting their waste. Enterprises carefully categorize the types of waste they produce and set their collection. Once the waste exits the production plant perimeter, its voyage is unknown to the companies producing it. This explains the high discrepancy of steps between the expected EoL treatment (pink in Figure 4.13) and the real ones (green in Figure 4.13). Direct interviews with downstream suppliers made the picture clear. Data, knowledge and information exchange could bring significant benefits to the OEM. A smoother communication among the actors in charge of the dismantling processes improved the level of detail of modeling the EoL phase, outlining the actors, the steps and what is done.

The implementation of the methodology identified the first potentialities of establishing relationships among companies acting in different sectors. In the first place, only components and scraps without special treatment were considered and studied to be employed as secondary raw materials. The focus of the study fell aside the recycling action; consequently, it neglected the chemical and thermochemical decomposition (i.e., pyrolysis, de-polymerization). From the arisen criticalities, guidelines and design strategies are derived to support the successful implementation of the methodology and establishment of IS:

- Dismantler's involvement. Enterprises have deficient awareness of how scraps and waste are treated; the analysis of the EoL of the scraps encountered difficulties in

tracking all the steps, especially for G2 and G3. First, it was based upon the information provided by the OEM; this was poor and generic and expected the waste to be only landfilled. The dismantler's interview brought more details and the researchers were directed to a second dismantler and found out that the final confinement of the waste was incineration, besides landfilling.

- Information. The case of EoL LCI is just an example of a lack of information sharing among the value chain actors. Information sharing can strongly support efforts toward a CE [302]. Currently, many firms, especially maintenance providers, re-manufacturers, and recyclers, lack important information to maintain products and keep products and materials in the loop, as information flows mostly halt after the production and sale of the product. Increasing access to information is needed, both supply chain (i.e., supply, demand, lead time) and technical (i.e., product performance data via life cycle information or feedback from service providers and re-manufacturers). Information can flow in multiple ways, either if they are static (constant information that cannot be changed, like the date of manufacture) or dynamic [303](information that changes in time, i.e., product performance [304]). This point is crucial, as scraps and waste are the resources flowing between the manufacturers.
- Networking. Strictly related to what previously explained, there is a need for cooperation with downstream and upstream suppliers. Enterprises should be open-minded and establish new partnerships. Those established with suppliers of the product value chain must aim to provide information about the product, and those settled with businesses from different markets pave the way to countless innovative solutions that prevent the disposal of materials after the first use. The literature claims to establish a CE Supply Network (CESN) with management characterized by a complex adaptive system [305]. In their work, the authors proposed a hybrid loop supply network configuration, combining closed and open loops. The present work presents some similar points; by applying the proposed approach, the loop is closed for G1, G2 and G3 materials; materials of host products temporarily maintain an open loop.
- Short distances. The case study involved companies settled in a small area (G1 and G2 are from the same district; G3 is located slightly further, still in the same Italian region). Proximity is very useful for maintaining a strong relationship and lowering

the environmental burden due to the variability in the transport phase and handling volumes.

- Simple shapes. The withstanding of functional, technical and aesthetic constraints sets multiple boundaries; a simple design helps in this sense and paves the way to the feasibility of the restricted number of processes that can be applied to the waste materials and the components. For example, the design (or re-design) phase must consider the un-weldability of analyzed composite materials.
- Modularity. The re-use of scraps often requires design modification on components. A modular product structure minimizes the changes in components (mostly functional modules rather than aesthetics), thus reducing the time and cost of modifications while increasing design flexibility [306]. In addition, a modular design of target products may lower components characterization phase time and enable the application of the same scrap typology to multiple models.
- Disassembly. The use of scraps may lead to the introduction of additional materials. This goes against the general disassembly guidelines that minimize the number of employed materials. Therefore, the re-design must make proper considerations about disassemblability to maximize environmental benefits linked to the re-used of composite materials and not hamper the target product's recyclability. Considering the current study, introducing additional materials does not hamper the product recyclability: the support and the guillotine are easily detachable, as they are fixed through bolts; similarly, the lid is removable and the knob attaches by a bolt. The back cover is also assembled with non-permanent fasteners and the recyclability of the remaining coffee machine is not hampered.

5.3 Design tool

The DfD tool counts 5 main functionalities implemented in 5 different tabs in the main interface. The tool's high usability and simplicity were among the main goals, next to the willingness to support the designer in the design process, the introduction of the environmental sustainability topic and the implementation of actions that improve the performances of the product lifecycle. The literature outlines a need for rationalizing existing and innovative tools. Also, by looking at the traditional design process, designers must handle a bundle of tools (3D CAD SW – SW -, Finite Elements Analysis (FEM) SW, simulation SWs). Regardless of the tool's purpose, each solution proposed and

delivered to the designers should be easy to use and well-integrated with the system already provided to the technicians.

These reasons triggered the development of the DfD tool and the User-Centered Design (UCD) approach. This should lead naturally and gradually to a usable and acceptable solution. According to ISO/IEC 25010⁵², usability is the ability of the product to be understood, learned, used and attractive to the user under specified conditions. Furthermore, the same standard identifies multiple types of users, that are:

- The primary user is the one who directly and entirely acts with the proposed solution and exploits its greatest potential, obtaining the obtainable outputs; relatively to the DfD tool, those will be the designers of the technical office. These are already skilled connoisseurs of CAD systems and product functionality; the proposed SW solution will be able to support them, integrating their knowledge and experience with notions related to the environmental aspect of the product/process and with the new rules derived from the correlation of the data output from the sensors.
- The secondary user is the one who interacts with the system but does not follow the normal flow of use; examples can be:
 - Content providers;
 - Maintainers.
- Indirect users are all users of the proposed solution. In the case of the DfD tool, indirect users may be internal and external figures. For example, the technician responsible for the disassembly of the electrospindles returning from the customers (i.e., under guarantee) may benefit from the tool outputs (which components to disassemble further to ensure higher recycling performances, or to make a tradeoff between used parts that, being easy to be disassembled, can be replaced, even if not fully broken yet). By looking beyond the OEM gate, the disposer of the product may also benefit from the outputs of the tool: by consulting the reports of the SW system (directly or by establishing an information exchange flow with the manufacturer), will be able to know in advance the number of materials contained in the product and their type, and will be able to know how these are divided into the functional groups of the product. The system can retrieve information from the CAD model. The insertion of a component in the CAD system, if the systems are open simultaneously, information

⁵² <https://store.uni.com/ec-1-2020-uni-cei-iso-iec-25010-2020>

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is updated. This allows the integration of inputs from the CAD and to make the user enter additional information related to the analyzed component (which may vary depending on the nature of the component and the number of information automatically imported from the CAD). The analysis results have different forms (graphic/numeric/guideline). The user can then assess whether these are acceptable or whether the product does not comply with the expected performance (e.g., reduction of environmental impacts compared to previous versions, compliance with threshold values for the indices, avoiding critical feedback). Consequently, the user can decide whether to continue the analysis or modify what previously modeled, focusing on targeted changes guided by the analysis results.

In the present form, the tool performs disassembly and complexity assessment starting from the tree of the product, as modeled in the 3D CAD SW. Consequently, the analysis does not rely on the disassembly sequence but instead considers the complexity of handling and removing parts by evaluating its geometrical data and how the part is connected to the other components/sub-assemblies.

Previous preliminary studies aimed at identifying the disassembly sequence deriving it from the geometrical features of the 3D model. Appendix B shows the preliminary algorithms developed. However the first release of DfD tool did not prioritized the functionality of retrieving the disassembly sequence starting from the 3D CAD model because it would have largely increased the developing time and the complexity of the tool and the interaction between the tool and the CAD model. Alternatively, it would have required identifying a commercial CAD-features recognition system, exploiting and eventually integrating it. The complexity, the longer development time and the low variation of outputs accuracy make this option a secondary priority. Two additional criticalities empower the de-prioritization of the identification of the disassembly sequence: first, the fact that potential uncertainties in the disassembly sequence would have required much more information to be inserted by the user; this would affect the usability of the tool, which was among the main objectives. Secondly, the disassembly sequence is strictly related to quantifying the disassembly time, which was not in the scope of the tool.

In a multivariable disassembly evaluator, as proposed by Zahedi et al. [307], a linear disassembly evaluator should be used to bring a multi-variable vision of disassembly performance based on four principal disassembly axes that are i) difficulty (technical

driver), ii) time (economic driver), iii) material compatibility (technical, economic and environmental driver), iv) weight (economic and environmental driver). In the current form, the DfD tool only exploits three axes, related to environmental drivers: further investigation may also include the economic ones, as the time.

The UCD approach led the development of the DfD tool; this should naturally and seamlessly guide toward an acceptable solution that ensures the highest efficiency, maximum satisfaction and lowest mental and physical stress. According to the ISO/IEC 25010 (Systems and SW engineering - Systems and SW Quality Requirements and Evaluation (SQuaRE) - System and SW quality models), a validation procedure should be developed, aimed at assessing the tool usability, where usability is defined as the ability of the product to be understood, learned, used and attract the user under specific using conditions. The quality of a system is the level at which it meets the specific needs of specific users and is therefore able to generate value. The measurable qualities of a system are called quality properties and have specific measurement methods established through their definitions. Characteristics or sub-characteristics define the different quality properties. The validation procedure should follow and evaluate the quality models summarized in Figure 5.1.

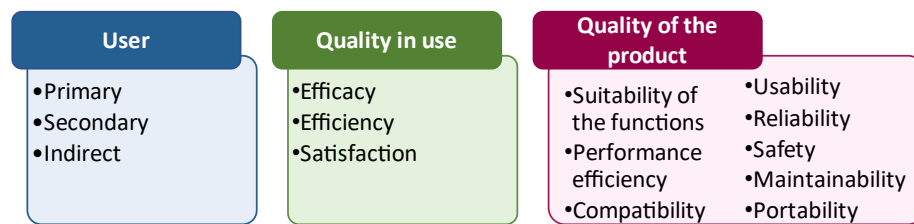


Figure 5.1 Requirements and assessment of system quality

5.4 Correlation matrix potentialities and limitations

The transition from linear to CE involves an increasing number of enterprises; however, their management and direction departments that have a leading role in guiding the company's transition toward the effective implementation of circular strategies [52] still need support, especially in the first steps of the metamorphosis. Several are the CBMs available to multiple genres of organizations, able to merge economic sustainability and its remaining pillars, the environmental one first. However, each enterprise is characterized on its own. When an organization is figuring out which CBM better fits its practices should follow the proposed approach. The main strengths of the proposed approach lay on:

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- It supports the exploitation of digitalization tools; with the advent of the fourth and fifth industrial revolutions [53], companies equip their products and processes with innovative tools. Their potentialities can be exploited more deeply and enlarged to a broader perspective with the proposed approach's support. The correlation matrix in its general form needs to be specified for the single organization and digitalizing tools are to be inserted among the core resources. The primary aim of the digitalization tools may be far from implementing CBMs; the correlation matrix can support the identification of lateral purposes.
- It is based on qualitative evaluations, to support the very first decision-making steps.
- It is widely applicable to enterprises of different sectors, as the correlation matrix is customizable according to the organization's peculiar needs and features.

The transformation from linear to CE may require significant changes in a company organization's relationship with the customers, the roles and activities of key resources, revenue streams and modes. Consequently, existing realities need to move toward circular equilibrium gradually. A precautionary strategy preventing the running business from bumping into hazardous modes of business is to carry out a progressive change. Therefore, the importance of roadmaps that gradually open to new BMs.

Each step of the roadmap introduces new tools; likely, they are used for their primary purpose in advance than the step of the roadmap; however, the step in which they appear is the one when the LCE and the CBM specifically require them. The application to the case study of Companies A and B, through the correlation matrix, supports the exploitation of tools for different purposes than the ones they were developed for. For example, the Prognostic and Health Management Toolkit's first scope was to be a tool-box with easily tailored combination of sensors and intelligence, applicable to the specific case and customer. The toolkit would engineer the data collected from machines (currently friction welding machines) to provide i) an understanding of the performance and use of the machine so customer complaints could be quickly responded and solved and ii) value to the customer providing feedback for better performance and predictive maintenance. Besides the maintenance phase, knowing the machine's status can help diagnose it before a cost-effective refurbishment for a new customer and a life span extension.

Similarly, the Optimization and Simulation Cooperation in Digital Twin is a system for machinery fault diagnosis and predictive maintenance and implements the simulation

environment integrating heterogeneous simulation tools, algorithms for fault diagnosis, remaining useful life prediction, and maintenance. The combination of the simulation environment and predictive maintenance through the collecting sensors and simulated data allows proper maintenance planning (i.e., set-up of machines), to optimize the production throughput and to reduce the production line stoppages. The knowledge acquired through this tool can be used to evaluate the best way to operate on a broken or close-to-a-failure machine.

5.5 Tackled CREDIT factors

The proactive and reactive approaches investigated successfully achieve their main goals and contribute to filling the gaps identified in the literature, namely CREDIT factors (Figure 3.3).

With its simple structure, the Durabot tool, supported by the dynamic approach for conducting an LCA, brings benefits by enlarging the perspective over a wider frame of the product lifecycle. The methods implemented (LCA and durability index) are widely used and affirmed: this is crucial, as it standardizes well-known methods, even if it exploits additional potentialities (i.e., the introduction of evolving factors such as the evolution of the energy grid mix or the performance of the product that make the ALCA dynamic). By the latter, the Durabot tool provides a valuable solution in the EoL decision-making process products reach in different conditions. This discourages consumerist behavior, which always pushes buying new products and discarding the old ones.

The second reactive approach, based on the establishment of IS through the re-design of existing products and the employment of materials that present high critical EoL treatments, successfully provides examples of integration of traditional design for Eco-design purposes, of re-valuation of critical materials, opening new opportunities to the involved companies, which may take advantage of the solutions proposed over the competitors. The present work does not deeply investigate the economic perspective, as prototypes only validate the technical feasibility of the identified solutions. However, i) the proximity of the companies' locations, ii) the current unique way for disposing the composite materials that does not have any competition and no reasons to be lowered, iii) the benefits that the companies' image may acquire by systematically implementing the identified processes and commercializing the re-design components, have great potentialities to compete with the actual costs related to the composite scraps' EoL.

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The DfD tool, aiming at introducing the environmental topic in the design driver, plays an active role in building a LCT approach in the design phase. The collection of data from the 3D model enables integration with traditional tools. Furthermore, through the analysis of the materials and their recyclability, it pursues the goal of training designers with new skills; they become more aware of the consequences of their choice from an environmental perspective.

Although born specifically for digitalizing tools, the correlation matrix has been proven feasible for offline tools (Section 4.6.10.2). The simple tool of the correlation matrix aims at paving the way to the most suitable CBMs. The correlation matrix bridges the technical sphere and the openness of BMs, and is the trait d'union between discarded products and their valorization.

The proposed approaches have been clustered into reactive and proactive, according to the needs they aim to fill; however, the reactive ones may also find application in proactive contests. First, the PReSCoM approach can be applied to not-developed-yet products and/or processes.

The Durabot tool is reactive when employed in the maintenance phase, as it outlines the less impacting alternative between product or part substitution. Indeed, whenever used in the design for de-manufacturing context, the preventive durability analysis can identify the components whose substitution is encouraged to lower the environmental impact of the whole product lifecycle. This might happen by upgrading the product and introducing more efficient components, i.e., more efficient motors, compressors or batteries. For those components, design should guarantee easy disassembly; the DfD tool may help do so.

The above-presented approaches intended explicitly for the design for de-manufacturing strongly rely on evaluating environmental impacts, faithfully referring to the LCA methodology. In any case, more than a single indicator can be selected. CC, also known as Global Warming Potential (GWP), is undoubtedly the most used and known in the industrial and governmental spheres. Therefore, the decarbonization analysis and strategies are the main focus [308], and multiple actions tend to net-zero carbon emission. Greenhouse gases (GHGs) warm the Earth by absorbing energy and slowing the rate at which the energy escapes to space. Different GHGs can have different effects on the Earth's warming. The GWP was developed to allow comparisons of the global warming impacts of different gases. Specifically, it measures how much energy the emissions of 1 ton of a gas will absorb over a given period relative to the emissions of 1 ton of carbon

dioxide. GWPs provide a common unit of measure, which allows analysts to add up emissions estimates of different gases and allows policymakers to compare emissions reduction opportunities across sectors and gases⁵³. The Intergovernmental Panel on Climate Change (IPCC) is responsible for CC state-of-the-art and reporting⁵⁴. However, besides the visible and escalating effects already shown to the worldwide population in recent years (i.e., changes in seasonal temperatures, rain and snow patterns, and intensity of events such as floods and wildfires in many geographies)⁵⁵, the global warming is not the only critical and irreversible effect of humankind on earth. The increasing demand for natural resources (food, metals, water) must cope with the finite dimensions of Earth, and thus of mineral resources: with growing consumption, it is only a matter of time before the supply of resources is no longer able to meet demand [2].

The Competence Centre on Foresight of the European Commission claims the state of ecological deficit for the world due to i) increased and increasing global demand for resources, ii) the use of resources that are primarily non-renewable (despite the Global installed capacity and production from all renewable technologies have increased substantially), iii) more erratic and uncertain water supplies (due to the combined effects of increasing demographic imbalances, growing consumerism and urbanization), iv) high water consumption (desalination only provides 1% of the world's drinking water) and v) deficit of global food supply system⁵⁶. Therefore, the need for high attention to all the criticalities the Earth and humankind face; in this perspective, the proposed tools quantitatively investigate the consequences of the users' actions on multiple categories.

Sustainability encompasses three main pillars (economic, environmental, and social [309]) and looks for their trade-off among costs, benefits for systems' stakeholders and the endangerment of the environment. Similarly, environmental sustainability should not leave behind any issue: the trade-off between convenience for different indicators should be the best strategy to pursue.

⁵³ <https://www.epa.gov/ghgemissions/understanding-global-warming-potentials>

⁵⁴ <https://lcanz.org.nz/best-practices/lcia-recommended-indicators/>

⁵⁵ https://www.elsevier.com/__data/assets/pdf_file/0006/1214979/net-zero-2021.pdf

⁵⁶ https://knowledge4policy.ec.europa.eu/foresight/topic/aggravating-resource-scarcity/more-developments-relevant-aggravating-resource-scarcity_en

6 Conclusion

The global market and growth are at a tipping point on sustainability [1]. Environmental, Social, and corporate Governance (ESG) criteria lead consumers' investments that demand transparency and attention to all pillars of sustainability. CE can be pivotal in tackling the current triple planetary climate, biodiversity, and pollution crises. De-manufacturing is a critical solution for an efficient and systematic implementation of CE; when focused on the first stage of a product lifecycle, design for de-manufacturing links the product development to careful management of resources employed. The scientific literature claims the need for methodologies and tools to support the design phase and improve the product lifecycle.

The present work investigated proactive and reactive approaches to launch products in circular, sustainable scenarios. The backbone lies in the awareness, arisen from a careful review of the SoA (Section 2), that (re-)designing disassemblable products is not enough for the remarkable metamorphosis towards CE (Section 3). Indeed, monitoring their lifecycle (Section 3.1) is important. This supervision enables i) to establish cooperation between the product lifecycle stakeholders (Section 3.2), ii) to identify criticalities before production (Section 3.3), to overcome them in advance. Additionally, iii) to make circular loops economically advantageous by commercializing innovative, circular products through CBMs (Section 3.4).

De-manufacturing, conceived as the summa of the EoL strategies, is the milestone where the subsequent applications of the methodology are shaped (Section 4). The application of CE principles requires enterprises to think of themselves as part of a system rather than a self-standing organization and thus give birth to cooperation and symbiosis with other enterprises, also those whose main activities do not involve the same sectors.

The dynamic approach proposed assessing the product's environmental impacts is a linear approach, able to involve all the external and internal factors that affect the product footprint along its lifecycle. The Durabot tool (Section 4.1) implements it in the context of durability assessment. Results (Section 4.2) show that the environmental performance may highly differ when assessed through traditional ALCA or the dynamic approach; for example, till 70% discrepancy in annual energy consumption is registered. Future versions of Durabot tool may include an improved products management system, the ability to evaluate more than one environmental impact at a time (currently, there are 5

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available indicators, but only one at a time can be considered in the analysis), a procedural interface to enable support for a wide range of analysis products, even from different manufacturers, fields and with different durability formulas. This would ease its use in design contexts (as a proactive tool). Another feature considered is the automatic import of products and components from well-established LCA DBs and/or SW so for an automatic fill-in.

Through the PReSCoM approach (Section 4.3), the current work contributes to filling the urgency to investigate the question related to the EoL treatment of composites by establishing design protocols that positively affect the EoL opportunity of this kind of materials and reduce the overall environmental impact. PReSCoM guides the choice of which and how scraps can be re-used and gain new value so that both their re-manufacturing and the reduction of required raw materials can reduce impacts. Five are the analyzed cases: three relate to the product re-design; for those a reduction of CO₂ emissions between 45% and 95% is registered. Two cases involved a production processes re-designing, almost nullifying their environmental impacts. The application of the methodology outlines important factors to consider while finding possible paths to establish successful IS: dismantler's involvement, information, networking, disassembly, modularity, simple shapes and short distances. Future works will focus on the economic evaluation of the proposed de-manufacturing actions that have been explored from the technical and environmental points of view and the identification of design strategies for all the companies to facilitate or support CE strategies implementation. This would be the basis of the supply analysis. It may be hard to balance and optimize volumes and demand. While process waste might be slightly predictable (if intrinsic to the process), and thus known, the off-specification scrap availability is unpredictable and highly variable, even if the production volumes are known. Therefore, compensating strategies must be investigated. The first approach in investigating alternative EoL of industrial process waste neglected off-the-shelf components; additional studies may investigate their potentialities too. If their materials changed, the coffee grinder and machine OEM could choose to i) insource the production process of those components or ii) extend the collaboration between the guest company, the OEM and the supplier. In this case, the available quantity of scraps should be higher to satisfy a greater demand. As previously mentioned, future works may investigate alternative applications for fiberglass patches and virgin material waste that are discarded only for their dimensions.

Conclusion

The DfD tool (Section 4.4) couples the potentialities of 3D CAD modeling SW and strengthen the environmental awareness of designers. Its relative simplicity informs designers about how their choices ease recyclability and disassembly or whether consistent or acceptable environmental footprints characterize the products they design. The connection with the CAD tool allows real-time simulation of design changes and the ability to check if the design change conforms to the production process. The use of simple indexes (i.e., RBR_n , R_{cyc} , I_{com}) enables to obtain of quantitative results, also with little information available. The outputs of the tool are useful either to identify criticalities and promote product modification yet in the design phase when costs are lower; when this is not possible, the outputs from the multiple functions may be joined (i.e., if a component is made of inappropriate materials, but there are no equally performing materials, the designer should work on allowing easy disassembly for that component).

To get a multivariable disassembly evaluator out of the DfD tool, the disassembly sequence should be retrieved and the disassembly time evaluated; economic feedback and assessment should also be considered. A higher resolution in differentiating the RCR values for materials may be investigated; this should involve dismantlers and recyclers. As the environmental impacts are retrieved through the support of the EcoInvent DB, the sensibility of the tool mirrors the one of EcoInvent. In the present form, the guidelines mix the outputs of the disassembly and compatibility function and disassembly complexity index. Future works should produce guidelines to retrieve criticalities and suggestions including the remaining analysis automatically. To pursue the objective of delivering complete information to the designer, scenarios that simulate maintenance and use phases should be implemented, so that the whole lifecycle impacts are preliminarily provided.

The main strengths of the approach that produces the correlation Matrix (Section 4.6) lay in the support provided in the exploitation of digitalization tools, its broad applicability by enterprises of different sectors and various tools, and the helpfulness provided in the very first attempts to approach CBMs. Future works should investigate and quantitatively set the boundaries of the ladders of the proposed roadmaps: for each step, KPIs should be defined, to guide enterprises in running through the roadmap and reaching the final goal. KPI should either look at:

- Economic sphere: only when a new practice expected by the exploited step is well-established and economically advantageous, the company may move to the following

Conclusion

one; economic KPIs should not only observe the total revenues or incomes derived from a certain LCE, instead might also evaluate the quantities of goods handles within that LCE.

- Environmental and social sphere: each step of the roadmap should be sustainable within all the pillars of sustainability, and benefits involving proper management of the resources (i.e., materials, EoL processes, waste reduction) and the impact of the organization on its employees and the surrounding citizenship should be quantified and reached, prior facing new challenges.

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7 Appendix A

Ref	P S S	S a l e	E c o d.	Method & Tools proposed/ analyzed	C	R	E	D	I	T	Reason 1	Reason 2
[43]		×	×	EDIT; D4N; EDST; MAAP; LCP			×				Value of recovered products < value Disassembly cost	De-manufacturing and re-manufacturing processes do not close the loop on their own.
[24]	×	×	×	CRR			×	×		×	Disparity of recycling processes adopted	Controversial guidelines
[71]	×		×	Mathematical formulation	×		×				More legislation for more changes	
[61]		×	×	ECMPRO			×	×		×		
[53]				DFMLC; MLCA		×	×	×		×	Skill operators for manual labour	
[13]			×	MLCA				×			Need boost for MLC purposed design	
[67]				D/APP; D/ALB; D/ASP		×			×		AP causes subproblems in ASP, ALB, APP	
[54]			×	Lean DFD			×		×		Non structured information about liaison dismantling times	
[69]		×	×			×	×	×			Features required are considered in isolation and not in an integrative fashion that together influence product Lifecycle	Labour costs for dismantling cannot be balanced by the greater material recovery value
[42]				Multiscale, multilevel recycling approach						×	Lack of multistage mechanical design	
[21]			×	Analitical calculation of disassembly time and cost and liaisons analysis		×	×				Difficult to estimate disassembly time and costs	
[28]			×	Collaborative-design platform					×	×	Suppliers retain most product information	Recycling technologies are not able to cope with products complexity
[99]			×				×				Value recovered < disassembly cost	
[121]		×	×		×			×	×		Difficulties to apport changes to product design	Reluctance to share product information
[46]	×			Mathematical formulation	×		×					
[26]				Dismantling tool		×	×			×	Smart tools are costly and not robust enough	
[16]				Analytical model			×	×			Future economic conditions uncertainty of recycled materials	Non satisfying metrics to assess Design for Recycling strategies

Appendix A

Ref	P S S	S a l e	E c o d.	Method & Tools proposed/ analyzed	C	R	E	D	I	T	Reason 1	Reason 2
[47]						×		×		×	Materials mixed in products	
[123]				Mathematical optimization model		×	×	×	×		Product status uncertainty	EoL management complex, costly and long or even impossible
[100]		×			×			×			Lack of parallelism Lifecycle thinking and costing	Despite WEEE, there have been no legislation to facilitation of reuse over recycling
[27]				PBM						×	High variability of products makes challenging developing recycling machines	
[55]		×			×			×			Failure uncertainty	No incentives to buy second-hand products
[52]		×		A set of design feature-based metrics		×				×	Fasteners accessibility	Disassembly complexity
[126]				ARTODTO				×	×		Product status uncertainty	Different design for similar products
[104]		×		LCA; LCC; FMEA			×	×	×		Need to know previous generations of products	High transport costs makes re-use/ re-manufacturing unsustainable
[96]		×			×						Targets must be set to speed shift to CE	
[85]	×		×		×			×			Need to consider all pillars of sustainability at the same time	Re-manufacturing needs a remanufactured products market
[82]	×	×	×		×		×	×			Existing companies may face cannibalization with remanufacturing	Need for corporates to include customers in their circular endeavours and create awareness
[12]		×						×			High level design needed to face Close Loop and CE	
[70]		×		DSS	×			×			Need to bridge the gap between the multi-material component designer and the a priori knowledge of disassembly features	
[92]	×	×		System dynamics	×		×	×		×	Lack of practice of Eco-design	Product longevity affects and replacement rates
[50]				Circularity degree of companies	×				×		Circularity measures are not reality in companies yet.	
[8]		×		V-Design			×		×		Dismantling times condition economic feasibility	Lack of information and systematic approach
[7]	×	×	×		×				×		Difficulties to share information	Lack of legislation

Appendix A

Ref	P S S	S a l e	E c o d.	Method & Tools proposed/ analyzed	C	R	E	D	I	T	Reason 1	Reason 2
[9]		×	×	Learning goals for designers	×				×		More legislation for more changes	Self-standing design for sustainability tools and guidance
[73]		×	×	TOPSIS					×		Product status uncertainty	
[74]				Eco-design policy process applied to enterprise servers	×			×			Accurate metrics depend on product variability	Need to ‘operationalize’ CE principles
[101]			×	DSP; Liason_DB		×	×		×		Dismantling centres retain most the information	Several different factors affect disassembly time
[107]			×	DSP; Liason_DB		×	×		×		Dismantling centres retain most the information	Several different factors affect disassembly time
[108]			×	DOG		×	×		×	×	AR too costly to be widely applied	Several different factors affect disassembly time
[102]			×	DSP			×	×	×	×	Long-time existing tool, late application	Proportionality disassembly cost and depth
[112]			×	G.EN.ESI		×		×	×		Low connection and operability between traditiona and eco-design	
[97]			×	Assessing the Disassembly of Critical Components in Products	×			×			Willing to maintain competitiveness	Design focused on hiding company IP
[98]			×	ARDET				×		×	Difficulties to implement KET of I4.0	Difficulties to accept KET of I4.0
[109]			×	LeanDfD	×	×					Lack of DfX	
[49]			×			×	×		×		Product status uncertainty	RL is complex and costly
[81]	×	×	×	Modularity matrix				×	×		Lack of product modularization	
[22]			×	Modify entropy theory				×	×		Difficulties to understand product complexity	
[51]			×	DEI		×			×		Difficulties to share info (dismantlers – designers)	Demufacturing occurs late in time and far in space from design
[95]			×	PDC				×	×	×	Product components accessibility	Multitude of tools needed
[25]			×	DisKnowDB; DKTool		×	×		×	×	High capital and labour cost	Lack of Disassembly embedded design
[87]	×		×	CAD tool for disassembly	×			×			Different purpose of design (maintenance /recycling)	
[122]		×	×	ECPD	×			×			Little knowledge of DfD concepts	
[66]		×	×		×			×	×		Lack of integrated information techniques to support innovative (Eco-)design	

Appendix A

Ref	P S S	S a l e	E c o d.	Method & Tools proposed/ analyzed	C	R	E	D	I	T	Reason 1	Reason 2
[116]			×			×	×			×	Manual disassembly	Disassembly cost and time
[117]			×	Multi-objective genetic for Pareto-optimal designs				×			Product components accessibility	
[91]	×				×			×		×	Need for contact with customers	Low use of big data by designers
[126]						×	×			×	Difficulties to implement KET of I4.0	Many skill operators for manual labour
[93]		×		DSP				×	×		Lack of modularization of parts subjected to wear	
[94]		×		LC option selection of disassembly parts for material-based CO2 saving rate and recovery cost		×	×				Manual disassembly	Cost of labour
[64]	×			Design method for ease of value recovery		×	×	×			Disassembly cost	Materials incompatibility
[113]		×		EoL value recovery			×	×		×	Disassembly is the bottleneck	Materials incompatibility
[18]				Integer programming; ε constraint		×	×	×	×		Accepting the rules is different from believing in the rules	Dismantlers know disassembly times and costs
[68]		×		Design method				×	×		DfX tools are theoretical and rarely applied	Knowledge Capitalization is not based on forward e backward knowledge sharing
[114]		×		Mathematical model	×				×		Lack of Environmental Product Profile	Dismantlers have no product design info
[127]				Math. Model and ACO model		×	×				Disassembly takt time different from assembly takt time	Unknown disassembly takt time
[73]		×		ELSEM	×	×			×		Designers have no information about product EoL	Multiple tools that require too many info or money or time
[124]								×	×		SMEs find hard to develop a Lifecycle Thinking	Lack of standards to make eco-design replicable
[77]				ELSEM; fuzzy			×			×	Dismantling techniques	Cost of recycling
[103]		×		layout and fastening method optimization			×				Full disassembly is not convenient	
[23]							×	×		×	Low revenue from retrieved parts	Irreversible connections/liaisons
[106]		×		DSSG				×	×		Lack of modular design	
[14]		×		Approach to topological				×			Lack of practical design approach	

Appendix A

Ref	P S S	S a l e	E c o d.	Method & Tools proposed/ analyzed	C	R	E	D	I	T	Reason 1	Reason 2
				disassemblability analysis								
[19]			×	Collision detection method				×	×		Product part accessibility	
[119]			×		×					×	Lack of recycled materials market	Vergin materials have higher quality than second life ones
[118]			×	CE product and business model strategy framework.	×		×				Low re-use rate of remanufactured parts	Need for time dimension (narrowing and slowing loops)
[78]				GFDA						×	Recycling technology	
[72]			×	Multi-objective fuzzy graph approach for modular formulation				×	×	×	Lack of product modularization	
[17]			×	Online DSS to select standards and assess product	×		×	×			Need to translate regulations into constraints	Need for homogeneity of materials
[105]			×		×	×	×				Reverse Logistics hard to apply	
[54]			×	EoL indices				×			DfRecycling must be paired to other, more eco-friendly, strategies	Lack of design for remanufacturing
[110]			×	IDEAssemble	×		×	×		×	Product complexity make decision making hard	
[62]			×	LCED	×			×			Too specific tools available for a single lifecycle stage	Need for a second life market (different from second hand)
[83]	×	×	×	TCE; HALG	×		×		×		Non-standard driver to lead make or buy decision	Product status uncertainty
[115]			×	RDMF	×			×			Lack of a comprehensive structure that considers all strategic aspects	
[89]	×				×	×	×				Need for harmonic laws in favour to remanufacturing	Remanufacturing (and transport) too costly
[120]		×	×		×	×	×	×			High labour cost (in EU)	Need for parallel product and process design
[86]	×		×	Development of a new BM	×	×		×	×		Need to rethink the product in rem. point of view prior shift to PSS	Need for cooperation with retailer to manage logistics
[20]		×		Fuzzy to evaluate disassembly strategies			×	×		×	For complex product full dis. is not economic viable	For complex products full dis. is not environmental viable
[88]	×		×	QFD				×			Lack of parallel focus on QFD and environmental aspects	

Appendix A

Ref	P S S	S a l e	E c o d.	Method & Tools proposed/ analyzed	C	R	E	D	I	T	Reason 1	Reason 2
[75]	×	×	×	GAIA; PROMETHEE	×			×			Product complexity makes decision making hard	Need for focus on fasteners
[310]			×	Disassembly petri-net model				×			Need for reducing conflicting issues practically considering an optimal disassembly sequence	
[35]			×	Repurposing; P.P.BM.	×		×				Need for integrate EoL strategy from early design	
[84]	×	×	×		×		×			×	Low cost, mass products discourage remanufacturing	Lack of legislation that support remanufacturing
[39]	×		×					×			Need for DfX approaches to fit with circular design perspective	
[35]	×		×	Repurposing	×		×				Need to think about the strategy for the distribution on the market	Decisions arising from design are not limited to the product
[90]	×			RIFF; RemPro matrix				×	×		Need for OEM to get information feedbacks	
[36]	×		×	Protocol analysis of a PSS design process								
[56]		×		Integrated multi-disciplinary research framework addressing			×	×	×	×	Inefficiency of disassembly processes, low productivity and labor cost of manual disassembly	Lack of EOL-oriented design practices that would ease automate disassembly
[37]			×	Conceptual Structure of CE levels	×			×			Lack of consideration of consumption patterns and citizen inclusion	Lack of integration of material, strategic, and consumer perspective
[29]			×	Active disassembly through SMA or SMP			×	×		×	Disassembly may need specific tool whose use requires special knowledge or experience	Automated disassembly needs high investment costs
[41]	×		×		×	×				×	Risk of cannibalization	Critical access to cores
[32]		×		Combines FDM; TISM; MICMAC	×	×				×	Low customer demand	Challenge of collaborative innovation among SC partners
[40]			×	SWOT; Triple-layered CBM innovation framework					×	×	Lack of repeated practice to understand the role of design	
[311]			×		×			×	×		Need for system or financial incentive to motivate R-strategies	

8 Appendix B

This appendix contains the algorithm developed in the first stage of study of the DfD tool. In particular, it relates to the identification of the disassembly sequence, starting from the geometric characteristics of the model. This function was not prioritized, as it would have largely increased the developing time, due to the requirement to identify a high number of features. Nevertheless, further steps may investigate this function. The disassembly sequence, in the first version of the DfD tool presented in section 4.4, is partially retrieved from the modeling tree of the 3D model; however, the disassembly complexity is evaluated only considering the characteristics and the number of liaisons. The complexity is given by exploding, level by level, the complexity of the assemblies that contain the component or sub-assembly that is the target of the analysis.

The following figures (from Figure 8.1 to Figure 8.14) shows the algorithm at the base of the disassembly sequence recognition. To contain it in reasonable space, the algorithm has been split in several blocks and shown in separated figures. In their caption a description is given, both their father diagram and the subsequent diagrams they are related to are provided.

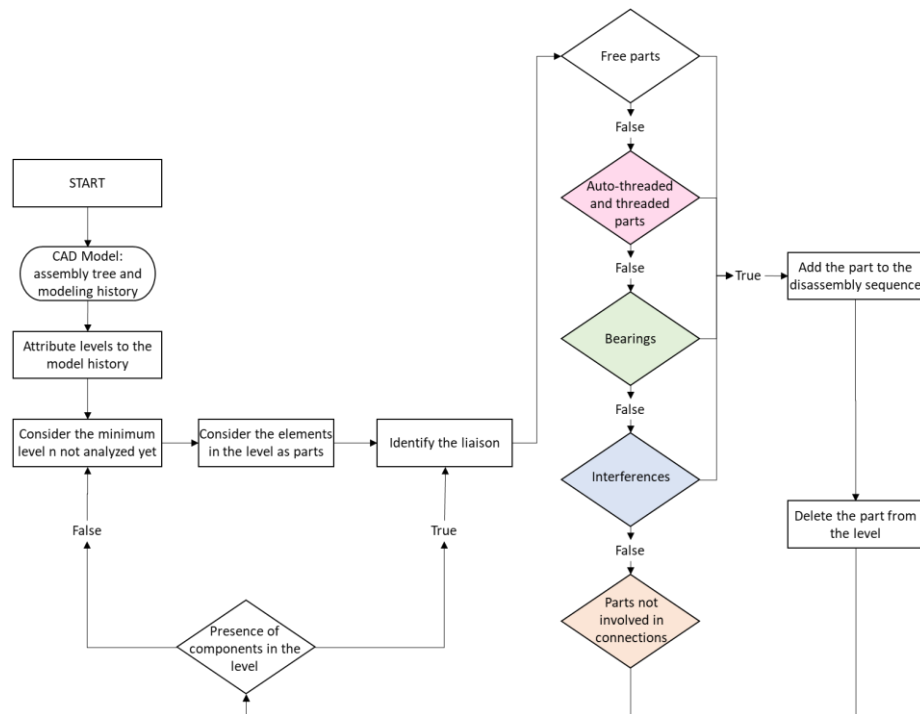


Figure 8.1 General disassembly sequence diagram, compact. Color-filled shapes are starting points for Figure 8.2, Figure 8.3, Figure 8.4, Figure 8.5, Figure 8.6

Appendix B

For example, in Figure 8.1, that is the higher level of the whole algorithm, there are four colored blocks; from each a secondary diagram departs, those are the *free parts* (Figure 8.3), the *auto-threaded and threaded parts* (Figure 8.4), the *bearings* (Figure 8.2), the *interference* (Figure 8.5) and the *parts non involved in connections* (Figure 8.6) diagrams. Their starting block is filled and highlighted in different colors.

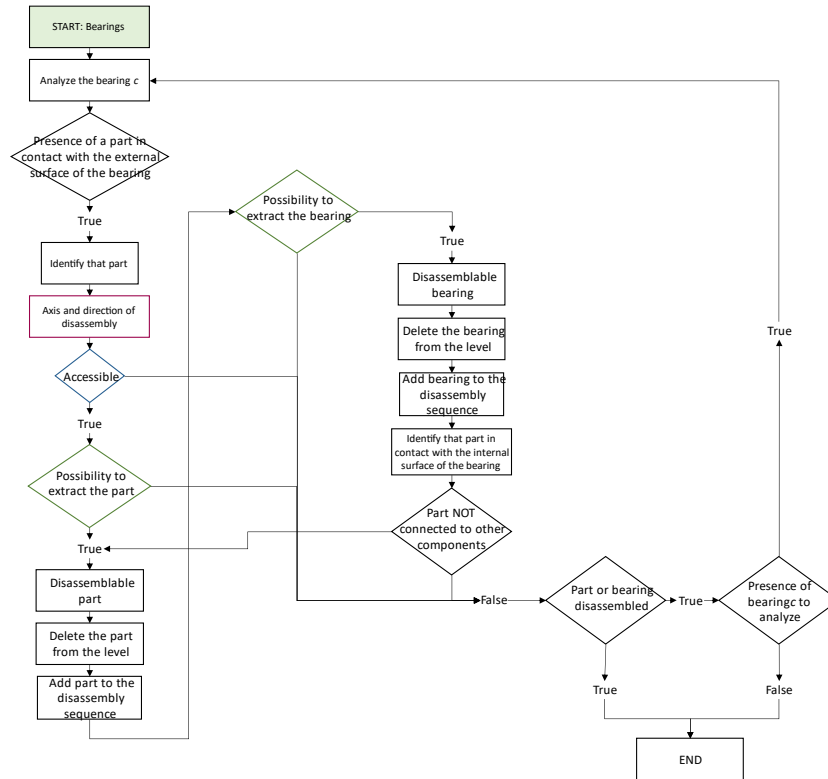


Figure 8.2 Bearings disassembly diagram. Color-bordered shapes are starting points for Figure 8.12, Figure 8.7, Figure 8.10. Father diagram: Figure 8.1

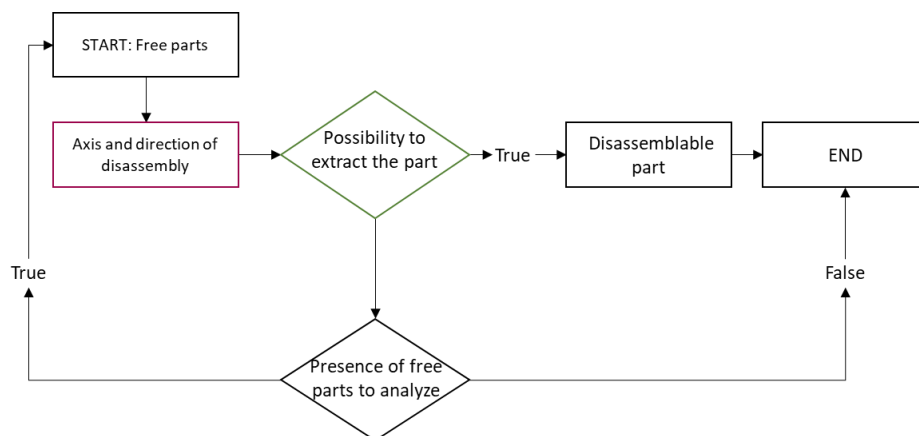


Figure 8.3 Free parts diagram. Color-bordered shapes are starting points for Figure 8.13, Figure 8.10. Father diagram: Figure 8.1

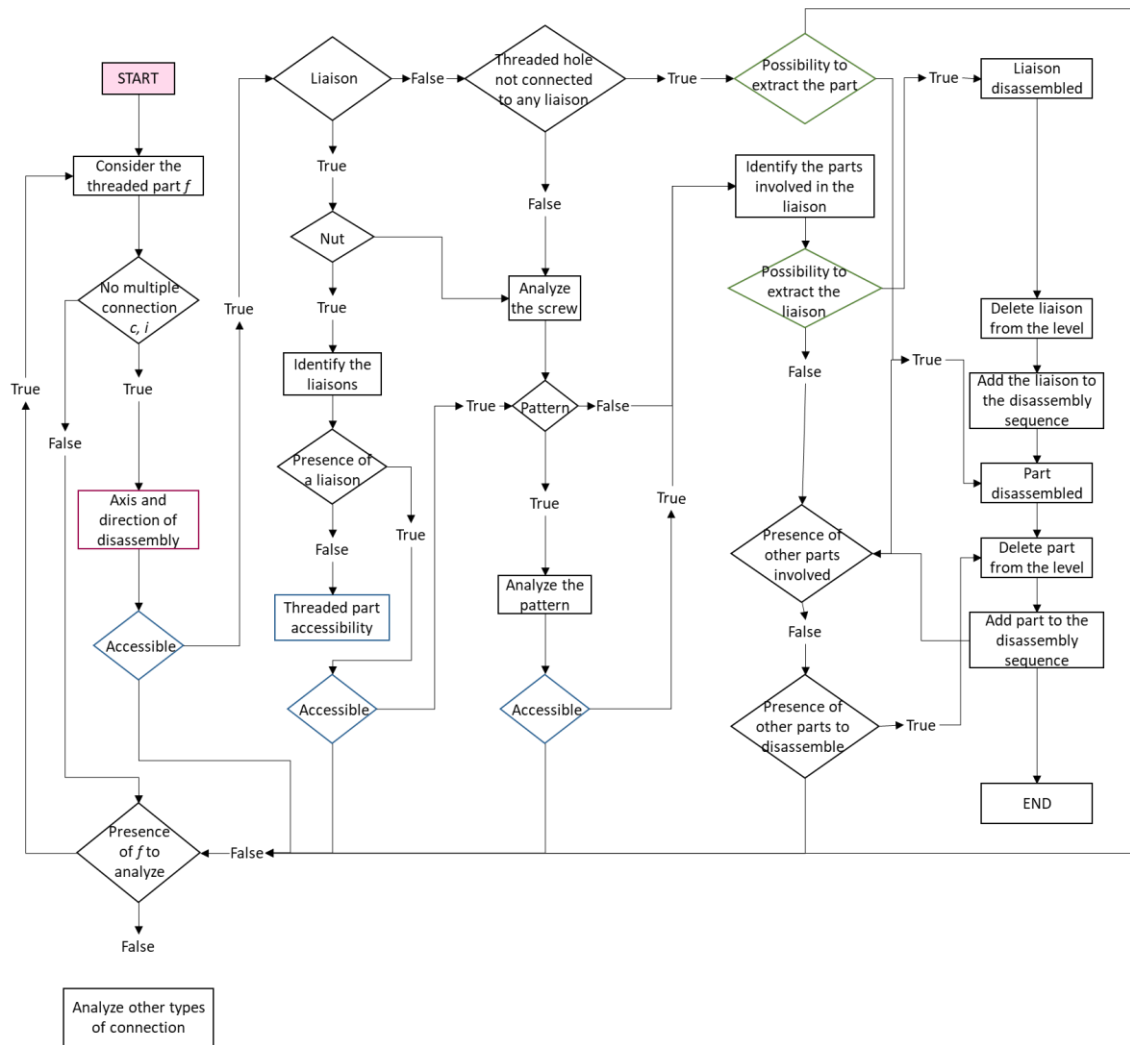


Figure 8.4 Threaded parts disassembly diagram. Color-bordered shapes are starting points for Figure 8.8, Figure 8.9, Figure 8.13, Figure 8.10. Father diagram: Figure 8.1

Some blocks are recurrent and are called-back from more than one point of the diagram; these are the accessibility diagrams for *general operation* (Figure 8.7), *threaded components* (Figure 8.8), *threaded bar* (Figure 8.9), the *extraction* (Figure 8.10) diagrams, and those which identify the direction and way for extracting *threaded parts* (Figure 8.11), *bearings* (Figure 8.12), *external* (Figure 8.13) and *internal* (Figure 8.14) parts involved in interferences.

They are recognizable as the shape from which the sub-diagram starts has a colored border. When a sub-diagram is ended, the reader should go back to the father diagram, indicated in the caption.

Appendix B

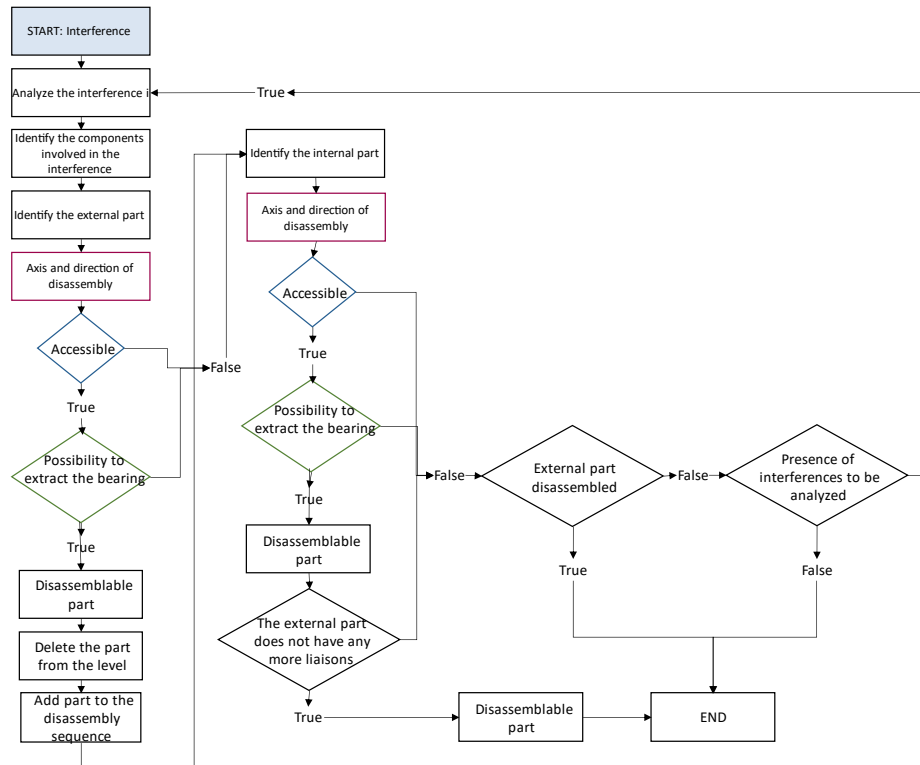


Figure 8.5 Interferences disassembly diagram. Color-bordered shapes are starting points for Figure 8.7, Figure 8.10, Figure 8.13, Figure 8.14. Father diagram: Figure 8.1

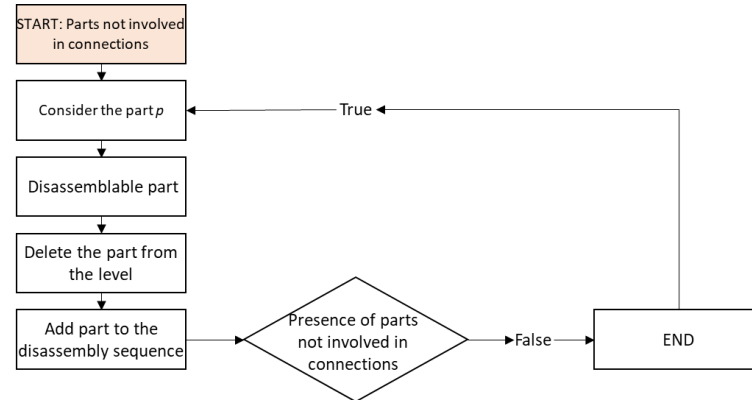


Figure 8.6 Disassembly diagram of parts not involved in any connection. Father diagram: Figure 8.1

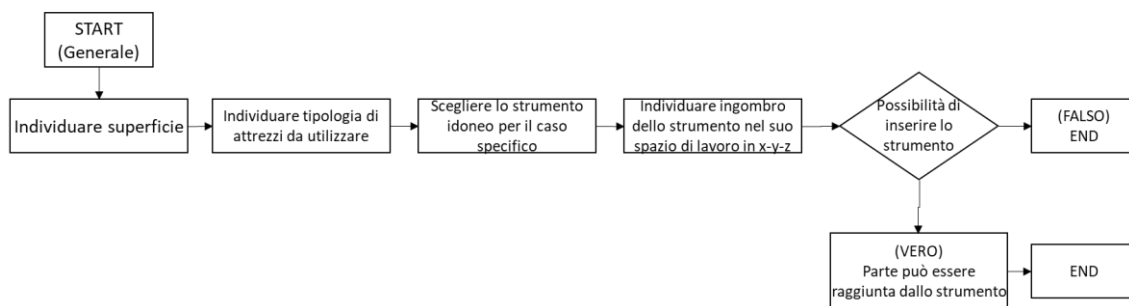


Figure 8.7 Accessibility diagram for general operation. Father diagram: Figure 8.2

Appendix B

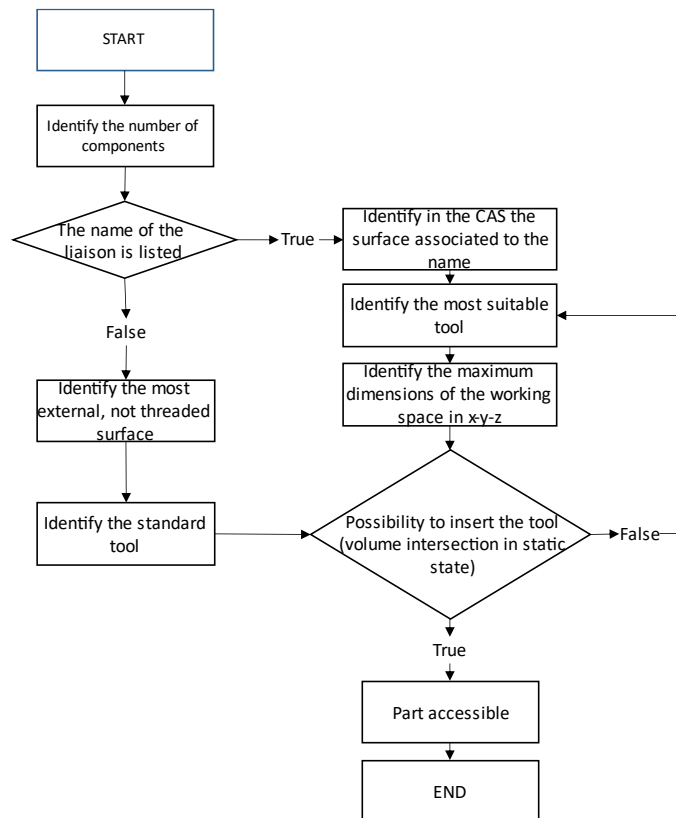


Figure 8.8 Accessibility diagram for threaded components. Father diagram: Figure 8.4

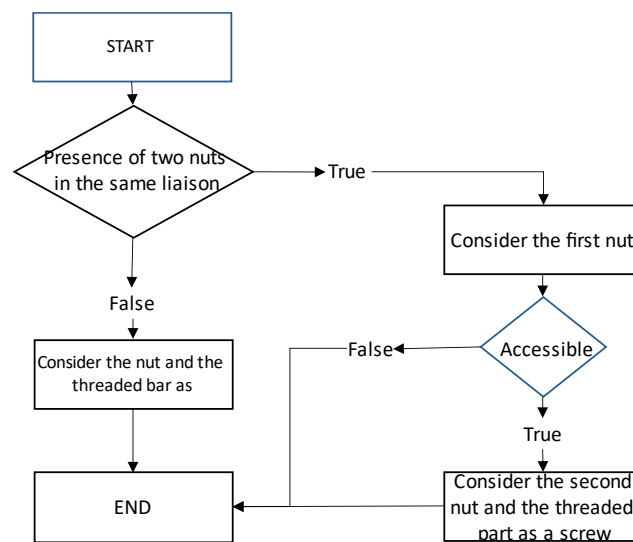


Figure 8.9 Accessibility diagram for threaded bar. Father diagram: Figure 8.4

Appendix B

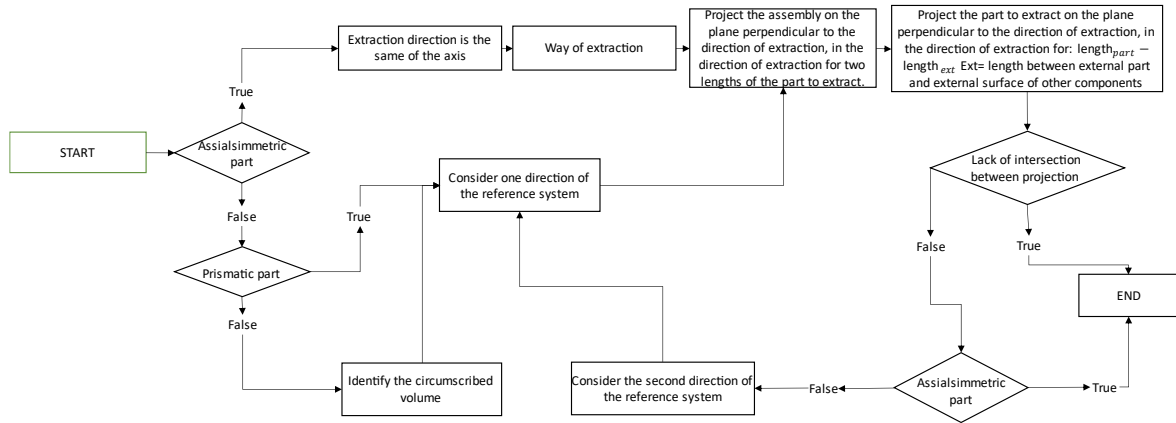


Figure 8.10 Part extraction diagram. Father diagrams: Figure 8.2, Figure 8.4, Figure 8.5

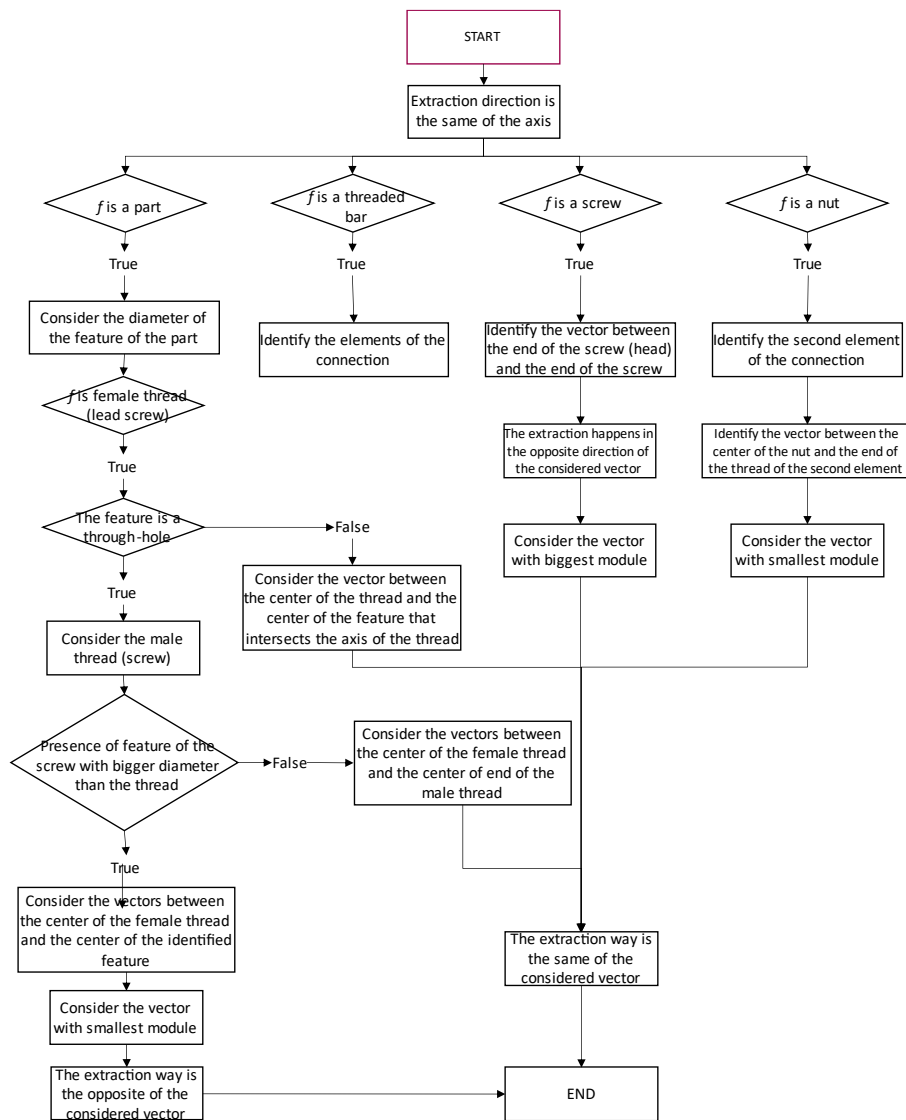


Figure 8.11 Disassembly direction and way diagram for threaded parts. Father diagram: Figure 8.4

Appendix B

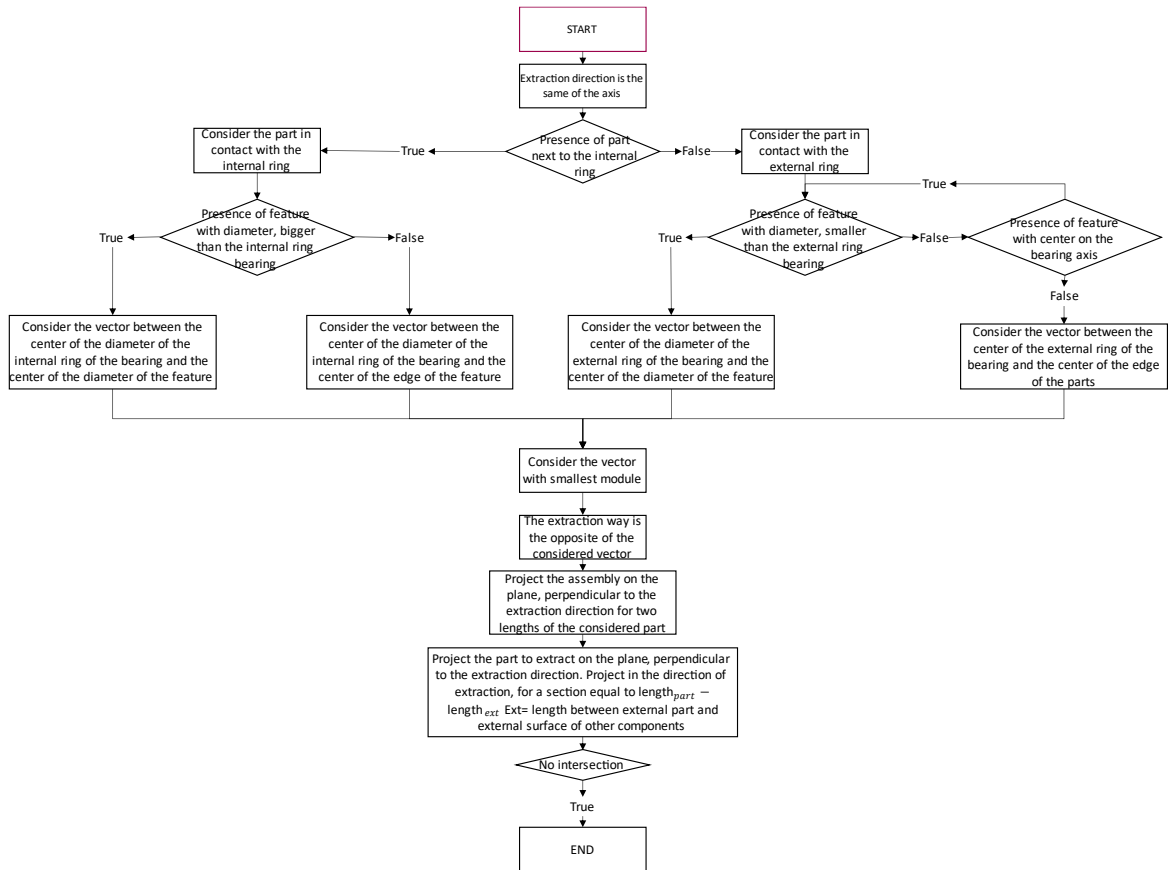


Figure 8.12 Disassembly direction and way diagram for bearings. Father diagram: Figure 8.2

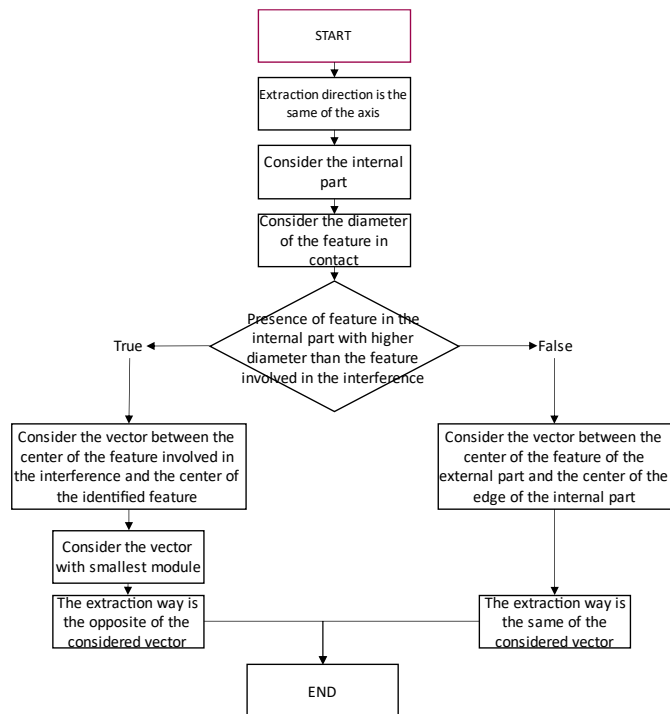


Figure 8.13 Disassembly direction and way diagram for external part involved in interferences. Father diagram: Figure 8.5

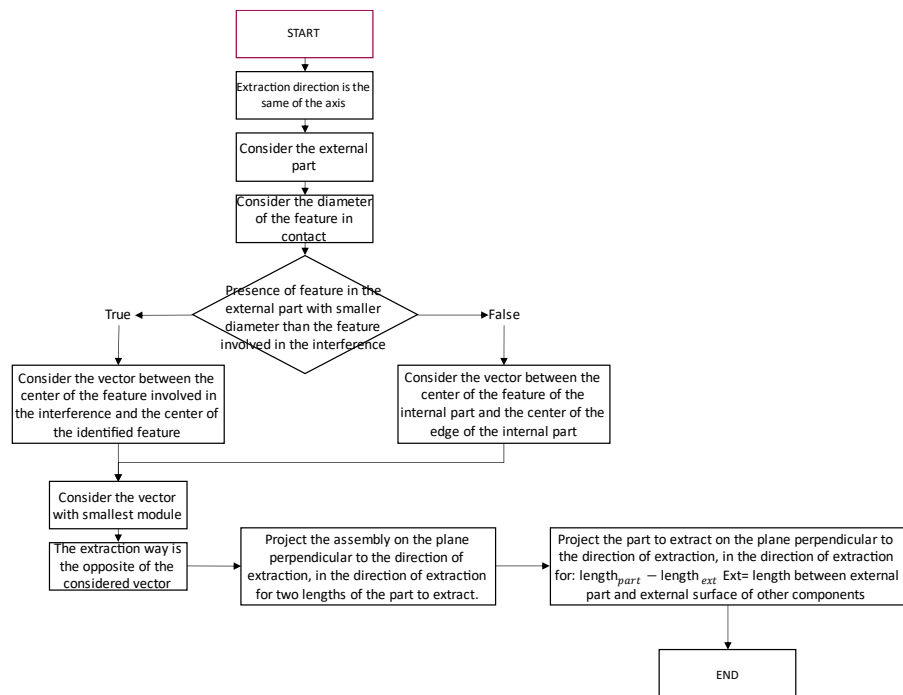


Figure 8.14 Disassembly direction and way diagram for internal part involved in interferences. Father diagram: Figure 8.5