Università Politecnica delle Marche

Scuola di Dottorato di Ricerca in Scienze dell’Ingegneria

Corso di Dottorato in Ingegneria Industriale

Toward circular economy: turning waste into resources through the adoption of End of Life oriented methods and tools

Ph.D. Dissertation of:

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XV edition – new series

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Verso un'economia circolare: da rifiuti a risorse attraverso l'adozione di metodi e strumenti orientati al fine vita

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Abstract

Waste management and resource scarcity are becoming key issues for the modern society. Circular economy is recognized as the most effective economic model that guarantees long term sustainability by decoupling economic growth and finite resources consumption. It aims to close the loop of product lifecycles by boosting reuse and recycling, with environmental and economic benefits. This requires to efficiently manage the End of Life (EoL) phase, which represents the joining link to close the product lifecycle. However, EoL management is a complex task since it is influenced by many different aspects and stakeholders along the whole product lifecycle.

The general objective of this research thesis is the definition of a holistic framework to monitor product EoL during the most affecting phases. The final aim is to develop a set of methodologies and tools able to support the different phases of the decision-making process (from conception to EoL management), in order to design products with improved performances in terms of disassemblability, maintainability, de-manufacturing and EoL.

The proposed EoL-oriented framework integrates four innovative methodologies and tools: (i) the *Target disassembly methodology* to assess the disassemblability through quantitative metrics, (ii) the *LeanDfD tool* to identify product criticalities, (iii) the *Disassembly Knowledge (DK) methodology* to support the redesign phase and (iv) the *Collaborative EoL platform* to favour the sharing of relevant data and materials.

The outcomes have been validated in two case studies. The first one, focused on a washing machine, demonstrated that the proposed design methodologies and tools are effective means to support the redesign phase oriented

toward the improvement of disassemblability and EoL performances. The second one, focused on the electronics sector, confirmed the usefulness of an EoL management platform in supporting the decision-making process, toward the implementation of reuse scenarios.

Riassunto

La gestione dei rifiuti e la scarsità di risorse stanno diventando problemi primari per la società moderna. L'economia circolare è riconosciuta il più efficace modello per garantire sostenibilità di lungo termine, grazie al disaccoppiamento tra lo sviluppo economico e il consumo di risorse. Essa mira a realizzare cicli di vita chiusi, sfruttando il riuso e il riciclo, con rilevanti benefici sia economici che ambientali. Questo richiede un'efficiente gestione del fine vita, che rappresenta l'anello di congiunzione per la chiusura del ciclo vita. La gestione del fine vita è però un'attività complessa e influenzata da numerosi aspetti e attori.

L'obiettivo del presente lavoro di ricerca è la definizione di un framework che permetta di monitorare il fine vita durante le fasi più influenti. Lo scopo finale è lo sviluppo di una serie di metodologie e strumenti per supportare le diverse fasi del processo decisionale, al fine di progettare prodotti con performances migliorate in termini di disassemblabilità, manutenibilità e fine vita.

Il framework proposto integra quattro innovative metodologie e strumenti: (i) la *Metodologia per la stima della disassemblabilità* attraverso indicatori quantitativi, (ii) lo *Strumento software LeanDfD*, per l'identificazione delle criticità di prodotto, (iii) la *Metodologia Disassembly Knowledge*, per supportare la fase di riprogettazione e (iv) la *Piattaforma Collaborativa*, per favorire la condivisione di informazioni e materiali.

I risultati del lavoro di tesi sono stati validati attraverso due casi studio. Il primo, riguardante una lavatrice, ha dimostrato che le metodologie e gli strumenti sviluppati rappresentano mezzi utili per supportare la riprogettazione orientata a migliorare le performances di disassemblabilità e fine vita. Il secondo, riguardante il settore elettronico, ha confermato l'utilità della piattaforma di gestione del fine

vita per supportare il processo decisionale mirato all'implementazione di scenari di riuso.

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List of Abbreviations

ABS	Acrylonitrile Butadiene Styrene
AISI	American Iron and Steel Institute
API	Application Programming Interface
BoL	Beginning of Life
BoM	Bill of Materials
BSI	British Standard Institution
CAD	Computer-Aided Design
DB	DataBase
DfA	Design for Assembly
DfD	Design for Disassembly
DfEoL	Design for End of Life
DK	Disassembly Knowledge
DSP	Disassembly Sequence Planning
EEE	Electric and Electronic Equipment
ELV	End of Life Vehicles
EoL	End of Life
EPR	Extended Producer Responsibility
EU	European Union
GA	Genetic Algorithm
G.EN.ESI	Integrated software platform for Green ENgineering dESIgn
GHG	GreenHouse Gases
GPN	Global Production Network
ISO	International Organization for Standardization

KB	Knowledge-Based
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCA	Life Cycle Assessment
LCT	Life Cycle Thinking
LE	Large Enterprise
MoL	Middle of Life
MTBF	Mean Time Between Failure
NN	Neural Network
NS	New Solution
OD	Original Design
PCB	Printed Circuit Board
PDF	Portable Document Format
PDM	Product Data Management
PLM	Product Lifecycle Management
PN	Petri Net
RFID	Radio-Frequency IDentification
RoHS	Restriction on the use of Hazardous Substances
SCM	Supply Chain Management
SD	Sustainable Development
SSCM	Sustainable Supply Chain Management
SME	Small and Medium Enterprise
STEP	Standard for the Exchange of Product model data
UNEP	United Nations Environment Programme
VR	Virtual Reality
WEEE	Waste of Electric and Electronic Equipment
XML	eXtensible Markup Language

1. Introduction

1.1. Research context

In modern society, environmental problems (e.g., water scarcity and pollution, air pollution, waste management, noise, etc.) are becoming some of the most important and complex issues that need to be efficiently faced to guarantee a liveable planet for future generations. This is due to different reasons, among them the continuous growing of the worldwide population, which is expected to reach 8,5 billion by 2030, 9,7 billion in 2050 and 11,2 billion in 2100, according to the United Nations estimations (UN DESA, 2015). The improvement of the overall economic conditions, together with an increment of the product discard rate, lead to an over-generation of waste and to an over-consumption of resources, needed to produce an increasing number of goods. Until today, our economies have been based on the assumption that resources are abundant, available, easy to source and cheap to dispose of (European Commission, 2015). Since 70's we are using more resources than nature can regenerate and we are emitting more carbon dioxide into the atmosphere than forests can sequester. In 2016, the Earth Overshoot Day (i.e. the date when the humanity has exhausted nature's resources for the year) landed on August 8. This means that we needed more than 160% of the generated nature's resources and for the rest of the year we consumed local resource stocks (Global Footprint Network, 2016). It is easy to understand that this kind of economic model is not sustainable in the long term.

In this complex context, Sustainable Development (SD) concept, defined more than 30 years ago by the Brundtland Commission (WCED, 1987), is currently emerging as a key aspect to take into account at different levels. It refers to the ability to produce goods or services without compromising the ability of future generations to meet their own needs. It focuses on human wellbeing, aiming to *"achieve continuous improvement of quality of life"*. A growing environmental awareness is also emerging and consumers now perceive green products and green labels with a positive attitude (Laroche et al., 2001). As a consequence, industrial firms need to produce sustainable and resource-efficient products (Swenson and Wells, 1997; Hauschild et al., 2005) and to become "active actors" of SD, connecting profitability with environment preservation (Markusson, 2001). This requires to change the way to conceive and design new products and services, starting from design departments of industrial companies (Baumann et al., 2002).

From the policy point of view, the European Union (EU) is facing the SD with increasing efforts, by issuing a series of legislations and long term programme with the final objective to provide a strategic vision to drastically reduce the impacts caused by human activities on the environment. The first relevant initiative is the *2020 Climate and Energy Package* (European Commission, 2007), which foresees a 20% cut in GreenHouse Gases (GHG) emissions from the 1990 level, a 20% of EU energy from renewables and a 20% improvement in energy efficiency. The final objective is to mitigate the climate change and the massive and irreversible disruption of the global ecosystem, by limiting the global average temperature increase to less than 2°C compared to pre-industrial levels. In addition, EU has already set the target for 2050: reduction of 80-95% of GHG emissions in comparison with the 1990 level.

The *European Roadmap to a Resource Efficiency* is based on the following vision: *"By 2050 the EU's economy has grown in a way that respects resource constraints and planetary boundaries, thus contributing to global economic transformation. Our economy is competitive, inclusive and provides a high standard of living with much lower environmental impacts. All resources are sustainably managed, from raw materials to energy, water, air, land and soil.*

Climate change milestones have been reached, while biodiversity and the ecosystem services it underpins have been protected, valued and substantially restored" (European Commission, 2011). It provides a framework to transform the economy in a more sustainable and competitive one, with new sources of growth and new jobs through improved efficiency and better management of resources. This framework aims to protect human and natural resources by stimulating consumption of resource efficient products, efficient production, management of wastes as resources and research and innovation activities.

The aforementioned principles represents the basis of the *7th Environment Action Plan "Living well within the limits of our planet"* (European Parliament and Council, 2013). One of the nine pillars is the transition to a resource-efficient, green and competitive low-carbon. It includes a special focus on turning waste into resource, through prevention, reuse and recycling.

Regarding waste, each year the EU produces about 2,7 billion tonnes of wastes. Only 40% of solid wastes are reused or recycled, while the rest goes to incineration and landfill or is illegally transported to EU and non-EU countries for economically non-optimal and environmentally unsound treatments. This situation forced EU to issue a *Waste Framework Directive* (European Parliament and Council, 2008), with the overall objective to establish broad actions for the reduction of waste production. It imposes to reach prefixed percentage of material recovery and recycling, encouraging to follow the priority order set by the waste management hierarchy: (i) prevention, (ii) preparing for reuse, (iii) material recycling, (iv) energy recovery, (v) disposal and, finally, (vi) landfilling. In addition, other directives have been issued during the last years to regulate the waste management in specific sectors:

- *Directive on End of Life Vehicles (ELV)* (European Parliament and Council, 2000), which imposes producers to organize an efficient End of Life (EoL) management chain in order to reach targets for reuse and recycle rates. Furthermore, it encourages to facilitate the vehicle disassembly and material separation, to minimize the use of hazardous substances and to maximize the quantity of recycled materials;

- *Directive on Vehicle Approval* (European Parliament and Council, 2005) to guarantee the possibility to reuse, recycle and recover vehicles at EoL. It imposes vehicle producers to provide a certificate with the indication of the recyclability and recoverability rates;
- *Directive on Restriction on the use of Hazardous Substances (RoHS)* (European Parliament and Council, 2011), which is based on the principle that *"prevent the use of hazardous substances is the best strategy to recover them"*. It facilitates the EoL management of Electrical and Electronic Equipment (EEE) by limiting the use of certain categories of substances (e.g., lead, mercury, cadmium, etc.);
- *Directive on Waste of Electric and Electronic Equipment (WEEE)* (European Parliament and Council, 2012), which regulates the EoL of EEE, imposing the separation from the other waste fluxes, the organization of an efficient EoL management chain and the achievement of prefixed recovery thresholds. In addition, it encourages producers to adequately design products in order to favour disassembly and EoL activities.

All these directives are founded on the concept of *Extended Producer Responsibility (EPR)*, defined as *"an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle"*. Unlike the traditional solid waste management approaches, EPR identifies producers as "polluter", involving them in the responsibility of waste management of products they produce and commercialize (European Commission – DG Environment, 2014).

A relevant initiative to favour the minimization of waste production and virgin resource consumption is the *European Action Plan for the Circular Economy* (European Commission, 2015), which aims to close the loop of product lifecycles by boosting reuse and recycling, with environmental and economic benefits. In a context where raw materials are limited and the economic growth cannot be interrupted, it is necessary to decouple these concepts. Circular economy is defined as an economy that is *"restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles"* (Ellen MacArthur Foundation, 2016). The implementation of circular economy models requires changes along the whole value chain and potentially leads to an estimated reduction of material inputs by 17%-24% by 2030 (European Commission – DG Environment, 2011), with an overall savings of €630 billion for the European industry (Europe INNOVA, 2012), as well as to other wider benefits as the reduction of carbon dioxide emissions levels (Ellen MacArthur Foundation et al., 2015). On one hand, a better product design can make products more durable or easier to repair, upgrade or remanufacture, helping recyclers during the disassembly and recovery of valuable and critical raw materials (e.g., rare earth elements). On the other hand, also waste management plays a fundamental role, since it determines if the system is efficient, with high rates of material recovery, or inefficient, with significant environmental impacts and economic losses (European Commission, 2015).

An important strategy within the circular economy and resource-efficient manufacturing is certainly the *Remanufacturing*. According to the definition provided by the British Standards Institution (BSI), remanufacturing is the process of *"returning a product to at least its original performance with a warranty that is equivalent or better than that of the newly manufactured product"* (BSI, 2009). Remanufacturing can be considered as one of the way to close the loop of product lifecycles, with the recovery of most of the value (Zero Waste Scotland Limited, 2015). It leads to material savings, environmental impact decrease, lower energy requirement and provides opportunities for the creation of jobs and economic growth. Remanufacturing is currently implemented in several industrial sectors, among them automotive, aerospace, EEE, etc. In Europe, the remanufacturing activities generates around €30 billion in turnover and employs around 190.000 people (European Remanufacturing Network, 2015). Even if, both in EU and United States, remanufactured goods currently represent about 2% of the total goods, an increase of the EU remanufacturing industry to €70 - €100 billion in turnover with 450.000-600.000 employees is expected by 2030. This highlights the opportunities for industries to shift from a traditional linear model to a circular business model (Figure 1), where EoL products and wastes become resources to exploit instead of problems to manage.

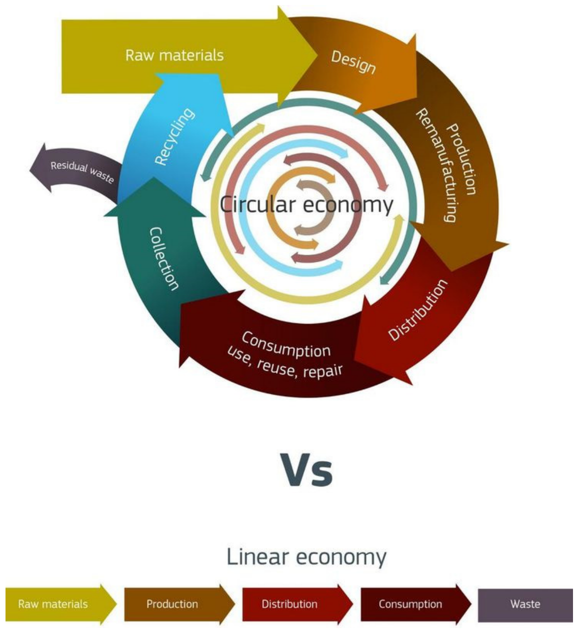


Figure 1. *Circular vs Linear economy models (European Commission, 2015).*

1.2. Research objectives and Contribution to the State of the Art

The economic convenience of the transition to a circular business model strictly depends by different aspects, among them: (i) possibility to efficiently take back products at EoL, (ii) cost of the reverse supply chain, (iii) product/component obsolescence, (iv) easy of disassembly (i.e. disassemblability) of products, (v) cost of EoL activities (e.g., disassembly, repair, cleaning, etc.), (vi) consumer awareness on green or remanufactured products and (vii) the legislative framework. These aspects are related to different product lifecycle phases, thus it is essential to consider the whole product lifecycle, from design and manufacturing to dismantling. The implementation of circular economy passes through the application of the *Life Cycle Thinking (LCT)* paradigm (UNEP, 2012), a key principle toward the SD. It allows to have a more complete view on the interactions between human activities and nature, thus to widen the perspective considering additional aspects that are usually neglected (UNEP, 2007). According to LCT principles, companies need to extend their view outside the traditional boundaries, considering not only internal activities.

Considering the different lifecycle phases, *End of Life* is certainly the most critical one because it is the moment furthest from product conception. However, it is a strategic phase because it represents the joining link to close the product lifecycle. In this context, *the general objective of this research thesis is to develop a holistic framework to monitor the product EoL during the most affecting phases of the product lifecycle*. This research originated from the in-depth understanding of industrial processes related to product design and lifecycle management, to identify issues and obstacles that currently limit the possibility to efficiently monitor and control product EoL. The starting point was the analysis of the activities carried out in the context of real industrial companies, during the product development process, as well as during the product lifecycle. This allowed defining the needs of the different company departments (e.g., design, research and development, marketing, purchasing, etc.). To converge to feasible and effective solutions, the gap between research methodologies and tools, previously proposed in the state of the art, and the real industrial needs has been analysed. The final aim is to provide companies with a set of methodologies and tools able to support the decision-making process at different levels (from conception to EoL management), in order to configure products with improved performances in terms of disassemblability, maintainability, de-manufacturing and EoL. The implementation of such framework in real industrial contexts could lead to the development of more sustainable products and, above all, could favour the shift toward circular business models, where companies manage the whole lifecycle and are directly involved in service, repair, maintenance, remanufacture and recycling activities. By using the proposed methodologies and tools, products can be designed with "EoL on mind", considering potential opportunities and drawbacks related to the EoL management. In this way, companies can conveniently use EoL products and components as precious resources, to minimize production costs and environmental impacts and thus maximize resource efficiency and economic revenues. The definition of a holistic approach, which integrates a set of novel and well-known methods and tools, allows taking into account the EoL aspects during the different lifecycle phases and supporting all the involved stakeholders (e.g., designers, EoL stakeholders, etc.). This is certainly the main novelty of this research work that overcomes the traditional approaches focused on specific objectives (e.g., design for X methods, tools to support designers through guidelines, PLM tools to manage lifecycle data, etc.).

The general objective has been reached through the development of four specific technical objectives.

The first technical objective is related to the *definition of quantitative metrics and of a methodology to assess the disassemblability of target components in complex products*. Within the product EoL, the disassembly is a preliminary but fundamental phase. Only reducing a product into its individual components it will be possible, for example, to reuse or remanufacture components. In order to univocally identify disassembly criticalities, three disassemblability metrics have been defined: (i) disassembly depth (i.e. number of operations to reach a target component), (ii) disassembly time and (iii) disassembly cost. Such metrics have been selected, on the basis of the industrial needs analysis, because they are quantitative, thus can be used to assess the performances of a product and to compare different products or product variants. In addition, they are significant and easy to be understood also by non-expert stakeholders (e.g., designers not skilled on ecodesign themes).

These metrics are estimated by using a five step methodology that, starting from the product virtual representations (e.g., 3D models, Bill of Materials), allows identifying the feasible disassembly paths to reach target components or to disassemble the entire product. The methodology essentially consists in the formalization of a systematic workflow that groups together several disassembly sequence planning methods. It is founded on a repository containing the most common liaisons (e.g., screws, electrical connections, snap-fits), which is possible to find within industrial products. Such liaisons have been classified and opportunely characterized by using a standard disassembly time, as well as representative properties to take into account two main aspects: (i) specificity of each liaison (e.g., dimensions) and (ii) condition at the moment of disassembly (e.g., wear). All these data are used to quantify the effective disassembly time and cost of each feasible disassembly paths, with the final aim to calculate the best one.

The use of the proposed methodology for the univocal identification of disassembly criticalities (e.g., disassembly paths with high number of operations, disassembly operations with high disassembly time, etc.) within complex products, represents the first step toward the definition of a focused strategy for the product improvement. The main novelty is the possibility to use fully quantitative metrics for the assessment of the product disassemblability and for the comparison between different design solutions. Other state of the art methodologies consider these indicators (in particular disassembly time), but they do not provide a formalized procedure for their estimation. Actually, disassembly time is generally considered as an input data, even if it is not an information directly available to designers. The proposed methodology, instead, provide all the resources (i.e. procedure and database on liaisons) for its estimation on the basis of data available during the design process (i.e. product virtual representations).

The second technical objective is related to the *development of a design for disassembly software tool able to support the identification of criticalities and the definition of the most suitable redesign strategy*. This tool is a necessary mean to practically exploit the proposed target disassembly methodology in real design contexts. It has been developed with a wizard-based interface to support end users in the input of needed information, in the execution of the four methodology steps and, finally, in the calculations and results interpretation phases. It contributes to strongly reduce the needed efforts in terms of time for inputting information and for performing calculations and thus to minimize the impacts on the traditional design process. The idea beyond the proposed tool is to monitor additional performance indicators related to disassembly and EoL, without introducing unsustainable extra-efforts and time-consuming activities.

The third technical objective is related to the *definition of a Knowledge-Based (KB) methodology to support the redesign phase oriented to EoL performances improvement*. Such methodology is based on the general idea that a link between stakeholders involved in the Beginning of Life (BoL), Middle of Life (MoL) and EoL management is needed to effectively guide the product redesign phase. This three steps methodology aims to formalize, collect and classify the EoL knowledge, in order to create a structured database containing positive and negative knowledge and expertise about disassembly processes carried out by dismantlers and remanufacturing centres. The knowledge classification rules are based both on product characteristics (e.g., product families, target components, assembly methods, etc.) and on other more general aspects (e.g., motivations of the disassembly, handling difficulties, etc.). The proposed knowledge database represents a concrete way to extend the producer responsibility and to close the current gap between manufacturers and dismantlers, with the final aim to reduce complexity and cost of the disassembly and remanufacturing operations/processes. The main contribution to the state of the art about Design for Remanufacturing and Design for Disassembly methods, is certainly the definition of a standardized procedure to elicit, formalize and classify knowledge coming from the observation of real EoL activities in order to be easily and effectively reused in the context of the design process, instead of the general ecodesign guidelines.

The fourth technical objective is related to the *development of a collaborative framework to favour the exchange of information and materials between the different stakeholders involved in the management of the product lifecycle*. In order to effectively implement closed-loop lifecycles, it is essential to facilitate the collaboration between the different lifecycle stakeholders (e.g., suppliers, manufacturers, consumers, service providers, etc.). The basic idea is to create a virtual environment to manage the product EoL phase and the reverse supply chain. The proposed EoL platform is able to share second-life components or products, to share knowledge about best practices and to support the decision-making process at EoL (e.g., reuse, remanufacture, selling to other companies, etc.), in order to maximize economic convenience, while minimizing environmental impacts. This collaborative environment is the needed resource to practically exploit the holistic EoL-oriented framework in real industrial contexts.

1.3. Research approach

To reach the abovementioned challenging objectives, a research approach has been defined at the beginning of this research works. The final aim was to organize all the foreseen activities in a clear workflow, to finally obtain relevant results, which are innovative from the scientific point of view and attractive for the industrial world. The following flowchart (Figure 2) illustrates the activities of the 3-years research work and the relative inter-relations.

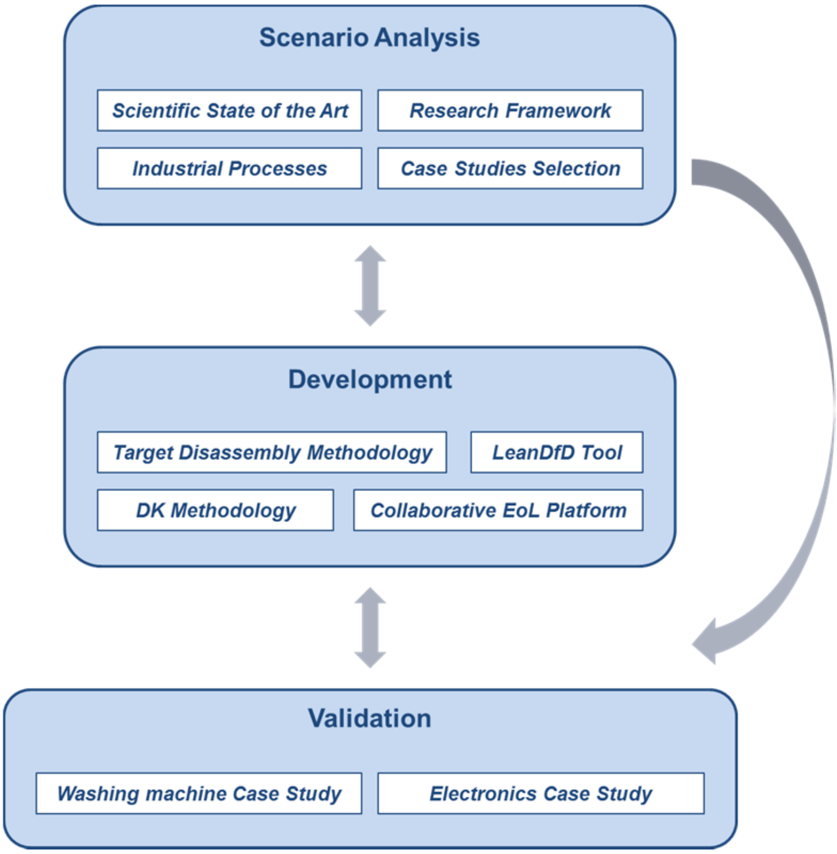


Figure 2. *Research approach.*

The first phase was entirely dedicated to the *Scenario Analysis* in order to understand the context in which this research work is positioned. The first activity was focused to understand the research framework, by analysing the existing normative and legislations, both at European and International levels (see details in Section 1). This was indeed essential to understand the opportunities and limitation, in order to correctly focus the development activities. Concurrently, the analysis of the scientific state of the art allowed understanding the main actors in the Design for Disassembly, Design for EoL and EoL management research topics, the methods and tools already developed, as well as the main lacks and the aspects that needed to be explored and improved (see details in Section 2). A fundamental step was certainly the deep investigation of the industrial processes, in particular those ones that are directly or indirectly correlated to product EoL (see details in Section 3). This activity has been performed in strict collaboration with several Italian and European industrial companies belonging to many different sectors (e.g., household appliances, fashion, wood and furniture, electronics, etc.). Direct interviews and surveys has been used for the direct involvement of industrial employees (e.g., mangers, designers, marketing experts, buyers, technicians, etc.) and to better understand their knowledge about EoL-related topics, their day-bay-day activities and the traditional modus operandi, the main lacks and their predisposition to innovate business, management and design processes. This direct collaboration with the industrial world allowed to converge toward solutions, which are feasible from the technical point of view, and aligned with the industrial needs. At the end of the Scenario Analysis the lifecycle phases that mainly influence the product EoL was identified and the EoL-oriented framework was defined, together with the needed resources to be developed (methodologies and tools) and the potential use scenarios in real industrial contexts (see details in Section 3). In addition, this analysis allowed selecting the two case studies (washing machine and electronics) involved for the validation activities.

The second phase regarded the *Development* of the methodologies and tools included within the holistic framework. A continuous update of the scientific and technological state of the art has been also performed to guarantee a high degree of novelty of the results. At the end, four main outcomes have been obtained: (i) the Target disassembly methodology (see details in Section 4), (ii) the LeanDfD tool (see details in Section 5), (iii) the Disassembly Knowledge (DK) methodology (see details in Section 6) and (iv) the Collaborative EoL platform (see details in Section 7). Preliminary validation activities and case studies have been carried out during the Development phase, to constantly verify the usefulness and effectiveness of the proposed methodologies and tools.

Finally, the last phase was focused on the validation of results in real complex case studies (see details in Section 8 and Section 9). Also in this phase, the industrial world has been directly involved in the different activities. This allowed verifying the applicability of the proposed EoL-oriented framework in real contexts and coherently set corrective actions to solve issues and optimize lacking aspects.

1.4. Thesis overview

Section 1 introduces the thesis by explaining the main topics faced by this research work. The overall context is depicted to illustrate the main problems about EoL management, the opportunities of circular economy, as well as the International and European legislative environment. The main scientific and technical objectives are described to clarify the expected results, together with the progress beyond the current state of the art. The research approach and the main activities performed during the research work are also explained.

Section 2 investigates the scientific literature regarding methods and tools for Design for Disassembly, Design for EoL and EoL management. A critical review of the most important research works on these topics is presented to understand the scientific basis of this research work and the most important lacks to bridge in order to make the presented methodologies and tools innovative and, at the same time, usable in real industrial contexts.

Section 3 explains the overall approach defined in this thesis. Starting from the analysis of the product lifecycle, the involved stakeholders and the correlations between the EoL and the other lifecycle phases, the most critical activities are identified. The four main results of this work are then contextualized within the product lifecycle to understand how and when they can be used as supporting methods and tools to effectively manage EoL-related issues.

Section 4 presents the *Target disassembly methodology* to analytically assess product and component disassemblability performances. Starting from virtual representations of a product, the five steps of the proposed methodology allow estimating three quantitative metrics for each chosen target component or for the entire product: disassembly depth, disassembly time and disassembly cost. A repository of the most common liaisons that it is possible to find in an industrial product, opportunely classified and characterized, represents the basis of the proposed methodology.

Section 5 presents a software tool, called *LeanDfD*, which aims to support designers in quantitatively assessing the product disassemblability and recyclability. The first evaluation is realized by implementing the methodology presented in Section 4. The results calculated (disassembly depth, disassembly time and disassembly cost) are then used to estimate the quantities of materials that could be potentially recycled at the product EoL. The LeanDfD architecture and modules, databases, internal data structure, input/output data and use scenarios are detailed in this section.

Section 6 presents a structured methodology to collect, formalize and organize knowledge coming from disassembly and EoL activities. Starting from the classification of products and components, positive and negative knowledge can be gathered, by observing typical disassembly and EoL processes, and successively organized in a structured repository, called *Disassembly Knowledge Database (DK DB)*. The final aim is to prevent possible disassembly/EoL issues by providing to designers specific design suggestions, defined on the basis of real observed problems and knowledge coming from the experience of disassembly/maintenance/EoL stakeholders.

Section 7 presents a *Collaborative EoL platform* to favour the collaboration between stakeholders involved in the different phases of the lifecycle of a product. The proposed platform aims to create new direct and indirect relationships and to close the gap between lifecycle stakeholders. Public and private functionalities are provided to the different users, in order to favour the practical implementation of closed-loop lifecycles and to maximize resource efficiency and economic revenues, while minimizing the environmental impacts.

Section 8 shows how the proposed methodologies and tools can be used in the context of the design process of a domestic appliance. The DK methodology and database and the LeanDfD tool have been used to redesign a washing machine, with the aim to improve the product disassemblability and EoL performances. The comparison between the original design and the new solutions, designed by young designers, with the support of the LeanDfD tool and of the knowledge gathered during manual disassembly activities performed by expert dismantlers, demonstrated the effectiveness of the proposed methodologies and tools in supporting the setting of a redesign strategy and the implementation of specific design actions. Moreover, the validation demonstrated that the estimated values, have an acceptable degree of reliability to support design activities oriented to product EoL.

Section 9 shows the implementation of an EoL decision-making algorithm in the context of electronic boards for industrial applications. The second case study aims to demonstrate that this kind of algorithm is useful in supporting companies to identify the best EoL scenario for electronic boards that comes back at the EoL. By considering that several electronic components (e.g., microprocessors, displays, etc.) have a residual life after the first lifecycle, thus can be reused as second-life components, the algorithm is able to evaluate the economic and environmental convenience of the different possible reuse scenarios. Results obtained confirmed that reuse of components leads to relevant economic savings due to the reduction of costs for purchasing new components from suppliers, and environmental benefits due to the avoided production of new components and reduced use of virgin materials.

Section 10 discusses the obtained results by highlighting strengths and weaknesses of the proposed methodologies and tools. Suggestions for future directions of research are also provided to stimulate the continuation of the work in the context of design for EoL and EoL management topics.

Appendix A reports all the details relative to the Liaison DB, integrated in the LeanDfD tool. All the classified liaisons are shown together with standard disassembly times, class and type properties and corrective factors.

Appendix B reports the LeanDfD user manual prepared in the context of the G.EN.ESI project, where this tool was partially developed

2. Research background

End of Life is critical and hard to efficiently monitor, since it involves many heterogeneous aspects and stakeholders. The objectives of the present work range from the improvement of the product design and development to the management of products and goods at the end of their useful life. This section illustrates the scientific state of the art regarding all the raised topics, in order to thoroughly understand the starting point of this work, as well as lacks and weaknesses that limit the application of the existing approaches in real contexts.

2.1. Introduction to Ecodesign and Design for X

The transition to a sustainable development requires the application of the LCT paradigm. This can be reached by using different methodologies, but generally the most common and useful is ecodesign. It has been developing since 1960s and generally refers to the *"integration of environmental aspects into product design and development"* (ISO, 2011). Ecodesign applies at every stage in a product's life: raw material extraction, production, packaging, distribution, use, EoL, etc. (UNEP, 2000). Many tools supporting ecodesign can be found in literature and different classifications have been proposed (Navarro et al., 2005; Bovea and Pérez-Belis, 2012). The most recent one includes: (i) Life Cycle Assessment (LCA) tools, (ii) Computer Aided Design (CAD) integrated tools and methodology, (iii) diagram tools, (iv) checklist and guidelines, (v) design for X approaches, (vi) methods for supporting company's ecodesign implementation and generation of eco innovation, (vii) methods for implementing the entire life cycle and user centred design for sustainability, (viii) methods for integrating different existing tools (Rossi et al., 2016).

Among them the most correlated to the objectives of present thesis are the approaches based on the Design for X concept, where "X" represents a product property to optimize. They were introduced to satisfy specific customer needs and to answer to the market pressure for products that meet not only the traditional requirements (e.g., functionality, cost, etc.), but also other aspects as, for example, safety, reliability, durability, recyclability, maintainability, etc. The principal Design for X approaches are the followings:

- Design for Assembly (Boothroyd and Alting, 1992);
- Design for Manufacturing and Assembly (Boothroyd et al., 2002);
- Design for Serviceability (Gersherson and Ishii, 1991);
- Design for Reliability (Rao, 1992);
- Design for Variety (Martin and Ishii, 2000);
- Design for Marketability (Zaccai, 1994);
- Design for Safety (Gauthier and Charron, 1995);
- Design for Environment (Hauschild et al., 2004);
- Design for Sustainability (Jawahir et al., 2005);
- Design for Disassembly;
- Design for EoL;
- Etc.

Design for Disassembly and Design for EoL approaches are key topics for the present research work, thus an in-depth review of literature in these fields is presented in the following two sub-sections.

2.2. Design for Disassembly methods and tools

Currently, de-manufacturing is becoming an important strategy and a new sustainable business model for the EoL management of industrial products, which reduces environmental footprints while increasing corporate profits (Rizzi et al., 2013). De-manufacturing is a reversal process in which a product is separated into its components (non-destructive disassembly) or constituent materials (destructive disassembly) by manual or automatic processes (Mule, 2012). The purpose of de-manufacturing operations is the fast and efficient separation of detailed product fractions to boost EoL closed-loop scenarios such as reuse, remanufacture and recycling (Duflou et al., 2008). Therefore, a key role in the de-manufacturing process is played by product disassembly.

Design for Disassembly (DfD) is a class of target design methodologies that gives a set of guidelines to help engineers and designers in the early phase of product design. An efficient product disassembly allows the easy separation of components for product maintenance and/or EoL treatments (Takeuchi and Saitou, 2006). DfD makes the de-manufacturing plans of goods and products more efficient, affecting EoL choices and strategies (Veerakamolmal and Gupta, 2000). Design for Disassembly studies started in the early 1990s when environmental concerns over the disposal of industrial products became a new world challenge. This topic was firstly presented by Boothroyd and Alting (1992), in combination with Design for Assembly (DfA). They demonstrated that redesign proposals resulting from DfA analysis are compatible with DfD. The literature is particularly broad in this field, and it includes several aspects, such as the application of rules and guidelines to design products with easy disassembly, the generation of Disassembly Sequence Planning (DSP), the mathematical optimization problem for the best disassembly sequence assessment, and the classification of knowledge (Lee et al., 2001; Santochi et al., 2002; Desai and Mital, 2003). Nevertheless, a key outcome of the DfD analyses is the estimation of disassembly time (Germani et al., 2014), which is the most important parameter for disassembly cost calculation and, consequently, for the evaluation of the economic feasibility of EoL scenarios that require disassembly (Bogue, 2007). Anyway, literature studies generally consider disassembly time as an input parameter and do not provide indications on how to quantify it on the basis of information available during the design process.

All these technical aspects must be addressed in the development of a design for disassembly methodology and software tool that aim to provide a holistic view of the disassembly problem, supporting designers and engineers in the decision-making process for the effective improvement of the product features.

2.2.1. Disassembly Sequence Planning (DSP) methods

Looking at the product development process, DSP is considered a fundamental task to judge the component or sub-assembly accessibility, as well as the disassembly paths, giving a quantitative measurement of product disassemblability (Favi et al., 2012). Therefore, DSP can be considered the starting point for the target disassembly analysis (Desai and Mital, 2003). Several research activities have been focused on the development of algorithms and procedures to find the best disassembly sequence of target components using exact and heuristic/meta-heuristic methods. Exact or deterministic methods have been investigated at the beginning as a reverse problem of assembly sequence definition, starting from the product structure.

Research works based on exact methods guarantee the finding of the global optimum in a disassembly problem. Product modularity and the arrangement of components (product architecture) are the bases for the definition of exact disassembly algorithms. Dewhurst (1993) evaluated the depth of disassembly for particular components in a product, to establish the effective cost convenience for disassembly operations. This approach, considered as the first example of quantitative assessment of the disassembly process feasibility, uses a deterministic method based on the knowledge of disassembly time and cost. Srinivasan et al. (1997) developed another popular deterministic method for selective disassembly, based on the "wave propagation" model. This latter allows analysing the type of connections between components, the arrangement of components (product architecture), the direction of extraction and the first components to be disassembled (Srinivasan and Gadh, 1998; Mascle and Balasoiu, 2003). Another important contribute in this context has been proposed by Gungor and Gupta (1998), through the definition of a "branch-and-bound" approach. This algorithm aims at optimizing the product recovery with a cost minimization function. Moreover, graphical supports for the visualization of the DSP has been introduced and defined (Gungor and Gupta, 2001; Lambert and Gupta, 2005; Zhang and Zhang, 2010). Other exact methods can be found in literature, as, for example, the "connectivity and interface relationship", proposed by Ong and Wong (1999), the "shortest path algorithm", proposed by Zwingmann et al. (2008) or the "connector-knowledge-based approach", proposed by Li et al. (2010). Each abovementioned exact method guarantees to find the global optimum in the disassembly problem, but generally they consider only the disassembly depth as the main key performance indicator in the optimization problem. None of the proposed methods provide indications on how to assess disassembly time and disassembly cost, which are the most useful and understandable indicators to be used during design activities.

The use of heuristic and meta-heuristic methods have been investigated to simplify the DSP problem and decrease computational time by searching the best sequence without analysing all the possible alternatives. These methods focus on detecting the best sequence when a combinatorial explosion of sequences takes place, as in the case of complex industrial products. Different heuristic methods have been developed in the past years.

Petri Net (PN) is one of the most diffused mathematical method for the solution of the DSP problem. It has the advantage to take into account several aspects, such as time, costs or environmental concerns. PN includes a graphical representation as a result of the optimization problem (Tiwari et al., 2002; Tang and Zhou, 2006; Zhang et al., 2012; Kuo, 2013). Zussman and Zhou (1999) developed a disassembly PN approach through the notion of the inverted assembly PN and taking into account uncertainties in future economic and technical conditions for the evaluation of EoL scenarios. Moore et al. (1998, 2001) presented a PN-based algorithm to automatically generate the DSP and to dynamically explore the lowest cost path of the graph. Rai et al. (2012) used heuristics to generate a component reachability graph to obtain a near-optimal disassembly sequence, based on the firing sequence of transitions of the PN model. The methodology reduces the search space in two areas: the ramification of disassembly graph and the selective tracking of the component reachability graph.

Genetic Algorithms (GAs) is another widely used approach to solve optimization problems due to its capability in solving large and complex models, compared with the other heuristic methods. Several studies proposed the use of GAs to determine the optimal disassembly sequence of a given product (Galantucci et al. 2004; Kongar and Gupta, 2006; Giudice and Fargione, 2007; Hui et al., 2008; Tseng et al., 2009; Go et al., 2010; Kheder et al., 2015; Meng et al., 2016). One of the most structured method, in this context, has been proposed by Smith et al. (2012). The authors defined a model to structure a disassembly sequence graph considering multiple-target selective disassembly sequence planning and the method for its assessment. The model contains a minimum set of parts that must be removed to disassemble the target parts, as well as, the best directions for removing each part. The model uses a GA to find solutions optimized in terms of product reorientations. Anyway, also this advanced method does not consider the disassembly time, which is directly correlated to product EoL management costs.

Neural Network (NN) approaches, including Bayesian networks, have been also investigated to perform rapid computations in parallel and solve the DSP problem in an efficient way (Huang et al., 2000; Godichaud et al., 2010).

Heuristic methods seem beneficial in terms of computational time, but they do not overcome the issue related to the large amount of manual input required for the analysis. A dedicated tool able to make available all the data and to guide designers in the analysis of the product disassemblability performances, seems to be a necessary resource to minimize the needed effort to perform a DSP analysis and thus the negative impacts on traditional company processes. Furthermore, DSP is only a specific aspect of the DfD and does not consider, for example, the way to improve the product.

2.2.2. Graphical representation and simplified DSP methods

DSP methods are often defined in combination with the use of simplification methods, to reduce the complexity of the DSP problem and its representation. Disassembly graphs are an example of simplified methods for the representation of DSP. The AND/OR diagram are the first and the most widely used method to represent assembly/disassembly sequences (Homem de Mello and Sanderson, 1990; Kara et al., 2005; Zhu et al., 2013). In the AND/OR diagram, each node represents a product, a component or a sub-assembly and the arc represents the link among them (which could also indicate the component to remove). The AND/OR diagram gives a clear picture of the problem, but the main issue of this approach is the computational time required for the combinatorial calculation of sequences.

The Precedence graph uses different notation than AND/OR diagram. In this case, each node represents a disassembly operation and the arc connects the operations each other (Johnson and Wang, 1998; Gungor and Gupta, 2001; Lambert and Gupta, 2008). Compared to the AND/OR diagram, the disassembly precedence graph has less nodes, even if the computational time to solve the disassembly problem is still very long.

The Connection graph (De Fazio and Whitney, 1987; Dong at al., 2006; Rickli and Camelio, 2013) and the Extended process graph (Kang et al., 2001; Lambert, 2007) provide a different way to represent and solve the DSP problem. However, there are different drawbacks related to these approaches, such as the computational time required for the analyses, a strong limitation in the complexity of products that can be analysed and the needs to involve experienced designers.

Another way to represent and simplify the DSP problem has been implemented by the use of disassembly matrices. The Transition matrix is obtained from a disassembly graph and it aims to represent the transitions caused by the possible disassembly operations (Lambert, 2003; Kang et al., 2010). The transition matrix shows, numerically, the connections between components and it analyses the existing joints through a time consuming process (Zwingmann et al., 2008; Behdad et al., 2014). Precedence matrix is another way to represent the DSP problem and it is based on the analysis of geometric precedence relationships (Gungor and Gupta, 1998; Tang et al., 2002). Interference matrix analyses the interferences among components along the path of extraction (following a particular direction/axis) (Ong and Wong, 1999; Jin et al., 2013). In all the cases, the process to set out each relation/interference among components is very long and time-consuming.

Nevertheless, some recent research studies have been focused on this issue. As example, Smith et al. (2012) introduced the Disassembly Sequence Structure Graph (DSSG) method aiming to improve the solution quality, minimize the model complexity and reduce search time. Also this interesting approach does not consider the disassembly time as the main indicator to identify the criticalities.

2.2.3. DfD frameworks and tools

The main concepts of DSP have been implemented in several software tools, mainly in prototypal versions (Santochi et al., 2002). As highlighted above, DfD is a very complex problem and needs a holistic approach.

Herrmann et al. (2008), for instance, presented an integrated framework for a holistic EoL-oriented product management. This framework allows the systematic integration of the EoL requirements into the product requirement management process, which is a typical task in the first phase of the product development process. Design data and evaluation results are also used for the planning of EoL processes. A set of different tools has been conceived: the recycling tool (ProdTect), the planning tool (SiDDatAS) and the conceptual design tool (FOD), as well as the interfaces between them. These tools allow the product manager to mitigate the lack of information feedback concerning the recyclability of products under development and already in the market and to utilise the design efforts in the optimization of the EoL processes. This is currently the most complete design framework for the product EoL management, but even this framework cannot provide design suggestions and feedbacks for a disassembly-oriented design.

Another interesting DfD framework was proposed by Go et al. (2010). The authors defined a set of modules that need to be developed to build a disassembly tool. The modules are software programs that are executed as part of various design steps: (i) product analysis, (ii) disassemblability analysis, (iii) optimal disassembly sequence generation and (iv) design rating. The aim of this framework is to develop an optimization model for the disassembly sequence generation of automotive components that have the potential for reuse/remanufacturing. The need of the practical implementation in a computer-based disassemblability evaluation tool is discussed in the paper but it is not realized.

To make DSP approaches more efficient and less time-consuming, designers' input should be minimised by extrapolating data from 3D CAD models (Santochi et al., 2002). For example, Kara et al. (2005) proposed an evaluation method to detect possible paths for the disassembly of a specific component, directly from the assembly CAD model. Adenso-Díaz et al. (2007) and Kang et al. (2012) defined useful methods for the automatic recognition of mechanical liaison types between components in the general assembly directly from the CAD model. Starting from a CAD representation, Cappelli et al. (2007) proposed an approach to automatically derive all the possible disassembly sequences of a mechanical product. This methodology provided the theoretical basis for a computer-aided design tool able to evaluate the easy of disassembly of a complex mechanical product during the early design phases. Issaoui et al. (2014) proposed a disassembly simulation tool based on integrating eliminatory rules in the sequence generation step. Optimization criteria are used in the evaluation step to propose an optimal disassembly sequence. The approach has been implemented in the Application Programming Interfaces (API) of a CAD environment with the aim of reducing the computing time. In the case of a large number of components connected to the target one, the number of permutations of branches in reading the connection tree increases, so the calculation time represents a limit of the proposed approach. Furthermore, guidelines for redesign activities are not provided.

A more complex approach uses the Virtual Reality (VR) to solve the DSP problem, as demonstrated by Mo et al. (2002). Virtual Reality is able to create a real-time visual/audio/haptic experience with computer systems. Aleotti and Caselli (2011) described a method to use VR to find all physical admissible sub-assemblies for the automatic disassembly planning. Chen et al. (2011) proposed a virtual disassembly system which enables operators to disassemble products interactively in a virtual environment. Virtual Reality provides a potential way for the disassembly simulation. In addition, the VR tools can support collaborative de-manufacturing (disassembly, service, recycling and disposal) among manufacturers/de-manufacturers, disposers and designers (Berg et al., 2015).

Often, disassembly issues are considered part of a wider ecodesign strategy. Pigosso et al. (2010) analysed different ecodesign methods and tools that emphasize the importance of disassembly when addressing EoL strategies. The most promising tools (called EDIT, D4N and EDST) use disassembly planning as an economical strategy to improve the environmental quality of products. It is clear that all these methods consider other life cycle phases in addition to the product disassembly and can be considered more complete and more closely related to the life cycle thinking. Nevertheless, all of these methods are highly influenced by subjective choices and require the involvement of designers with significant expertise in environmental issues to choose the best design solution.

2.3. Design for product EoL and EoL Management

An accurate definition of the EoL scenario in the early design stage is a key ecodesign strategy for companies, which often must assume responsibility for ‘retiring’ the product at the end of its life (Rose and Ishii, 1999). Only in this way products can be configured to have closed-loop scenarios, which allow the reintroduction of parts or materials into the productive chain (reuse of the entire product or some components, remanufacture of components or recycling of materials). On the other hand, two alternative open-loop EoL scenarios can be considered: incineration, which only recovers energy from the combustion and reduces the original waste volume, or landfill, which is the worst scenario considering the environmental hierarchy (Fukushige et al., 2012). Furthermore, through the management of EoL strategies, the cost of product disposal could be reduced, while revenues could be increased (Cappelli et al., 2007). The final goal is to encourage the implementation of EoL closed-loop scenarios (reuse, recycle and remanufacturing) (Zwolinski and Brissaud, 2008).

To reduce the amount of waste going to landfills, favouring closed-loop scenarios, products need to be appropriately designed to also consider EoL aspects (Hauschild et al., 2004). Many studies in the literature focus on the detailed assessment and comparison of different EoL operations (Abu Bakar and Rahimifard, 2008), optimization of EoL processes (Jun et al., 2007) or even selection of the best recovery strategies during EoL (Ziout et al., 2014; Cheung et al., 2015). All of these studies only try to improve the EoL treatments of post-consumer wastes without considering the possibility of improving products as early as the design stage, aiming to reduce the amount of wastes and to favour the recovery of components and materials.

With the diffusion of the EPR paradigm, many companies have been obliged to pay even more attention to the EoL of their products, trying to determine the best EoL option for entire products and critical components. The development of a decision model for selecting among these different options requires the consideration of various qualitative and quantitative factors, such as environmental impact, quality, legislative factors and cost (Ilgin and Gupta, 2010).

Several studies have focused on this topic. Generally, target design methodologies about Design for EoL (DfEoL) emphasize single aspects or scenarios of the product EoL. For example, design for remanufacturing focuses on methods and tools for establishing or identifying the product properties with respect to remanufacturing. In this field, Sundin (2001, 2004) defined a matrix to correlate product properties and generic remanufacturing processes, to assess remanufacturing potential of household appliances and define design changes.

Zwolinski et al. (2006) developed a computer-aided tool (REPRO2 for Remanufacturing with PROduct PROfile) to help designers incorporate remanufacturing earlier in the design phase. Their work is based on the concept of Remanufacturable Product Profile (RPP), that embraces knowledge of both remanufacturing contexts and remanufactured product properties. Kwak and Kim (2015) proposed a method to search the optimal product design to maximize economic profit and environmental impact savings, considering initial manufacturing and EoL stages. However, they only focused on remanufacturing activities, thus neglecting other possible EoL strategies.

Another common approach is design for material recycling, which aims to increase the recyclability of products at EoL, by using generic material compatibility charts (e.g., thermoplastic material compatibility table for recycling, metals compatibility table, glass and ceramic compatibility table, etc.). Some specific material compatibility methods exist, such as the tool proposed by Le Pochat et al. (2007), which facilitates the choice of plastic materials by integrating the separation ability of the current recycling routes, the compatibility of mixed plastics combinations and the quality of the secondary material product. Philips company defined a material compatibility table to be used by designers to take into account metals, ceramic and glass compatibility (Brezet et al., 1997). Froelich et al. (2007) proposed a tool based on recycling process performances, to support in choosing the best plastic materials, by considering the separation ability of the current recycling routes, the compatibility of mixed plastics combination and the quality of the secondary material products. Mathieux et al. (2008) proposed a method called ReSICLED to assess product recoverability. The main limitation of these methodologies is the preventive exclusion of more environmentally friendly scenarios, such as reuse or remanufacturing.

Regarding Design for EoL methods and tools, several studies are available in the literature. Rose and Ishii (1999) proposed a structured method entitled End-of-Life Design Advisor (ELDA) to guide product designer to specify EoL strategies during design process. Doi et al. (2010) proposed an optimization method to incorporate lifecycle considerations into the design process, aiming to reduce the use of raw materials and to facilitate the reuse of products or their parts. Kwak and Kim (2010) highlighted the importance of modularity to configure product families that are easy to treat at the EoL, maximizing the recovery of parts or materials. Gehin et al. (2008) proposed a new approach to integrate EoL strategies in the early design phases, considering the evolving architecture of the product and the translation of transversal information into design criteria. Bufardi et al. (2003) proposed a Multiple Criteria Decision Aid (MCDA) method to support designers in selecting the best scenario for treating an EoL product based on their preferences and the performances of the EoL scenarios. Chan (2008) extended this proposal using a Grey Relational Analysis (GRA) to rank the EoL options under the uncertainty condition of incomplete information.

Concerning the use of a design index, only a few examples can be found in the literature. An interesting index to evaluate the efficiency of EoL treatment is described by Dewhurst (1993). This index can be used by designers to evaluate the break-even point at which disassembly operations should be stopped because, beyond this point, disassembly costs are greater than revenues. Rao and Padmanabha (2010) defined an EoL scenario selection index based on the relative importance of the different EoL scenarios to evaluate and rank alternative product EoL strategies. Lee et al. (2014) developed a more complex index methodology. Their proposed index gives aggregate values representing the design performance under available EoL options and can act as an advisor to judge available design options. However, all of these approaches are also based on qualitative information and on subjective preferences, which reduces their effectiveness or limits the field of application.

2.4. EoL knowledge sharing

Data and knowledge sharing is worldwide considered as a crucial step forward, both in industry and research, as science is becoming more data intensive and collaborative (Tenopir et al., 2011). Among the different fields of application, a particular focus is given to data sharing in the context of product design. Specifically, the level of competitiveness that characterises current market products asks for an efficient, reliable and flexible system to manage data. Such trend encourages corporates to collaborate at different levels by sharing data which try to cover the entire life cycle of a product (Bakis et al., 2007; Srinivasan, 2011). Also in the context of Circular Economy, the knowledge capitalization plays a key role in supporting companies. A forward (from design to EoL) and backward (from EoL to design) knowledge sharing process is crucial for the economic sustainability of any EoL scenario.

Approaches based on forward sharing processes, leveraging on the availability of innovative software and hardware technologies to efficiently share the product information, defined during the design phase, with the dismantling centres. Parlikad and McFarlane (2007) qualitatively showed that the availability of product information has a positive impact on product recovery decisions. In particular, they discuss how Radio-Frequency IDentification (RFID) technologies can be employed to provide necessary information. Another approach to support dismantlers during decision-making process is suggested by Das and Naik (2001), which presented a standard coding structure for documenting the disassembly knowledge to dismantlers. The authors expect that in the near future product manufacturers will create and distribute the product Bill of Materials (BoM) to collection and disassembly facilities through product labelling or a public access website. This is an attractive scenario with further potential advantages, which can be achieved only if recycling problems are faced during the design stage by adopting Design for EoL and DfD theories. Although the great potentialities of those approaches (forward knowledge sharing), the general infrastructure is far to be applied for products where the manufacturer is not directly responsible of the EoL management.

To support design activities, different sets of DfD and Design for EoL guidelines have been defined (Active Disassembly Research Ltd, 2005). Anyway, usually guidelines are too general and lack for precise recommendations, thus more specific suggestions are needed (Peters et al., 2012).

The first step for an effective backward knowledge sharing consists in the capitalization of the positive and negative knowledge coming from dismantling activities. Lederer et al. (2015) presented a method to gather knowledge from stakeholders of the dismantling sector, with the aim to optimize the waste management. Reyes-Córdoba et al. (2008) presented a theoretical framework of a tool to represent the knowledge of dismantling processes. However, in both the research works, the final aim is to support EoL activities, thus the knowledge is not formalized in a way that can be used by designers. Terazono et al. (2012) studied the advantages of sharing the recycling knowledge among stakeholders of the same sector, but none method to formalize the knowledge has been proposed. According to a research leaded by Li et al. (2015), the designers' attitude and perceived behavioural control have the largest and most significant effects on the waste minimization, thus it is necessary to give them the required knowledge. Lee, et al. (1997) presented a method to support designers in considering de-manufacturing processes and material recovery with the aim to reduce the retirement costs. Vongbunyong et al. (2013) proposed a method to learn and reuse the knowledge related to the automated disassembly process of particular product (i.e. LCD screen) using a cognitive robotic agent. This knowledge has been used for the definition of disassembly sequence plan and disassembly process plan (Vongbunyong et al., 2015). Soh et al. (2015) proposed a conceptual framework based on practical considerations to aid the product designer in prioritizing the relevant DfD guidelines used to increase the product disassemblability. Although this is a knowledge-based approach, it does not present a method to capitalize the knowledge and expertise of stakeholders working at dismantling centres. In the context of building constructions, Godfrey et al. (2012) presented a study showing how experience has the greatest influence on building waste knowledge, nearly twice that of data/information and three times that of theory. One of the most interesting works was presented by Movilla et al. (2016), who defined a method to analyse dismantling practices and derive useful data to be used during product design. The paper is focused on WEEE and in particular on displays (i.e. LCD), demonstrating that quantitative data coming from the recovery phase can be used to significantly improve product design.

All these researches demonstrate that the sharing of useful EoL information among product designers and EoL stakeholders is needed to close the product lifecycle.

2.5. Collaboration between lifecycle stakeholders

Global Production Networks (GPNs) are characterised by the collaboration of different actors, which contribute with competences and experiences to the realisation of products. Such environment is of increasing importance for the sustainable competitiveness of companies in the global market and the adaptation process is a growing challenge for the management (Lanza and Moser, 2014).

In scientific literature several research works focus on the different aspects of the GPN. Tchoffa et al. (2016) presented an approach to combine model-based enterprise platform engineering, model-driven architecture and system engineering in order to address the establishment of a sustainable interoperability within dynamic manufacturing networks. Palmer et al. (2016) presented a reference ontology to accelerate the development of new product-service systems, considering all the information exchanged between the actors of the GPN.

Supply Chain Management (SCM) is another widely used approach to manage materials and information flows and increase the collaboration between supply chain and lifecycle stakeholders (Chardine-Baumann and Botta-Genoulaz, 2014). Over the last decade, the sustainability concept applied to SCM has received considerable attention in literature (Pagell and Shevchenko, 2014). Sustainable Supply Chain Management (SSCM) is an extension of the traditional concept of SCM, where the aim is to maximize the value creation, adding environmental and ethical aspects (Wittstruck and Teuteberg, 2013). In the context of SCM, the collaboration between stakeholders is recognized as an essential point to improve the overall performances of the entire network (Germani et al., 2015).

Regarding the sharing of knowledge, during the last years, several studies aimed to develop conceptual frameworks to support designers during the product conception and embodiment design phases with better environmental performances from a system perspective (Lee et al., 2006). Manakitsirisuthi (2012) proposed a Knowledge Management Architecture based on a Multi-Agent System approach. The system establishes the link between agents, who hold knowledge related to environmental performances and the Product Lifecycle Management (PLM) system. The connection encourages companies to consider the environmental impacts in their decision-making at every stage of product lifecycle. Xu et al. (2014a) proposed a knowledge evolution process in product development activities and a knowledge evaluation method in product lifecycle design. Vareilles et al. (2012) investigated how it is possible to support design decisions with two different tools relying on two kinds of knowledge: case-based reasoning, operating with contextual knowledge embodied in past cases, and constraint filtering, operating with general knowledge formalized using constraints. Shrivastava et al.

(2005) proposed a decision support system, based on information about optimal disassembly sequences, cost and time and composition of the different components, to take informed decisions about the electronics EoL. Bovea et al. (2016) proposed a general methodology to estimate the potential reuse of small WEEE, with the final aim to create a specific protocol to identify the potentially reusable appliances. Jin et al. (2015) defined a systematic EoL management approach to handle WEEE considering economic and environmental aspects. The final aim is to choose the best EoL option which allows maximizing revenues and minimizing the environmental load.

Although reuse is recognized as the best option to maintain economic value, while reducing resource consumption and environmental impacts, so far this EoL scenario is not largely implemented in real contexts. In order to mitigate barriers to reuse, more incisive national and international regulations are needed, as well as collaborative systems to support the decision-making process (Milovantseva and Fitzpatrick, 2015). Therefore, the definition and implementation of an EoL platform to improve the collaboration and the exchange of information and materials between the actors involved in the management of the different lifecycle phases, seems to be an essential step toward the implementation of more sustainable product EoL scenarios (e.g., reuse, remanufacture).

2.6. Outcomes from the literature review

A general outcome from the presented literature review is the extreme complexity of issues related to product EoL management. The high number of different approaches and methods proves that aspects to take into account are numerous and the stakeholders involved are heterogeneous.

Most of the literature works lack of a holistic view, since they take into account the optimization of specific aspects related to EoL, such as product design (e.g. design for X methods), EoL processes, EoL management, reverse supply chain, etc. The most important step forward of this research work is the definition of an integrated approach in which traditional and new supporting methods and tools live together to help involved stakeholders to take informed and objective decisions about EoL issues, during all the most affecting phases of the decision-making process.

Literature is full of methods and tools dedicated to monitor disassembly and EoL issues during the different phases of the design phase (i.e. DfD and DfEoL). The most important lack is relative to the absence of a systematic procedure to preventively estimate product disassemblability through the use of quantitative metrics. Several methodologies (both exact and heuristic) have been developed to solve the DSP problem, but they are usually based on the minimization of the number of de-manufacturing operations (i.e. disassembly depth) and not on the disassembly time required to reach the chosen target components. In this sense, this research work aims to go beyond the state of the art about design for disassembly, presenting a structured methodology, based on a set of novel and known steps, to analytically estimate the disassembly time and cost for each product component/sub-assembly. These indicators represent tangible and very useful metrics for designers, in order to assess the cost related to the maintenance and EoL phases, in a lifecycle perspective. The main novelty is certainly related to the definition of a knowledge database containing essential data about liaisons to be used during the disassembly time estimation. Using this methodology, designers can rapidly identify the most critical components from a disassembly point of view, with the aim of conceiving the correct product architecture or choosing the most appropriate joint methods. In addition, to favour the methodology exploitation in real industrial contexts, a dedicated DfD tool is proposed. This is a needed resource to guide designers in performing the disassemblability analyses without heavily altering their modus operandi.

Once the criticalities have been univocally established, the product improvement phase can start. To be effective this activity should be based on precise indications coming from real issues, instead of on general guidelines. In literature, there is not any general approach that can be used to gather disassembly and EoL knowledge (mainly experience) and to effectively formalize it. This research work aims to go beyond the state of the art by defining a useful methodology for the backward sharing of knowledge from EoL stakeholders to manufacturers. The developed classification rules, based both on product features and other more general aspects, allows overcoming the well-known limitations of the general ecodesign guidelines. In this way most of the criticalities for future generations of products can be avoided, since they will be conceived by preventively considering specific issues that can arise later in the lifecycle.

Internal and external stakeholders, located in different geographical areas, usually collaborate to manage the product lifecycle phases that occur in a variable time span. EoL is the last phase, but decisions made in the other ones have an high impacts on it (see details in Section 3). In this context, the present research work would try to overcome issues coming from the advanced and complex domain previously introduced, such as lack of effective tools for the collaboration. The exploitation of the proposed EoL-oriented framework in real industrial applications strictly requires the building of a collaborative network to share relevant information and materials. The proposed EoL platform aims to involve actors of the BoL (i.e. producers), together with MoL stakeholders (e.g. consumers, distributors, etc.) and EoL dealers, with the final objective to implement the most sustainable and economically convenient EoL scenario for products and components.

3. An integrated approach to efficiently manage the product EoL

3.1. Lifecycle phases and the influence on product EoL

To better understand which are the phases that mainly influence product EoL, an in-depth analysis of the product lifecycle is needed. It is worth to notice that this analysis has been performed by investigating both literature studies and the product development and lifecycle management processes of different industrial companies (both LEs and SMEs). An industrial surveys has been realized by involving employees with different roles (e.g., designers, buyers, marketing experts, workers, maintainers, operators of dismantling plants, etc.). The objective was to understand:

- which are the most common tasks performed for the product lifecycle management;
- how the involved stakeholders currently perceive the product EoL and the relative business opportunities;
- the knowledge of each involved stakeholder on product EoL;
- which are the real industrial needs related to product EoL;
- which are the most important lacks and the lacking tools that currently limit the implementation of circular business models in real contexts.

The following Figure 3 summarizes the outcomes of the analysis, by highlighting the most important product lifecycle phases, together with the EoL-related aspects.

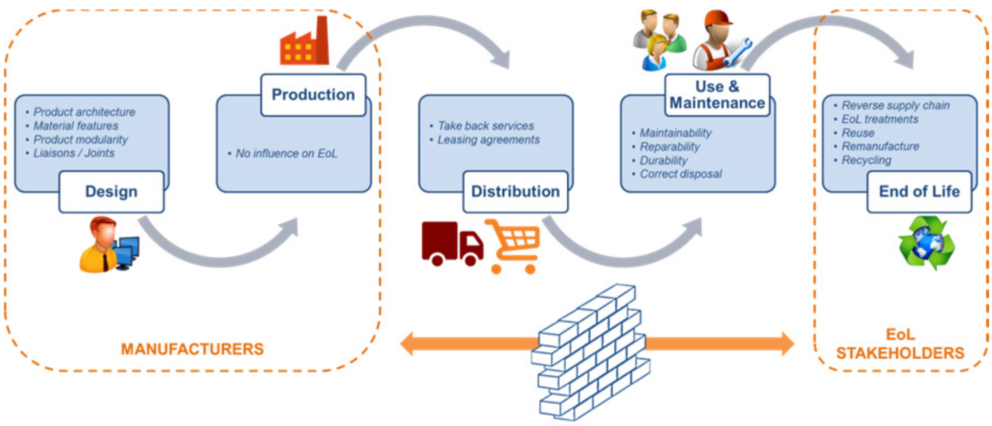


Figure 3. *Product lifecycle phases and influence on product EoL.*

Starting from the left part of Figure 3, the product BoL is managed "within the wall" of a manufacturer that conceives a new product idea (or a variant for existing products), on the basis of different aspects, such as market requirements or legislative constraints. When definitive and feasible design solutions are established, products can be manufactured. Going outside the manufacturer boundaries, the distribution and use represents the MoL phases, when retailers/distributors, consumers and service providers have a central role. Finally, the EoL can involve different actors, depending on several aspects, such as the product typology, the geographical area or the existing regulations.

3.1.1. The key role of the Design phase

In general, the *Design* phase can be viewed as an activity to solve problems reaching a feasible solution to satisfy prefixed objectives (e.g., performances, cost, etc.). It is a very complex process influenced by a plurality of domains and by an high number of parameters (technical, social, strategic, economic, etc.) that stakeholders involved (i.e. the design team) have necessarily to take into account to configure the final solution. One of the most popular representation within Engineering Design circles is given in Pahl et al. (2007), where a detailed description of each important activity is offered. According to this vision, called *Systematic Approach*, the design process can be subdivided in four main phases:

- the *Planning and Task clarification*, when the collection and clarification of requirements and product constraints is realized;
- the *Conceptual Design*, when one or more principle solutions (represented in the form of function structure, circuit diagram, flow chart, etc.) are defined;
- the *Embodiment Design*, when, starting from a concept, the design team determines the overall layout of the product by concurrently considering different aspects, such as technical and economic criteria;
- the *Detail Design*, when shapes, dimensions, materials and surface properties of all the product components are defined. In addition, production processes are considered to assess the production costs and, finally, the necessary documentation to start with the manufacturing phase is generated.

This structure includes all the essential activities for engineering designers. However, authors also specify that *"these plans must be adapted in a flexible manner to the specific task at hand"*, in order to best fit the general definition with the particular needs of each company and of each product. This was confirmed by analysing the product design process of real industrial companies. They tend to follow quite different steps, thus a more "realistic and practical" product design process can be defined. Figure 4 clearly shows the most important phases in which the traditional product design process of a real manufacturing company is usually subdivided, as well as the main inputs and outputs of each step.

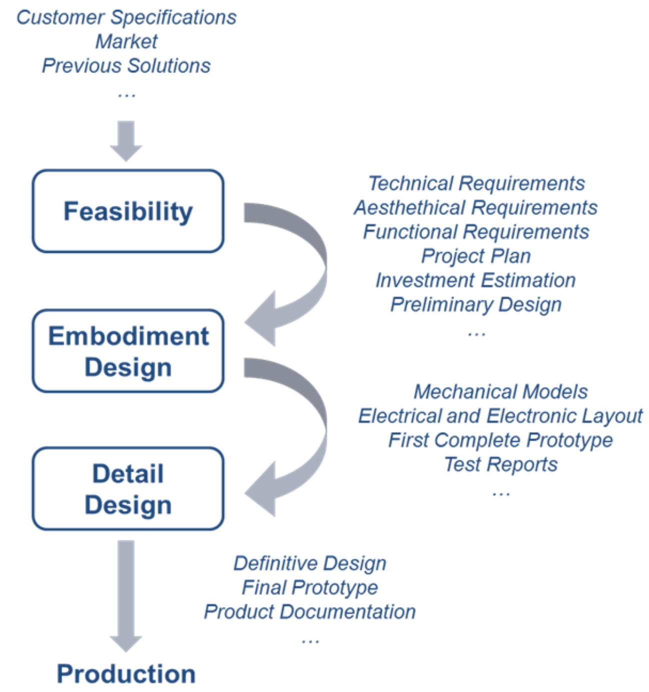


Figure 4. *Steps of the "traditional" product design process derived from the analysis of real companies.*

As reported in Figure 4, the product design process starts with the *Feasibility* phase, when a preliminary study of the project is carried out, with the final aim to establish the necessary efforts and time to complete all the needed activities. The main target is the proof of the project conception and if the result is not positive the project is immediately rejected to avoid waste of time and resources (human and economic). At the beginning, a design team, headed by a Project Manager, is constituted involving people with different expertise. The first design step is the definition of the aesthetical, technical and functional requirements, directly derived from customer specifications and market requirements. An initial solution is defined and preliminary product component models (i.e. concepts) are developed, with the aim of determining an indicative cost and the required investment. Sometimes also simplified prototypes of product components or parts are manufactured and successively tested.

The design process continues with the *Embodiment Design*, when the design team develops the different product components/modules. For these activities, designers of different areas (mechanical, electrical, electronic, software, etc.) are involved to choose product and component features (e.g., product architecture, tentative materials, etc.). Several simulations are usually performed to verify the validity of the design choices (e.g., fluid dynamic, thermal, electromagnetic, etc.). A continuous and iterative process of analysis and assessment, implementation of improving actions and performances check is needed to reach a satisfying solution. The final objective of this phase is the realization of a prototype (or more than one) of the entire product to assess performances and verify the fulfilment of all the requirements, before the final project approval.

The last phase of the design process is the *Detail Design*, when all the choices made during the previous phases are revised and optimized. Definitive models are developed and all the features of each component are finally defined. During this phase also the documentation required in the successive production phase (e.g., technical documents, Bill of Materials – BoM, cost reports, etc.) is generated. A final prototype is usually manufactured using the definitive moulds and equipment to verify the expected performances. After this phase the production of the first pilot series can start.

Product design plays a critical role in the efficient management of product EoL and thus in favouring the viability of circular business models (Hatcher et al., 2011). In particular, product design features, such as material, shape and dimension, product architecture, functionality and modularity should be thought considering the entire lifecycle, with a focus on service, maintenance and final disposal. Improving the product maintainability/serviceability means considering the disassembly features for those target components subjected to scheduled maintenance and service, with the aim to develop a new sustainable business model (product-service) (Szwejczewski et al., 2015). Improving and upgrading product recyclability means to include several aspects (e.g., reverse logistics, disassembly, etc.) in the design stage, to facilitate the efficient recovery of components and materials from the product (Goodall et al., 2014).

3.1.2. Production phase

The *Production* phase can be essentially viewed as the "concretization" of the product idea and model conceived and developed during the design process. In general, a product is the result of internal and external productive steps performed by different subjects (e.g., manufacturers, suppliers, contractors, etc.) that interact together for exchanging materials, semi-finished goods and information. To fruitfully manage the production phase, it is not sufficient to have a view limited within the boundaries of a single company: all the actors that contribute to manufacture the final products and the semi-finished goods have to be considered.

Anyway, during the production phase, product features cannot be changed, since they derive from choices performed during the previous design process. Production stakeholders have not any degree of freedom to change and optimize products. Eventually, they can only stop the production due to intrinsic difficulties relative to wrong design choices and advise the design team that changes need to be implemented. For these reasons, it is possible to conclude that the product EoL is not directly influenced by the production, thus none supporting method or tool is needed in this phase to improve product EoL performances and to favour the implementation of closed-loop lifecycles.

3.1.3. Product distribution

Distribution is the process that allows making a product available in the market and supplying it to consumers. Depending on how this process is realized, different configurations can arise and different stakeholders can be involved:

- direct chains, in case of direct relationships between producers and consumers;
- short chains, in case of distributions realized by means of retailers;
- long chains, in case of distributions realized by means of several wholesalers and retailers.

During this phase producers, distributors or retailers can stipulate agreements with consumers to manage the product lifecycle. This is the case of leasing agreements and product-services that generally include take-back services for maintenance or at the product EoL. Summarizing, the distribution phase has a potential relevant influence on product EoL, thus it is necessary to involve distribution stakeholders for an efficient EoL management.

3.1.4. Use and Maintenance phases

Use is generally the longest phase of the entire product lifecycle. Its duration is influenced by technical and non-technical factors, such as damages, product obsolescence, change of consumers' preferences and needs, etc. It is clear that consumers play an important role in lifecycle management, since products are designed to meet final users' needs, identified before the beginning of the product design process by means of accurate market analyses.

During the use phase, *Maintenance* activities can occur when product components need to be replaced according to a predefined maintenance plan (ordinary maintenance) or due to breakings (extraordinary maintenance). This phase is particularly relevant in case of leasing agreements, since manufacturers or service providers have to guarantee full efficiency of products or services supplied. Stakeholders in charge of maintenance can be different, depending on the typology of product or service: producers, maintainers, service providers, final users, etc.

Both Use and Maintenance phases are strictly correlated to product EoL. For example, if these phases are correctly managed, they positively influence the durability of a product, extending its life. Final users decide when a product reach the end of its useful life and need to be disposed. Moreover, the EoL scenario is a direct consequence of choices performed by final users (e.g., landfilling, disposal in specialized recycling centres, repair, etc.). In conclusion, stakeholders of the use and maintenance phases have to be necessarily involved to improve efficiency in product EoL management.

3.1.5. Product End of Life

End of Life is the last phase of product lifecycle and for different reasons it is recognized as a key phase. Circular business models can be practically implemented only finding an efficient solution to manage the product EoL. Through EoL activities, materials can be recycled, components or product can be remanufactured, products can be reused and, in general, the residual value in EoL products or materials can be recovered. The efficiency and convenience of EoL activities is strictly correlated to the reverse supply chain that includes *"the process of moving goods from their typical final destination for the purpose of capturing value, or proper disposal"* (Hawks, 2006).

This complex environment requires the involvement of numerous and heterogeneous stakeholders. Each one is in charge of a specific phase: shippers to transport wastes and EoL goods, authorized recycling centres to disassemble products and/or recover materials, remanufacturers for refurbishment activities, etc.

The number and typology of stakeholders depends on the typology of products to treat. Moreover, dedicated legislations regulate the product EoL for specific product categories. As stated in the Introduction (Section 1), currently European Directives are dedicated to the management of vehicles at end of life and waste of electric and electronic equipment (European Parliament and Council, 2000, 2012). The development of tools to support the efficient product EoL management should consider all these aspects, the most important actors and their inter-relations.

3.2. The approach

The analysis of the most important lifecycle phases confirmed that product EoL is influenced by many different aspects and stakeholders. Design certainly plays an important role, since decisions taken during this phase greatly affects the entire product lifecycle (Mihelcic et al., 2008). Moreover, design stakeholders have the highest degree of freedom to change product features. Anyway, also the other lifecycle stakeholders have strong influences on the EoL performances. Summarizing the outcomes obtained from the analysis of literature studies and of the modus operandi of real industrial companies, it is possible to assert that the most EoL-affecting decisions are taken during the following activities:

- definition of company objectives and long-term strategies;
- identification of criticalities to correctly focus a redesign strategy;
- implementation of concrete redesign actions to improve product EoL performances and reach the prefixed targets;
- management of the reverse supply chain with the relative flows of information and materials;
- decision-making process on how to proceed with a EoL product (e.g., which is the most convenient EoL scenario to implement?).

The following Figure 5 depicts the new configuration of the product lifecycle. According to the proposed approach, the involved stakeholders are now supported, during key activities, by specific additional methodologies and tools. In this way different issues related to product EoL can be managed to avoid waste of residual value or the implementation of inefficient and inconvenient EoL scenarios.

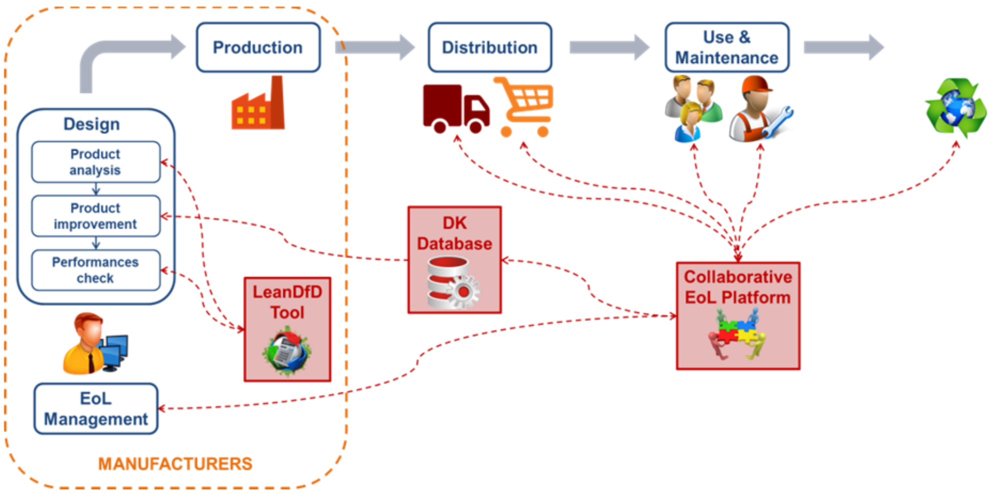


Figure 5. *The proposed integrated approach to manage product EoL.*

3.2.1. Target disassembly methodology and LeanDfD tool

The first methodology (*Target disassembly methodology*) and tool (*LeanDfD*) are dedicated to manufacturers, with the aim to manage the disassembly phase during the product design process. Disassembly is a preliminary but essential process toward product/component reuse or remanufacture, thus its influence on EoL performances is very high. Considering disassembly during the design process allows preventing potential issues and focusing the redesign strategy. However, due to the complexity of the design process, an important decision to take is to understand which specific activities and steps have to be supported by the proposed

Target disassembly methodology and LeanDfD tool. The degree of freedom concerning design choices, such as, for example, materials or product structures, should be high, in order to not limit the possible interventions and the relative positive impacts (Bahmra et al., 1999; Karlsson and Luttrop, 2006; Lindahl, 2006). But, at the same time, different information are essential to perform the analyses, such as, shapes of components, materials or liaisons between components/parts.

The first design activities (Feasibility or Conceptual design) are often not organized as a systematic process, creativity techniques can be used to generate product ideas (i.e. concept) and the tools used are very different and non-standardized. In this phase many information regarding the product are lacking (e.g., material, geometrical shapes, etc.). For these reasons, it is clear that the integration of the proposed analysis methodology and tool, dedicated to assess product disassemblability during the first phases of the design process is very hard.

During Detail Design most of the product features are fixed and cannot be changed. Choices made during the previous design phases are only optimized to finally prepare all the needed data to start with the production phase. Indeed during this phase the degree of freedom seems to be too low.

During Embodiment Design, instead, the most important activity performed by the design team is relative to the development of product and components models. Most of the design choices are made during this phase and the design team can change product and components features without particular impacts in terms of cost of the project. Simulations about product disassemblability performed by using the proposed LeanDfD tool are possible during the Embodiment Design phase, since the needed input data are available. The tool allows monitoring additional aspects during the iterative process of analysis, change and check, usually performed by the design team to reach the final solution.

Full details on the proposed *Target disassembly methodology* and *LeanDfD tool* can be found in Section 4 and Section 5.

3.2.2. DK Methodology and Database

The second proposed methodology and repository (*DK Methodology and Database*) aims to support design tasks of manufacturers. As the LeanDfD tool, also the DK Database finds its proper place in the Embodiment Design phase, but it is dedicated to another important step. Through the assessment of quantitative EoL performance indicators (e.g., disassembly time), the LeanDfD tool supports the design team in the identification of product criticalities and in the verification of impacts correlated to design changes. However, the product improvement phase is not properly covered, since the LeanDfD tool does not give any specific design suggestion on how to modify the product in order to solve the identified issues. The DK Methodology and Database intends to overcome this lack by providing practical and specific design suggestions based on knowledge coming from disassembly and EoL activities and processes. This KB methodology supports design activities performed by product manufacturers, but requires the collaboration of EoL stakeholders and service providers that have the needed knowledge to effectively improve the product EoL performances. At the end, manufacturers will improve products to increase their sustainability and the economic convenience for the implementation of closed-loop scenarios, while the activities performed by EoL stakeholders will be easier and cheaper, since most of the common issues are preventively managed and solved.

Full details on the proposed *DK Methodology and Database* can be found in Section 6.

3.2.3. Collaborative EoL platform

The third proposed system (*Collaborative EoL Platform*) aims to favour the collaboration between the most important lifecycle stakeholders. On the basis of the analysis presented before in this section, it is clear that the product lifecycle is a complex and long sequence of stages, in which different actors separated in space and time play important roles. To "close the loop" of the product lifecycle it requires to "close the gap" between lifecycle stakeholders, in order to take relevant decisions and create added value for the entire network. In this context, the proposed *Collaborative EoL Platform* is a shared environment to favour the creation of additional physical (e.g., materials, components) and virtual (e.g., information) flows needed to implement circular business models, with clear advantages for all the involved actors.

Full details on the proposed *Collaborative EoL Platform* can be found in Section 7.

4. The target disassembly methodology: How to quantitatively measure the disassemblability ?

The optimization of the product disassembly performances necessarily requires their estimation during the design process, when only product virtual representations are available. Designers need to evaluate the disassemblability of certain components and sub-assemblies, critical at EoL or important for maintenance reasons.

The main goal of the proposed methodology is the improvement of the efficiency and robustness of a complex product disassembly analysis. The best disassembly sequence is retrieved by solving the optimization problem of an exact DSP approach, using a smart algorithm and a structured repository of disassembly operations, called *Liaison DB*. The proposed methodology allows overcoming two main issues highlighted in the literature: (i) the time required for data input and computational analysis and (ii) the quality and consistency of results. Manual inputs are limited to the identification of disassembly levels and to the assignment of the liaison types among components and/or sub-assemblies. These activities are supported by the use of the product virtual model (3D CAD model).

Some basic concepts need to be introduced before detailing the methodology steps. The first one is the concept of *disassembly level*, defined as "*the level in which one or more components/sub-assemblies, connected through a liaison to other components/sub-assemblies, can be disassembled without any physical obstruction*".

The second definition regards the concept of *disassembly precedence* that can be explained with the following sentence: *"If the component A obstructs one or more components (e.g., component B), which are in relation only with the component A, in case the component A is removed at the level n, the other components (e.g., component B) are free to be removed at the level n+1"*.

Following these two rules previously introduced, *level 0* is the first disassembly level that includes components located in the external shelves of the general assembly, which can be disassembled as first in the disassembly path, since there are no obstructions with other product components. After the removal of components at the *level 0*, other components can be removed and a new level can be defined (i.e. *level 1*). The procedure is iterative and, generally, components belonging to *level n* can be removed only after the disassembly of one or more components of the *level n-1*.

Another important concept is relative to *inherited precedencies* and can be explained with the following sentence: *"If the component C obstructs component B and component B obstructs component A, then component A is free to be removed after component B (direct precedence) and component C (inherited precedence)"*.

The concept of *liaison* is another important notion, which characterizes the proposed approach. While a level identifies which components can be removed in a specific disassembly step, the liaison identifies a relation between components, i.e. the physical links between them. A *liaison* is defined as *"the type of connection (e.g., mechanical, electrical, etc.) between two components which can be removed by a specific disassembly operation (e.g., unscrewing, etc.)"*.

In the present work, a *disassembly operation* is defined as *"the disassembly of a component/sub-assembly from the general assembly"*. It could include the disassembly of more than one liaisons that join the component with other parts.

The definition of the disassembly levels can be assisted by computer-aided tools (e.g., CAD system), which permit the navigation of the virtual model for an easy identification of levels, while considering the target components. Components or sub-assemblies removed in previous levels can be hidden in the CAD viewer to facilitate the definition of disassembly levels and precedencies. The definition of disassembly levels allows reducing the number of feasible disassembly paths for the selected target component, avoiding to waste time in the calculation of non-optimum disassembly sequences (i.e. sequences with higher disassembly time). By using this approach grounded on disassembly levels, precedence relationships among components (i.e. components that can be disassembled only after the disassembly of other components) are defined, thus the calculated feasible paths are only a subset of all the possible sequences deriving from the combinatorial calculation. In this way, a computational time reduction has been achieved, while keeping the quality and the accuracy of the result.

The identification of liaisons is a fundamental task for the achievement of a robust and consistent estimation of disassembly time and cost. The approach requires the definition of a repository (*Liaison DB*) that stores a list of liaison types with relative characteristic properties. Firstly, a list of liaisons (i.e. assembly connections) has been pointed out based on the common mechanical, electrical and physical connections. Afterwards, a standard disassembly time has been assigned to each specific liaison and thus to each specific disassembly operation. Finally, specific properties and corrective factors have been defined to estimate the effective disassembly time of each liaison.

The chosen quantitative metrics to estimate the product/component disassemblability performances are:

- the *disassembly depth*, defined as the number of disassembly operations needed (i.e. number of components to disassemble) to reach a target component within a complex product;
- the *disassembly time*, defined as the time needed to disassemble a target component from a complex product;

- the *disassembly cost*, defined as the cost needed to disassemble a target component from a complex product.

These three indicators allow monitoring the disassembly performances of a product and univocally identifying disassembly criticalities. The first metric (i.e. disassembly depth) can be estimated by calculating the feasible disassembly paths, by taking into account obstruction between components. It is useful to monitor the disassembly depth to understand if particular target components are difficult to reach, since they are located in the internal part of a product, and the product architecture needs to be simplified.

The second metric (i.e. disassembly time) can be estimated by considering the time needed to disassemble each liaison to remove in order to reach a target component, according to a particular feasible disassembly path. It is useful to identify critical operations that require a high disassembly time to understand which components and liaisons within a product requires a redesign.

The third metric (i.e. disassembly cost) is clearly related to the disassembly time, thus allows deriving the same conclusions. It can be calculated by considering the number of workers involved in the disassembly operations, the labour unitary cost and the unitary cost of disassembly equipment and tools (e.g., bridge crane). In addition, the use of this metric is essential to have a first rough estimation of the economic convenience of a manual disassembly. If, for instance, a company decides to proceed with the take back and remanufacturing of a product, the disassembly cost is a key parameters to evaluate the feasibility of this EoL scenario and business model.

Figure 6 depicts the general workflow of the proposed approach. Full details of each step are described in the following five sub-sections, while the last one reports an example of the methodology application to analyse a complex product (combustion engine).

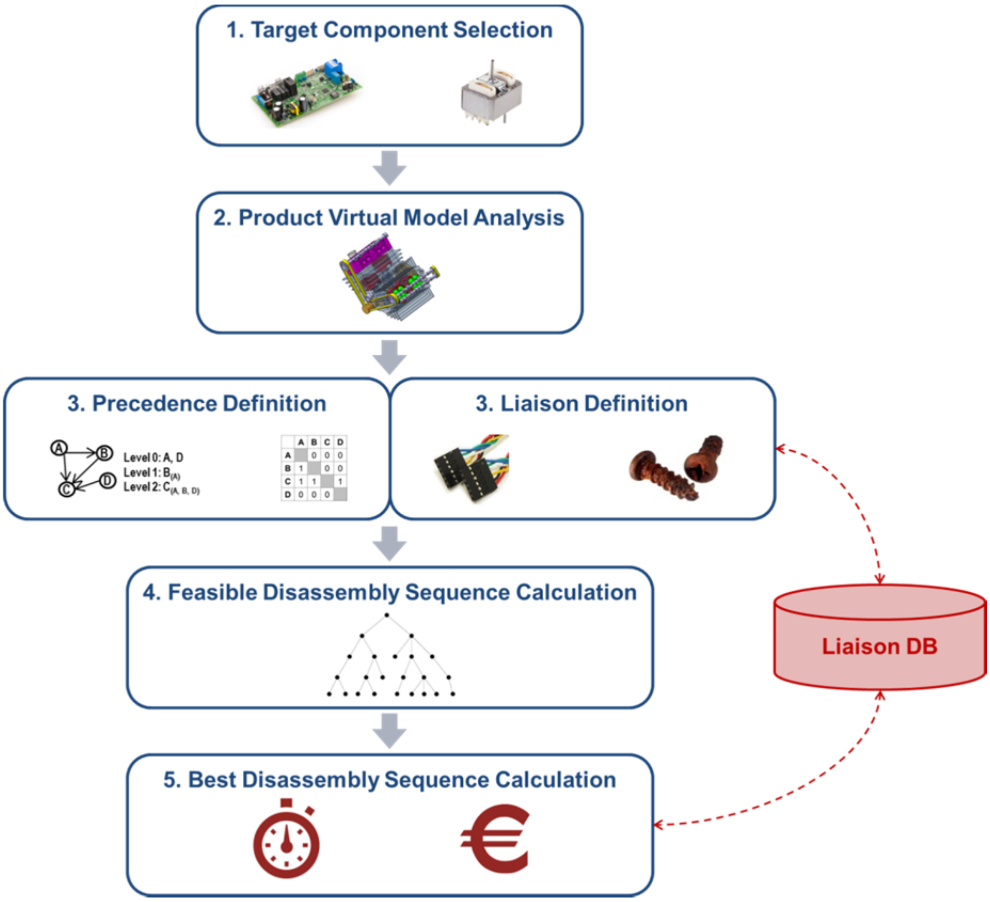


Figure 6. *Workflow of the proposed target disassembly methodology.*

4.1. 1st step – Target Component Selection

The proposed Target disassembly methodology starts with the definition of components or sub-assemblies (called *target components*) to be analysed from a disassembly point of view. Target components can be single parts (product components) or groups of parts (product sub-assemblies). Even if target components are depending by the product, they generally belong to one of the following categories:

- high value parts to reuse or sell to get a considerable direct or indirect (i.e. material) revenue. This category is particularly interesting in the case of shifting toward new circular business models (e.g., reuse, remanufacture, recycling, product-service, etc.);
- hazardous components to dismantle following proper ways, in order to be compliant with EoL regulations (e.g., critical components defined in the European WEEE directive);
- components to maintain during the useful life of a product, according to the maintenance/service plan. Examples of this category are lamps or electric motors in electric appliances;
- parts containing incompatible materials to manually separate before their shredding, in order to avoid mixed materials (e.g. incompatible plastic polymers in a product).

In case of complex industrial products, target components can be located in a very deep position, hence, several disassembly paths are feasible to reach the target. For this reason, it is important to know the best one that allow minimizing the disassembly time and cost.

A concrete example of target components is represented by *critical components* of household appliances. According to the WEEE directive (European Parliament and Council, 2012), these parts have to be manually disassembled at the beginning of the recycling process. This is due to the fact that critical components potentially contain hazardous substances (e.g., lead, mercury, toxic gases, etc.) that need to be treated separately from the remaining materials (e.g. metal scraps, plastic parts, etc.). The following Table 1 illustrates some examples of critical components for the most common household appliances.

Table 1. Examples of critical components in some household appliances

	Washing machine	Cooker hood	Dishwasher	Oven	Refrigerator
Capacitor	X	X	X	X	X
Electronic board	X	X	X	X	X
Electric motor	X	X	X	X	
Transformer	X	X	X	X	X
Lamp		X		X	X
Electric pump	X		X		
Thermostat Sensor Switch	X		X	X	X
Electric cables	X	X	X	X	X
Compressor					X
Oil					X
Refrigerant					X

4.2. 2nd step – Product Virtual Model Analysis

The second step of the approach is the analysis of the product model, which means the analysis of the product structure starting from the virtual model. This latter can be available with its geometrical representation (i.e. CAD model) or with its structure (i.e. BoM – Bill of Material). Both these virtual representations are useful to retrieve data necessary for the disassembly analysis. In particular, the following information can be retrieved from the CAD model:

- number and name of components;
- component geometry;

- general arrangement and physical obstructions among components and sub-assemblies;
- extracting directions;
- dimensions, weights and materials;
- features of components and sub-assemblies (e.g., cutting edges, holes, tapered geometries, etc.).

Using the BoM, a complete list of components is available, as well as the constituent materials. Furthermore, the BoM components are organized in sub-assemblies facilitating the definition of relations between parts. Anyway, in the BoM, most of the information related to geometry and physical obstructions are not available, thus the analysis is generally time-consuming and less accurate. In cases when only the BoM is available, approximations are necessary for the analysis. For example, the component geometry requires to be summarized using the component bounding box (envelope), thus loosing potentially useful information such as specific product features.

The list of components is the starting point for the compilation of the product matrix template (also called *precedence matrix* template), a NxN square matrix, where N is the total number of components. Each row and each column represents a component of the general assembly and the cells of this matrix are filled during the 3rd step of the methodology, by defining precedencies between components/sub-assemblies. It is important to highlight that the liaison elements (e.g., screws, connectors, etc.) are not considered as components in the precedence matrix, thus their extraction does not need to be simulated with a clear reduction of time for inputting the needed information.

4.3. 3rd step – Precedence & Liaison Definition

The aim of this step is the definition of disassembly levels, precedence relations among components and sub-assemblies, as well as liaisons. The method does not foresee the definition of the precedencies and liaisons for all the components because the procedure can be stopped when all the target components, chosen in the 1st methodology step, have been reached. This hypothesis strongly contributes to reduce the needed time to carry out a complete analysis.

4.3.1. Precedence Definition

The precedence relations among product components/sub-assemblies can be represented by using two different notations: (i) *disassembly level graph* and (ii) *precedence matrix*.

The *disassembly level graph* maintains the components/sub-assemblies belonging to each disassembly level, together with the precedence relations with components/belonging to the previous level. Therefore, only direct precedencies are represented, while the other ones has to be extrapolated by analysing the graph.

The *precedence matrix*, briefly introduced in the previous sub-section, is a more complete representation, since it maintains all the precedence relations within a product. In the precedence matrix, cells in the diagonal are always null. Each row and each column represents a specific component and each cell of a row/column identifies the relation of that component with the other components of the assembly. The cells of the matrix are filled using two possible values as follow:

- "*1*" for those components in the column which require to be disassembled before the component in the row under analysis;
- "*0*" for all the other cases.

For example, if the component A is not in any relation with component B, the cell in the row A and column B is set to “0”. If the component A must be removed after component C, the cell in the row A and column C is set to “1”.

To better explain how precedence relations can be set and how they can be represented by using the two notations (i.e. disassembly level graph and precedence matrix), a simple example is presented. The following Figure 7, Figure 8 and Figure 9 shows the definition of disassembly levels, the creation of the disassembly level graph and the filling of the precedence matrix for a carjack, starting from the CAD 3D model of the product.

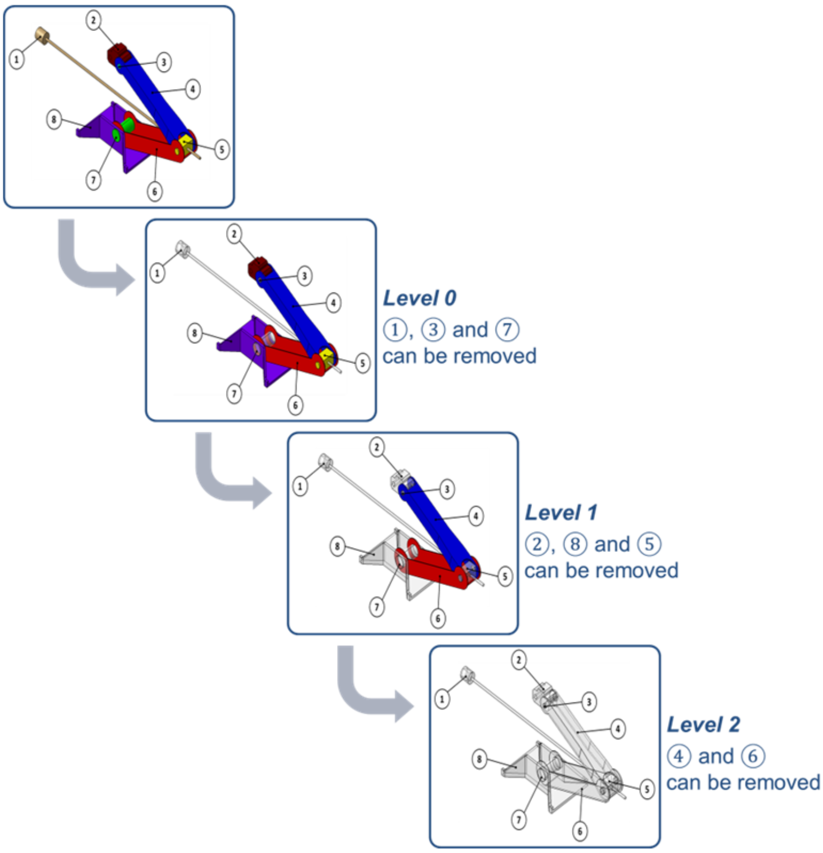


Figure 7. *Definition of disassembly levels for the carjack example.*

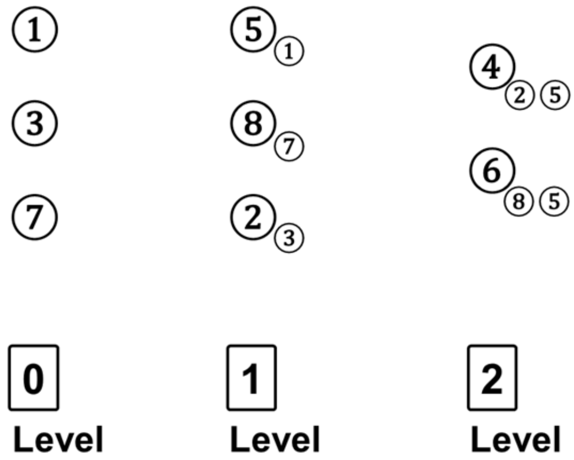


Figure 8. *Disassembly level graph for the carjack example.*

	①	②	③	④	⑤	⑥	⑦	⑧
①		0	0	0	0	0	0	0
②	0		1	0	0	0	0	0
③	0	0		0	0	0	0	0
④	1	1	1		1	0	0	0
⑤	1	0	0	0		0	0	0
⑥	1	0	0	0	1		1	1
⑦	0	0	0	0	0	0		0
⑧	0	0	0	0	0	0	1	

Figure 9. *Precedence matrix for the carjack example.*

The precedence matrix (Figure 9) can be easily read following each row. An important consideration is that the sum of the items in each row identifies the number of disassembly operations to perform (i.e. number of components/sub-assemblies to remove) before the disassembly of the analysed component. This represents the first quantitative metric used in this research work to assess the product/component disassemblability: the disassembly depth. Considering the matrix in Figure 9, the component ④, for example, can be removed after the disassembly of two components positioned in the level 1 (components ② and ⑤), as well as after the two components with an inherited precedence relation (components ③ and ①). Component ⑧, instead, can be removed after the disassembly of only one component (component ⑦) which is positioned at the level 0.

The definition of the disassembly levels and precedencies are essential tasks to calculate the feasible disassembly sequences and the disassembly depth for each target component (4^{th} methodology step).

4.3.2. Liaison Definition and Classification

The second main task of this step is the definition of liaison types between components/sub-assemblies in the general assembly. The easiest and fastest approach for the liaison assignment is to perform this activity concurrently to the level and precedence definition. This task leverages on a comprehensive database (called *Liaison DB*) containing the typical liaisons for mechanical products, properly classified and characterized with relative standard disassembly time and appropriate corrective factors.

The classified liaisons have been subdivided in two different hierarchical levels: classes and types. Each class contains one or more liaison types, as described in the following Table 2.

Table 2. *Classified liaison classes and types with the standard disassembly time.*

Liaison Class	**Liaison Type**	**Standard Disassembly Time [s]**
Threaded	Screw	4
	Threaded rod	4
	Nut	4
Shaft-hole	Pin	3
	Linchpin	3
Rapid joint	Snap-fit	2
	Guide	3
	Dap joint	2
Electric	Coaxial cable	4
	Electric plug	2
	Screw terminal	2
	Ribbon cable	2
Prevent extraction	Circlip	4
	Split pin	4
Not removable (destructive)	Nail / Rivet	6
Motion transmission	Tang / Key	3
	Spline profile	3
Magnetic	Magnetic	2
Washer	Washer	2
Bearing	Bearing	5
Visual obstruction	Visual obstruction	1

For each liaison type, a standard disassembly time has been defined (Table 2). It is relative to a reference liaison type, in standard conditions (e.g., length, diameter, tool, etc.) and without damages. This last assumption is particularly important because, generally, the purpose of manual disassembly, both in cases of services and EoL, is the possibility to recover products and components without destructive actions. For example, in the case of a screw liaison type, the reference is set to a new screw (not used or damaged), with hexagonal notch head, a length of 20 mm or less, a diameter between 4 mm and 12 mm and disassembled with a pneumatic screwdriver. In this case, the standard disassembly time (4 seconds) equals the assembly time.

Additionally, to take into account real conditions of the product during the disassembly activities and the peculiarity of each liaison type, different corrective factors have been defined for each liaison type. So doing, for instance, if the product life was particularly long and in a severe working environment, rust and oxides formation, wear deposition, etc. can increase the disassembly difficulties and then the time necessary for the specific activity (e.g., unscrewing, etc.). Concerning the peculiarity of liaisons, each variation from the standard condition is considered for the calculation of the disassembly time. It includes variation in geometrical features (e.g., screw length, screw diameter, screw head type, etc.) and variation in assembly/disassembly tools used during the disassembly operations (e.g., manual screwdriver, hex key, etc.). A corrective factor has been associated to each particular condition (e.g., the kind of tool used directly influences the disassembly time). These values are used to adjust the standard disassembly time, obtaining the effective disassembly time.

The standard disassembly time and the corrective factors have been defined according to an in-depth literature review, some empirical case studies and analysing different products in collaboration with expert stakeholders involved in the EoL management (i.e. dismantling centres). In particular, the information maintained in the *Liaisons DB* mainly derives from discussions, interviews, surveys and observation of dismantling activities. Firstly, the disassembly and EoL activities relative to different products (e.g., WEEE) have been recorded and annotated. Then the disassembly time and the standard conditions of each liaison type has been defined on the basis of the recorded videos. Finally, the different conditions have been classified and the relative corrective factors defined, through the observation of the difficulties encountered during the operations. More details on the procedure used to formalize the knowledge can be found in Section 6.

For a better explanation of the influence of corrective factors, we can take the example of a rusted screw. For this liaison type, the parameters are the followings:

- Standard disassembly time (Ts) = 4 s
- Liaison properties:
  - Wear: completely worn → CF1 = 1,5
  - Head type: cylindrical with notch → CF2 = 1
  - Length: > 20mm, < 40mm → CF3 = 1,1
  - Diameter: < 4mm → CF4 = 1,2
  - Tool: spanner → CF5 = 1,2
- Effective disassembly time = Ts*CF1*CF2*CF3*CF4*CF5 = 9,5 s

The gap between the standard and the effective disassembly times highlights the importance of the corrective factors in modelling the specificity of each analysed liaison. This represents an essential feature of the proposed approach, with the aim to guarantee a high reliability in the time estimation.

Full details on the classified liaisons, with the relative properties and corrective factors, included in the *Liaison DB*, can be found in Appendix A.

The liaison type assignment is an essential task to calculate the best disassembly sequence to reach each selected target component (5^{th} methodology step), considering the chosen quantitative metrics (i.e. disassembly time and disassembly cost).

4.4. 4th step – Feasible Disassembly Sequence Calculation

The disassembly precedence matrix and the disassembly levels are the two models required for the definition of the feasible disassembly sequences to reach each target component. The following rule can be adopted in the calculation: *"Considering a generic level n, only the components belonging to the same level (n) or to the subsequent level (n+1) are removed. After the removal of a component at the level n, the removal of components which belong to the level n-1 is not considered in the calculation"*. This rule generates an important limitation in the "explosion" of the combinatorial sequences and permits to drastically reduce the computational time keeping the quality and the accuracy of results.

Figure 10 highlights two feasible disassembly sequences for the car jack example, considering ④ as target component.

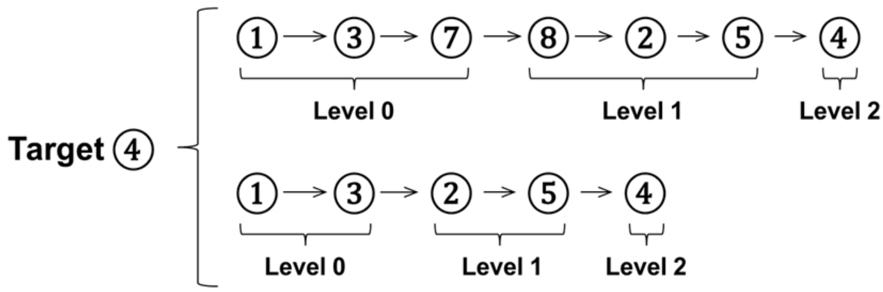


Figure 10. *Example of feasible disassembly sequences for target component ④ of the carjack example.*

4.5. 5th step – Best Disassembly Sequence Calculation

The calculation of the disassembly time for each feasible disassembly sequence is achieved by considering liaisons between components/sub-assemblies, defined in the context of the 3rd methodology step. Considering the information stored in the proposed *Liaison DB*, the disassembly time for each specific liaison can be calculated by using the following equation (1):

$$T_{ej} = T_s \cdot \prod_{i=1}^{I} CF_i \tag{1}$$

where T_{ej} is the effective disassembly time of the *j-th* liaison, T_s is the standard disassembly time of the considered liaison type and CF_i are the corrective factors relative to each *i-th* chosen condition.

Concerning the disassembly cost for each liaison, instead, it can be calculated by using the following equation (2):

$$C_j = T_{ej} \cdot (C_l + C_{tool}) \tag{2}$$

where C_j is the disassembly cost of the *j-th* liaison, T_{ej} is the effective disassembly time, C_l is the labour hourly cost and C_{tool} is the tool hourly cost.

The disassembly time for each disassembly operation is obtained by summing the disassembly time relative to each liaison to remove to disassemble a component from the general assembly. It can be calculated according to the following equation (3):

$$T_{ok} = \sum_{j=1}^{J} T_{ej} \tag{3}$$

where T_{ok} is the effective disassembly time of the *k-th* operation (i.e. disassembly time of the *k-th* component/sub-assembly) and T_{ej} is the effective disassembly time of the *j-th* liaison to disassemble.

Considering that a disassembly sequence is a series of disassembly operations, the disassembly time and cost for a particular target component can be analytically estimated using the following equations (4):

$$T_t = \sum_{k=1}^{K} T_{ok} \qquad\qquad C_t = \sum_{k=1}^{K} C_{ok} \tag{4}$$

where T_t and C_t are respectively the total disassembly time and cost of a particular component/sub-assembly, T_{ok} and C_{ok} are respectively the effective disassembly time and the disassembly cost of the *k-th* operation.

To derive the best disassembly sequences, the optimization problem uses a simple mathematical model in which the purpose of the optimization is the minimization of the disassembly time (or disassembly cost) for the selected target components. In fact, for complex products, an inconsistency can arise during the solution of the disassembly problem. It can happen that the shortest path (minimum disassembly depth and number of disassembly operations) is not the best way to reach the target (minimum disassembly time). Using this proposed approach, the disassembly path that minimize the disassembly time is pointed out as the best disassembly sequence. The mathematical model used for the minimization of the disassembly time is simply a step-by-step comparison among the feasible disassembly sequences, with the selection of the sequence with the minimum value for the disassembly time, as reported in the following equation (5):

$$BDS_j = \min(seq\_1_j, seq\_2_j, seq\_3_j, \ldots, seq\_N_j) \tag{5}$$

where BDS_j is the Best Disassembly Sequence for the *j-th* target component, *seq_n* is the *n-th* feasible disassembly sequence and *N* is the overall number of feasible disassembly sequences calculated for the *j-th* target component.

4.6. Methodology application

To demonstrate how the proposed approach can be used in a realistic example, this section explains the analysis of a 4-cylinders combustion engine. The choice of this product is justified by its complexity that allows testing the robustness of the approach, by considering hundreds of components. In this case, some components are grouped in sub-assemblies to simplify the analysis, which finally considers 30 items. The objective is to demonstrate the ability of the proposed methodology in the identification of feasible disassembly sequences, starting from the virtual model and following the described workflow.

In this application, a complete disassembly of the analysed engine has been carried out, thus all the components can be considered as target (1st step). Figure 11 shows the 3D CAD model used to perform the disassembly analysis (2nd step).

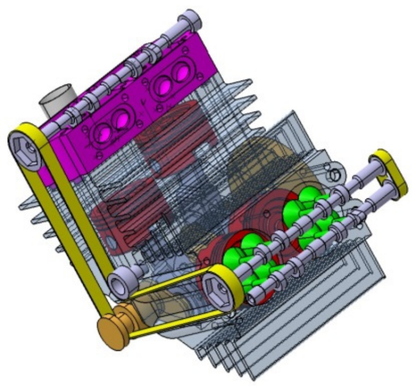


Figure 11. *Combustion engine 3D model.*

Based on the information extrapolated from the product virtual model, the implementation of the 3rd step of the approach consisted in the definition of precedencies between the 30 components/sub-assemblies to obtain, at the end, a 30x30 precedence matrix (Table 3).

__Table 3.__ Initial precedence matrix for the combustion engine.

		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD		Disassembly depth
Crankcase	**A**		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	→	29
Crankshaft	**B**	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	→	1
Connecting rod 1	**C**	0	1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	→	2
Connecting rod 2	**D**	0	1	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	→	2
Connecting rod 3	**E**	0	1	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	→	2
Connecting rod 4	**F**	0	1	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	→	2
Piston 1	**G**	0	1	1	0	0	0		0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	→	4
Piston 2	**H**	0	1	0	1	0	0	0		0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	→	4
Piston 3	**I**	0	1	0	0	1	0	0	0		0	0	0	1	0	1	1	0	0	1	1	0	0	0	0	1	1	1	1	0	0	→	11
Piston 4	**J**	0	1	0	0	0	1	0	0	0		0	0	0	1	1	1	0	0	1	1	1	1	1	1	0	0	0	0	0	0	→	11
Pin 1	**K**	0	1	1	0	0	0	0	0	0	0		0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	→	3
Pin 2	**L**	0	1	0	1	0	0	0	0	0	0	0		0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	→	3
Pin 3	**M**	0	1	0	0	1	0	0	0	0	0	0	0		0	1	1	0	0	1	1	0	0	0	0	1	1	1	1	0	0	→	10
Pin 4	**N**	0	1	0	0	0	1	0	0	0	0	0	0	0		1	1	0	0	1	1	1	1	1	1	0	0	0	0	0	0	→	10
Camshaft 1	**O**	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	→	2
Camshaft 2	**P**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	1	1	0	0	0	0	0	0	0	0	0	0	→	2
Camshaft 3	**Q**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	1	0	0	0	0	0	0	0	0	0	0	0	→	1
Roller adjuster	**R**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	→	0

		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD		Disassembly depth
Timing belt	**S**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	→	0
Drive belt	**T**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	→	0
Valve 1	**U**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1		0	0	0	0	0	0	0	0	0	→	3
Valve 2	**V**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0		0	0	0	0	0	0	0	0	→	3
Valve 3	**W**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0		0	0	0	0	0	0	0	→	3
Valve 4	**X**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0		0	0	0	0	0	0	→	3
Valve 5	**Y**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0		0	0	0	0	0	→	3
Valve 6	**Z**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0		0	0	0	0	→	3
Valve 7	**AA**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0		0	0	0	→	3
Valve 8	**AB**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0		0	0	→	3
Exhaust pipe	**AC**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	→	0
Cylinder head	**AD**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0		→	2

In the last right-hand column of Table 3, the disassembly depth values for each engine component/sub-assembly is shown. This information allows easily evaluating how much each component is reachable and, in particular, how many components have to be disassembled before reaching a particular target. Components with disassembly depths = 0 can be disassembled at first, thus they belong to the disassembly level 0 (this is the case of components R, S, T and AC, highlighted in light red in Table 3).

In addition, all the 30 components have been grouped in 6 different disassembly levels (from 0 to 5), to have a complete view of the disassembly model. Figure 12 represents the disassembly level graph and shows in which phase each component (big circles) can be removed, listing, for each one, which components have a disassembly precedence (small circles). For example, the component M, belonging to the level 3, has to give the precedence to five components, belonging to the level 2: E, Y, Z, AA and AB. The disassembly level graph is a simplified representation of the product disassembly model that contains only aggregated information as a graphical simplification of the precedence matrix.

The implementation of the 4th step of the approach consisted in using the information contained in the product precedence matrix (or in the disassembly levels graph) to derive the feasible disassembly sequences. From Table 3 and Figure 12 it emerges that all the feasible disassembly sequences for the analysed combustion engine have to start with one of the following components: R (Roller adjuster), S (Timing belt), T (Drive belt) or AC (Exhaust pipe).

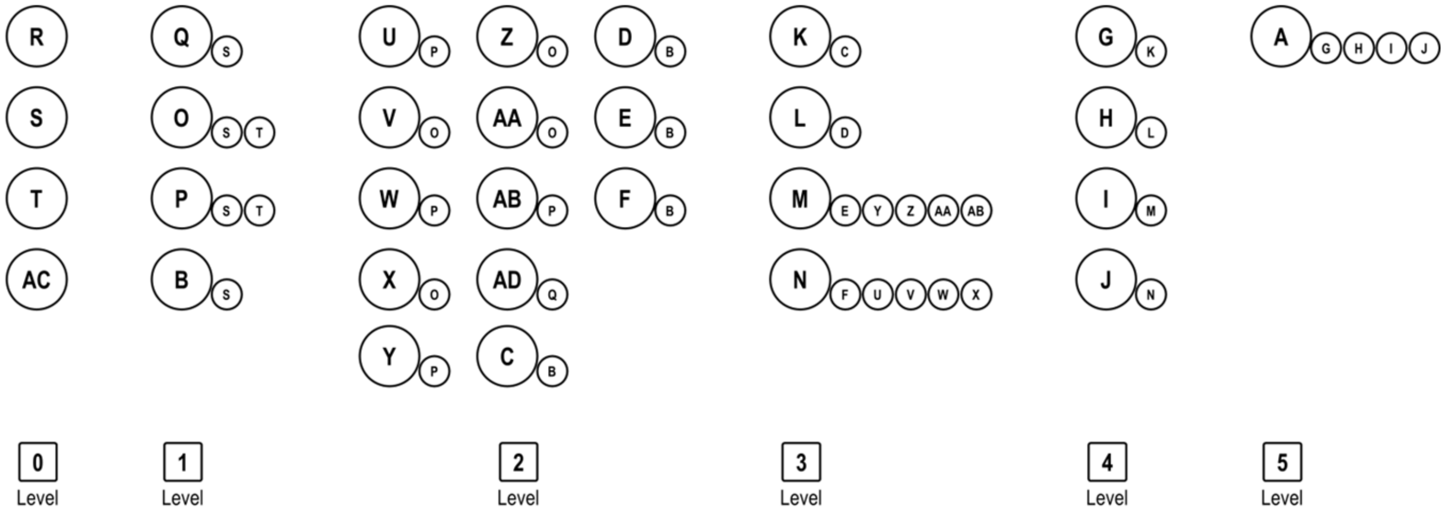


Figure 12. *Combustion engine disassembly level graph.*

If we suppose to disassemble the component S (1st disassembly operation), it is possible to reduce the initial precedence matrix by eliminating the corresponding row and column. As a consequence, the disassembly depth for each component has to be updated (Table 4). At this stage (i.e. after the 1st disassembly operation), other components could have a disassembly depth of 0, which means that they are free from obstruction and thus they are ready to be disassembled. In this case, the group of components with disassembly depth equal to 0 contains those components already free from obstructions at the beginning (R, T and AC), as well as the components released by removing the component S (B and Q).

Continuing with the disassembly process, we can suppose to disassemble the component T (2nd disassembly operation) and to reduce the precedence matrix as shown in Table 5. Components O and P are added to the list of candidates to disassembly at the next operation, since they have a disassembly depth equal to 0.

Iterating this process, it is possible to calculate all the feasible disassembly sequences for the entire product under analysis, as well as the disassembly sequences for specific target components.

Applying the procedure to reach the component J (Piston 4), some examples of calculated disassembly sequences are listed below:

- S → T → B → O → P → F → U → V → W → X → N → J;
- S → B → T → P → U → W → O → V → X → F → N → J;
- T → S → P → O → U → V → W → X → B → F → N → J;
- AC → R → S → T → Q → B → AD → O → V → AA → X → P → W → X → U → D → F→ L → N → J;
- …

In conclusion, this case study demonstrates that the proposed approach is useful to derive the feasible disassembly sequences for each component. If, instead, the objective is to establish the best disassembly paths, the definition of the liaisons between components is needed (see Section 8).

__Table 4.__ Reduced precedence matrix for the combustion engine, after the disassembly of the Timing belt (component S).

		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	T	U	V	W	X	Y	Z	AA	AB	AC	AD		Disassembly depth
Crankcase	**A**		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	→	28
Crankshaft	**B**	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	0
Connecting rod 1	**C**	0	1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	1
Connecting rod 2	**D**	0	1	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	1
Connecting rod 3	**E**	0	1	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	1
Connecting rod 4	**F**	0	1	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	1
Piston 1	**G**	0	1	1	0	0	0		0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	3
Piston 2	**H**	0	1	0	1	0	0	0		0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	3
Piston 3	**I**	0	1	0	0	1	0	0	0		0	0	0	1	0	1	1	0	0	1	0	0	0	0	1	1	1	1	0	0	→	10
Piston 4	**J**	0	1	0	0	0	1	0	0	0		0	0	0	1	1	1	0	0	1	1	1	1	1	0	0	0	0	0	0	→	10
Pin 1	**K**	0	1	1	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	2
Pin 2	**L**	0	1	0	1	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	2
Pin 3	**M**	0	1	0	0	1	0	0	0	0	0	0	0		0	1	1	0	0	1	0	0	0	0	1	1	1	1	0	0	→	9
Pin 4	**N**	0	1	0	0	0	1	0	0	0	0	0	0	0		1	1	0	0	1	1	1	1	1	0	0	0	0	0	0	→	9
Camshaft 1	**O**	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	1	0	0	0	0	0	0	0	0	0	0	→	1
Camshaft 2	**P**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	1	0	0	0	0	0	0	0	0	0	0	→	1
Camshaft 3	**Q**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	→	0
Roller adjuster	**R**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	→	0

		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	T	U	V	W	X	Y	Z	AA	AB	AC	AD		Disassembly depth
Drive belt	**T**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	→	0
Valve 1	**U**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1		0	0	0	0	0	0	0	0	0	→	2
Valve 2	**V**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0		0	0	0	0	0	0	0	0	→	2
Valve 3	**W**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0		0	0	0	0	0	0	0	→	2
Valve 4	**X**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0		0	0	0	0	0	0	→	2
Valve 5	**Y**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0		0	0	0	0	0	→	2
Valve 6	**Z**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0		0	0	0	0	→	2
Valve 7	**AA**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0		0	0	0	→	2
Valve 8	**AB**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0		0	0	→	2
Exhaust pipe	**AC**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	→	0
Cylinder head	**AD**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0		→	1

Table 5. *Reduced precedence matrix for the combustion engine, after the disassembly of the Timing belt (component S) and of the Drive belt (component T).*

		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	U	V	W	X	Y	Z	AA	AB	AC	AD		Disassembly depth
Crankcase	**A**		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	→	27
Crankshaft	**B**	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	0
Connecting rod 1	**C**	0	1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	1
Connecting rod 2	**D**	0	1	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	1
Connecting rod 3	**E**	0	1	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	1
Connecting rod 4	**F**	0	1	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	1
Piston 1	**G**	0	1	1	0	0	0		0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	3
Piston 2	**H**	0	1	0	1	0	0	0		0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	3
Piston 3	**I**	0	1	0	0	1	0	0	0		0	0	0	1	0	1	1	0	0	0	0	0	0	1	1	1	1	0	0	→	9
Piston 4	**J**	0	1	0	0	0	1	0	0	0		0	0	0	1	1	1	0	0	1	1	1	1	0	0	0	0	0	0	→	9
Pin 1	**K**	0	1	1	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	2
Pin 2	**L**	0	1	0	1	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	2
Pin 3	**M**	0	1	0	0	1	0	0	0	0	0	0	0		0	1	1	0	0	0	0	0	0	1	1	1	1	0	0	→	8
Pin 4	**N**	0	1	0	0	0	1	0	0	0	0	0	0	0		1	1	0	0	1	1	1	1	0	0	0	0	0	0	→	8
Camshaft 1	**O**	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	→	0
Camshaft 2	**P**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	→	0
Camshaft 3	**Q**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	→	0

		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	U	V	W	X	Y	Z	AA	AB	AC	AD		Disassembly depth
Roller adjuster	**R**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	→	0
Valve 1	**U**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0		0	0	0	0	0	0	0	0	0	→	1
Valve 2	**V**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0		0	0	0	0	0	0	0	0	→	1
Valve 3	**W**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0		0	0	0	0	0	0	0	→	1
Valve 4	**X**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0		0	0	0	0	0	0	→	1
Valve 5	**Y**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0		0	0	0	0	0	→	1
Valve 6	**Z**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0		0	0	0	0	→	1
Valve 7	**AA**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0		0	0	0	→	1
Valve 8	**AB**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0		0	0	→	1
Exhaust pipe	**AC**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	→	0
Cylinder head	**AD**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0		→	1

5. LeanDfD: A design tool oriented to disassembly and EoL

The target disassembly methodology, presented in Section 4, has been implemented in a software tool called *LeanDfD*. The tool is based not only on disassemblability metrics, such as the disassembly time and cost, but also on the Recyclability Ratio (see the next sub-section for details). The calculated disassembly time and cost, determined considering the real conditions of the product at the moment of disassembly, feed the recyclability calculation, which estimates the quantities of materials that could be potentially recycled at the EoL. All these metrics are useful to estimate how easily products or particular target components can be managed during maintenance/service or at the EoL.

After a brief explanation of the Recyclability Ratio methodology, this section is completely dedicated to present the LeanDfD framework, data structure, databases, input/output data and use scenarios. Full details about the LeanDfD functionalities can be found in the user manual reported in the Appendix B.

5.1. Product/component Recyclability Ratio

To define the product EoL performance, the chosen metric is the *Recyclability Ratio* (Ardente et al., 2011). This index has the aim of preventively estimating the quantities of materials that could be potentially recycled at the product EoL, according to the material masses and different corrective factors, as depicted in the following equations (6) and (7):

$$RR = \sum_{i,k} \frac{m_{recycle_{i,k}}}{m_{i,k}} \tag{6}$$

$$m_{recycle_{i,k}} = m_{i,k} \cdot D_{i,k} \cdot C_{i,k} \cdot M_{R_{i,k}} \tag{7}$$

where *RR* is the product Recyclability Ratio, $m_{recycle,i,k}$ is the potentially recyclable mass, $m_{i,k}$ is the total mass, $D_{i,k}$ is the disassembly index, $C_{i,k}$ is the contamination index, and $M_{R,i,k}$ is the material degradation index. All these quantities are referred to the *k-th* material contained in the *i-th* component.

Parameter values can be retrieved from different sources:

- The material mass ($m_{i,\ k}$) is extrapolated from the CAD model;
- The *Disassembly Index* ($D_{i,\ k}$) is retrieved from the literature (Ardente et al., 2011) by using (as input) the quantitative metrics (i.e. disassembly time and disassembly depth) calculated according to the proposed target disassembly methodology;
- The *Material Degradation Index* ($M_{R,i,\ k}$) is retrieved from the literature (Ardente et al., 2011), considering the ease of degradation and the potential recyclability of the different materials in the real recycling chain (e.g., it is easier to recycle steel than plastics);
- The *Contamination Index* ($C_{i,\ k}$) is retrieved from the literature (Ardente et al., 2011), considering the material contaminations (e.g., coatings) and incompatibilities.

In particular, for plastic materials, which are the most critical to separate and recycle, due to chemical differences between different polymers, a compatibility matrix (Figure 13) has been implemented in the tool as an additional corrective factor. It allows analysing which polymers can be recycled together and which have a partial or total incompatibility and thus should be separated before the recycle to obtain second-life materials of acceptable quality.

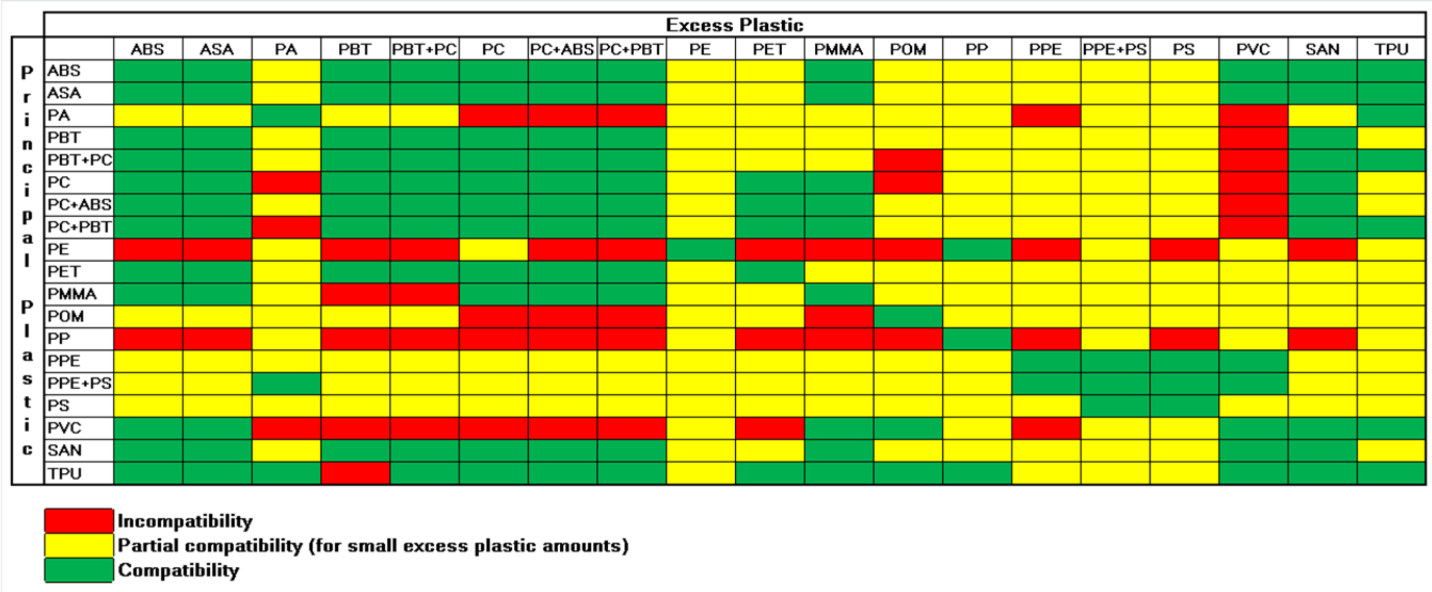


Figure 13. *Plastic compatibility matrix (ECMA International, 2008).*

5.2. Tool architecture and modules

LeanDfD is a desktop application based on the *Microsoft .NET framework*, oriented to engineers and designers. LeanDfD consists of five modules and two different databases, as depicted in the general software architecture proposed in Figure 14.

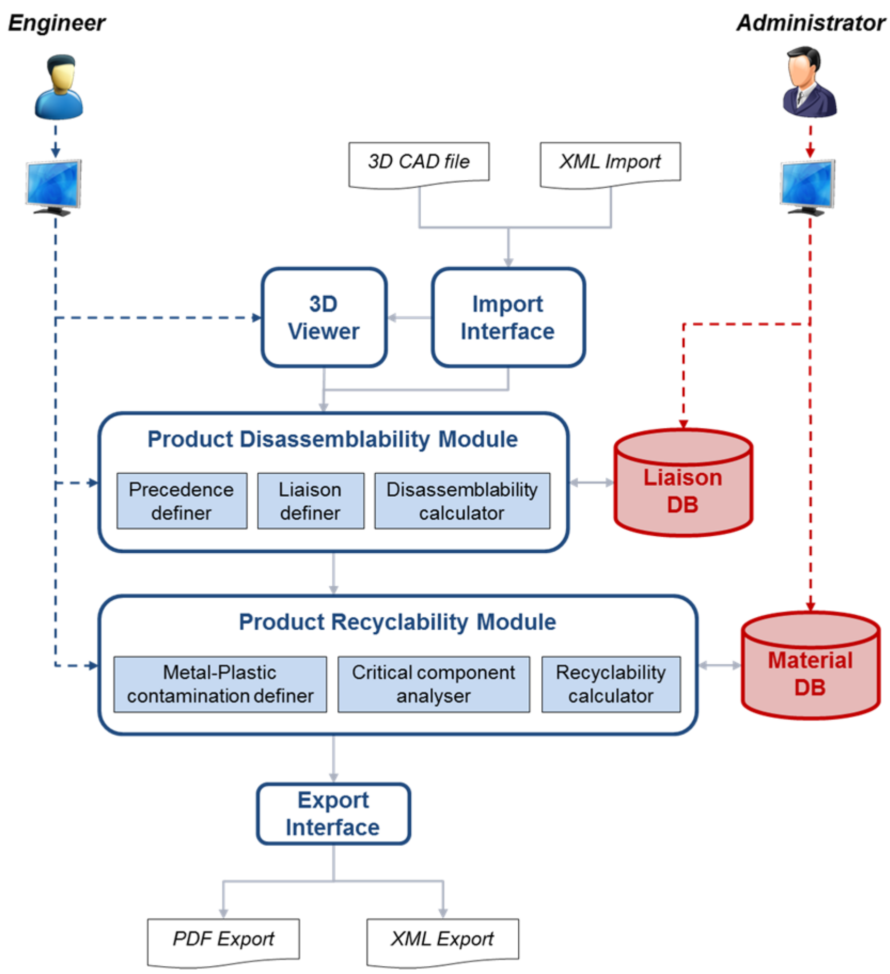


Figure 14. *LeanDfD tool architecture: modules and databases.*

The first module, the *Import Interface*, permits the import of an external file from a 3D CAD or PDM (Product Data Management) system. LeanDfD accepts as input a 3D geometry that can be read from a standard 3D CAD file (STEP format – STandard for the Exchange of Product) or through a direct connection to a CAD system (*SolidEdge*® *ST4* by *Siemens*®). The latter, which uses the SolidEdge API, is preferable to the first one since LeanDfD reads from the CAD a more complete set of information, not only the 3D geometry but also additional information required for the analysis, such as the mass, materials and surface coatings (component attributes). Since LeanDfD has been developed in the context of a European Research Project, called G.EN.ESI (Integrated software platform for Green Engineering dESIgn and product sustainability, www.genesi-fp7.eu), the tool is able to interact, exchanging information, with other tools of the G.EN.ESI platform. For this reason, LeanDfD also accepts input files that describe the product BoM by using a specific XML-based format (eXtensible Markup Language), developed in the context of the G.EN.ESI project.

The second module is the *3D Viewer*, used by engineers to navigate the 3D CAD model of the product (in the case of importing a 3D geometry). It allows engineers to evaluate aspects such as the accessibility and the connections among components, which are applied during the disassemblability analysis. LeanDfD is able to highlight, view/hide and explode the components/sub-assemblies to facilitate the analysis.

The third module, called the *Product Disassemblability Module*, is the core of the tool since it evaluates the product disassemblability. Connected to the *Liaison DB*, it consists of three sub-modules. The first one, *Precedence Definer*, allows the engineer to define the list of disassembly levels and precedencies, following the methodology steps detailed in Section 4. The precedence is a consequence of a visual obstruction if physical liaisons are not present. Conversely, if the precedence is related to contact or assembly connections, then the *Liaison*

Definer module (the second sub-module) must be run to define the liaison properties (e.g., dimensions, weight, wear condition tools to remove it). The possibility of importing and viewing a 3D CAD model is an essential feature to facilitate the input phase, since most of the required information can be easily extrapolated by interoperating with the 3D geometry directly within the LeanDfD environment. Once all the precedencies and liaisons of the target components have been defined, the *Disassemblability Calculator* (the third sub-module) assesses all the feasible disassembly sequences and determines the best one, which guarantees the minimum time and/or cost, for each chosen target component.

The fourth module, called the *Product Recyclability Module*, is used to evaluate the product recyclability ratio, supporting designers in improving the product EoL performances. Connected to the *Material DB*, it inherits information from the previous module, in terms of the product BoM, materials of the components, liaisons and relative attributes, target components and disassembly sequences. The first sub-module, *Metal-plastic contamination definer*, permits the engineer to set additional information concerning the material contamination (e.g., glues and foams). Moreover, it also evaluates the partial or total compatibility between plastics and the presence of non-recyclable plastics (e.g., Polychloroprene). The second sub-module, *Critical component analyser*, supports engineers in improving the recyclability ratio of critical/target components, defined as components that have to be separated at the EoL for normative compliance. Through accessing the *Material DB*, the sub-module presents a list of alternative components, materials and assembly solutions, each one with pros and cons in terms of recyclability and cost. The third sub-module, *Recyclability calculator*, uses the data elaborated by the first sub-module to calculate the recyclability ratio for the entire product as well as for each component.

The last module of LeanDfD, *Export Interface*, generates a report (PDF file format – Portable Document Format) on the product disassemblability and recyclability. Product and design managers subsequently can analyse and store this report within the PDM and PLM systems. Moreover, the tool is able to export a G.EN.ESI compliant XML file for the management of the data calculated by LeanDfD with external software tools included in the G.EN.ESI platform.

5.3. Tool user interface

The LeanDfD main panel (Figure 15), based on the five modules described above, consists of the following elements:

- the *Toolbar*, with the main software functionalities such as 3D model import, product disassemblability and recyclability analysis, and result exporting;
- the *Product Structure window* (the left part in Figure 15), which contains the product BoM with the relative disassemblability times/costs and recyclability indices for the analysed components. The BoM viewer is an alternative to the 3D model viewer (hidden in the screenshot of Figure 15).
- The *Product Assessment window* (the right part in Figure 15), which reports the described disassembly/recyclability indices and the values calculated by LeanDfD. The results, highlighted in both numerical and graphical formats, refer to the overall product or to specific target components.

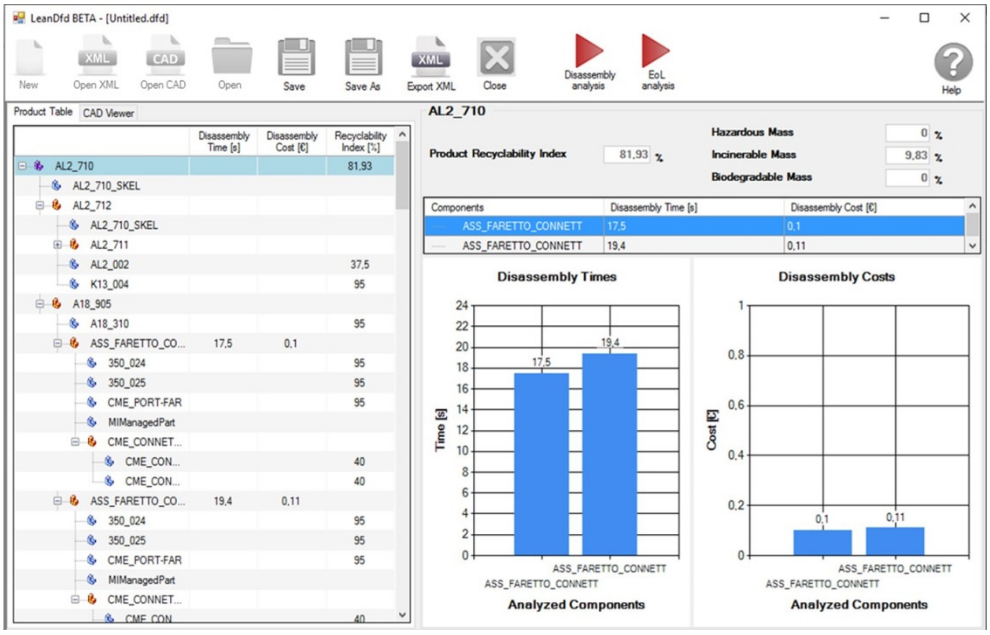


Figure 15. *LeanDfD main panel.*

5.4. Tool databases

The LeanDfD assessment modules (*Product Disassemblability Module* and *Product Recyclability Module*) are linked with two different databases (both developed using *Microsoft Access 2007*).

The first database, *Liaison DB (*Figure 16), contains data required for the calculation of the product disassemblability (e.g., liaisons, disassembly times, tools required) and consists of the following tables:.

- *Liaison Classes*: it stores all the liaison classes (e.g., Threaded, Shaft-Hole, Rapid joint);
- *Liaison Types*: it stores the liaison types (e.g., screw, nut and threaded rod for the threaded Liaison Class) that typically characterize a

product. For each *Liaison Type*, which belongs to a specific Liaison Class, there is a relative disassembly time in standard conditions;

- *Liaison Type Properties*: it contains the properties that are relative only to a specific *Liaison Type* and are required to consider the real liaison conditions (e.g., screw length, diameter, head type and unscrewing tool for the Screw Liaison Type);
- *Liaison Type Factors*: it contains the corrective factors for each *Liaison Type Property*. This factor is multiplied by the standard disassembly time to obtain the effective disassembly time;
- *Liaison Class Properties*: it contains the general liaison conditions, which are independent of the Liaison Type and valid for each *Liaison Class* (e.g., wear, length, diameter, etc. for the Shaft – Hole Liaison Class);
- *Liaison Class Factors*: it contains the corrective factors for each *Liaison Class Property* (e.g., for the wear property, typical factors are 1 for not worn, 1.3 for partially worn, and 2 for completely worn). This factor is multiplied by the standard disassembly time to obtain the effective disassembly time;
- *Tools*: it contains the list of tools used to disassemble the liaisons. Each tool is associated with a particular *Liaison Type* or *Liaison Class* and has an hourly cost used for the disassembly cost calculation.

The second database, *Material DB* (Figure 17), contains data for the calculation of the product recyclability ratios (e.g., material properties, material compatibility matrices, etc.) and consists of the following tables:

- *Material Classes*: it stores the materials classes (e.g., Aluminium, Copper, Carbon Steel, Thermoplastic Polymers);
- *Materials*: it stores the materials, for each class, and relative attributes (e.g., possibility to recycle, heat of combustion, possibility to dismantle

in a landfill), as well as a set of indices for the recyclability ratio calculation (material degradation and disassembly index);

- *Plastic Compatibility*: it stores a matrix about the compatibility between different plastics to determine if two or more plastics can be recycled together (compatible polymers) or not (partially compatible polymers or incompatible polymers);
- *Plastic Contamination Index*: it stores the Contamination Index (from 0 to 1) relative to compatible (1), partially compatible (0.5) or incompatible plastics (0) that is used to calculate the recyclability ratio. The contamination is defined between two specific materials for the wide variety of plastics and great variation in recyclability ratios;
- *Metal Contamination Index*: it stores the Contamination Index (from 0 to 1) to characterize the different possible metal contaminations of the product. The contamination is defined between a specific material and a class of materials;
- *Product Families*: it stores the product families (e.g., household appliances);
- *Product Typologies*: it stores the product typologies relative to a specific *Product Family* (e.g., cooker hoods, washing machines);
- *Critical Components*: it stores the critical components for each *Product Typology* (e.g., electric motors, capacitors). Each critical component is characterized with a document relative to the EoL information.

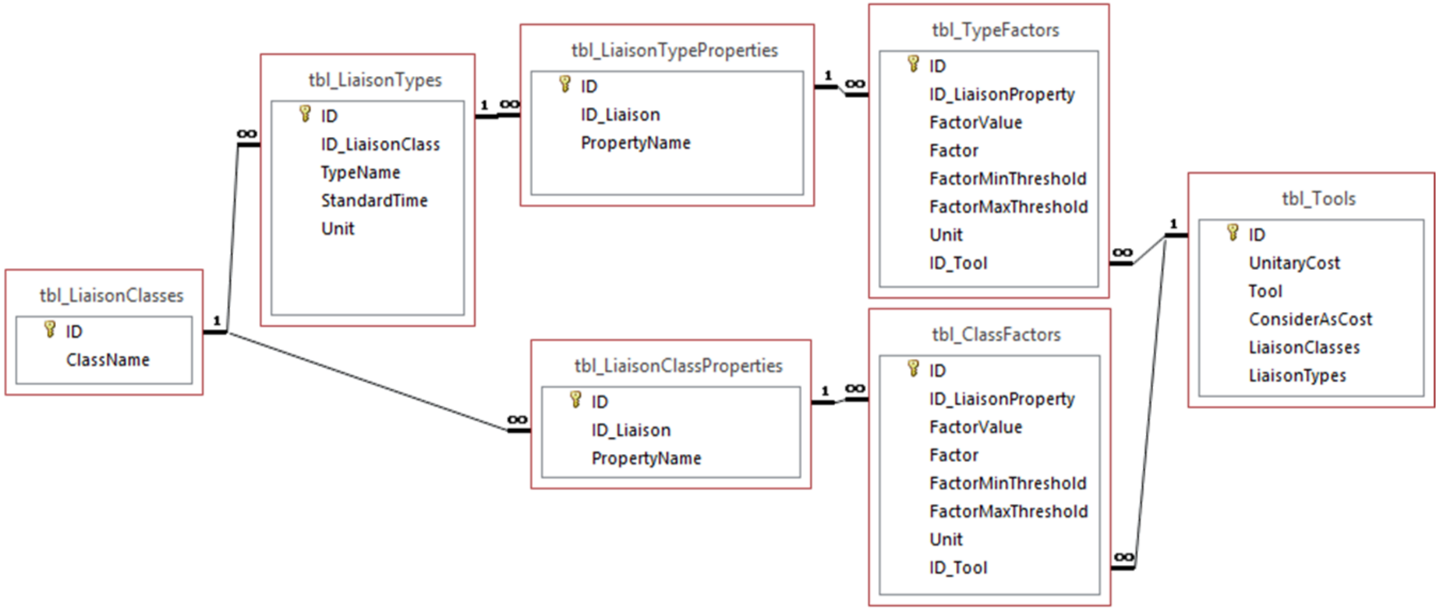


Figure 16. *Liaison DB structure.*

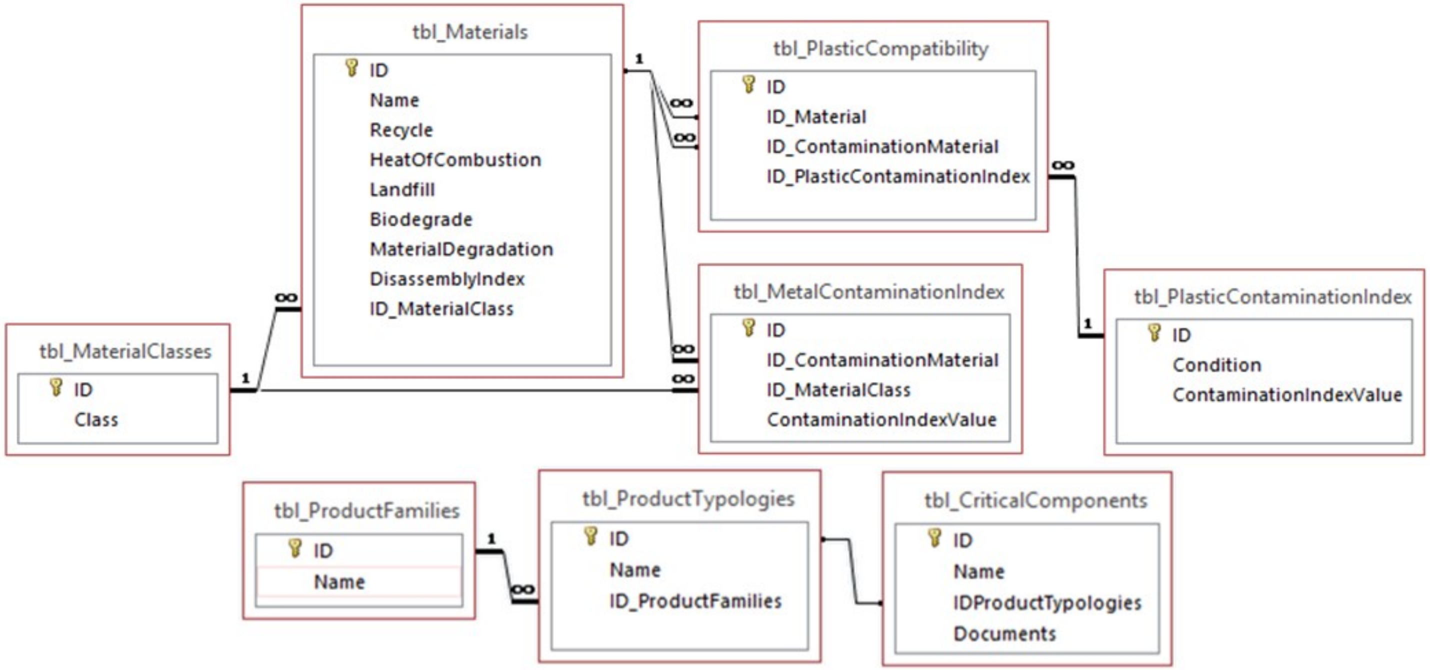


Figure 17. *Material DB structure.*

5.5. Tool data structure

For a better understanding of the system and the data required as inputs and available as outputs, the LeanDfD file data structure is hereunder described (Figure 18). The main entity, which contains all the information related to a disassemblability/recyclability analysis carried out using LeanDfD, is the *Document*. It consists of a *Product Structure*, a hierarchical structure comprising a list of *Components*, which describes the product BoM. After the CAD model is imported, the *Component* contains only the information related to the *Material* (with relative compatibility values read from the *Material DB*), *3D Model* and *Mass*. During the use of LeanDfD, this entity is enriched with information about *Liaisons*, *Precedence Components*, *EoL indices* (retrieved from the *Material DB*) and the *Recyclability Index*. A *Liaison* consists of a list of *Tools*, used to remove the liaison itself, *Liaison Properties*, to characterize the specific liaison under analysis, *Liaison Classes*, to specify the class to which the analysed liaison belongs to, *Connected Components*, to store the couple of components joint by the analysed liaison, a *Standard Disassembly Time*, to store the disassembly time in standard condition used in the calculations and a *Quantity*, to specify the number of liaisons of a particular typology.

After the completion of the LeanDfD analysis, each *Document* also contains information about the overall *Product Recyclability Ratio* (calculated by the *Product Recyclability Module*) and the list of *Feasible Disassembly Sequences* (calculated by the *Product Disassemblability Module*). The latter consists of a list of Disassembly *Operations*, comprising a list of *Removed Components*, the needed *Tools* and a *Time* and a *Cost*.

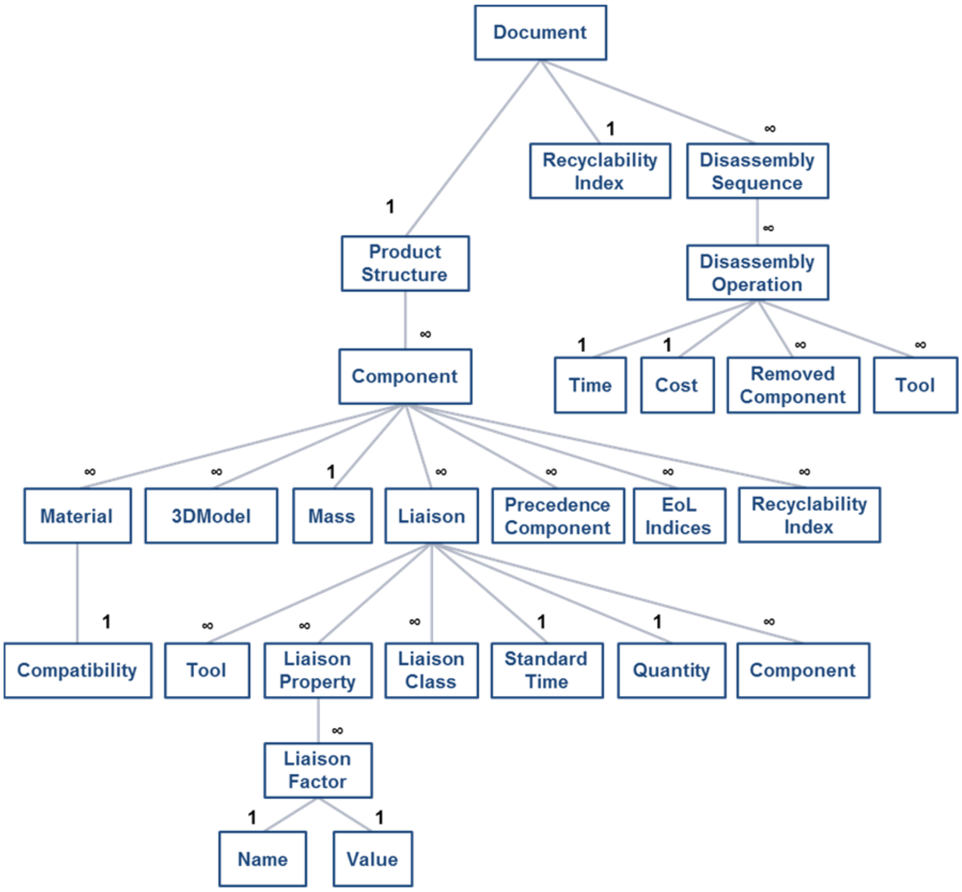


Figure 18. *Internal LeanDfD data structure.*

5.6. Tool input/output data

LeanDfD has import/export functionalities to exchange data with the external systems commonly used by engineers during the different phases of the product design process. The following tables explain the data required as inputs (Table 6) and the data available as outputs (Table 7), with relative data types. Table 6 also contains the data source (3D CAD model or User) of each input data.

Table 6. *Input data with types and sources.*

Data	Data type	Source
Bill of Material and 3D Model	Product Structure	3D CAD model
Material for each component	String	3D CAD model
Mass for each component	Numeric	3D CAD model
Contamination of materials (coatings, adhesives, etc.)	List (of Materials)	3D CAD model
Target components	List (of Components)	User
Disassembly levels	List (of Integers)	User
Precedence between components/sub-assemblies	List (of Components)	User
Liaisons between components/sub-assemblies	List (of Liaisons)	User
Properties of each liaison	List (of Liaison Properties)	User

Table 7. *Output data with types.*

Data	Data Type
Disassembly cost for each target component/sub-assembly	Numeric
Disassembly time for each target component/sub-assembly	Numeric
Feasible disassembly sequences for each target component/sub-assembly	List (of Disassembly Sequences)
Recyclability rate for each component	Numeric
Recyclability rate for the entire product	Numeric
Material EoL properties	List (of Materials)
Critical component EoL documentation	List (of Documents)

5.7. Tool workflow

Figure 19 presents the design framework and the general workflow illustrating how the proposed tool can be used to support designers in improving the current product under development.

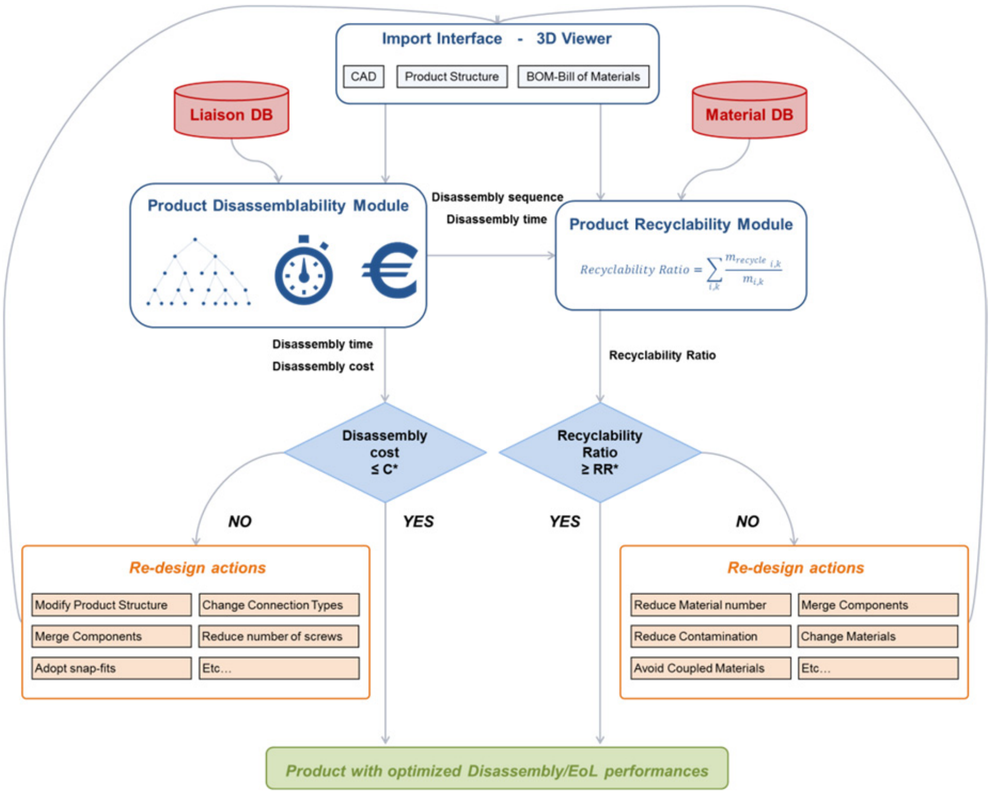


Figure 19. *General framework of the design method.*

The starting input data are the product virtual models (e.g., BoM and CAD models), which can be imported through the *Import Interface* and visualized using the *3D Viewer* integrated within the LeanDfD tool. Taken together, these virtual representations contain all the needed information to realize the assessments. By using the *Product Disassemblability Module* it is possible to calculate the feasible disassembly sequences and consequently to derive the best one in terms of the disassembly time and/or disassembly cost (C). In this phase, data about the standard disassembly times, corrective factors and unitary costs, stored within the *Liaison DB*, are needed to estimate the effective disassembly time of each liaison and each feasible disassembly sequence. The calculated disassemblability metrics and the material properties (e.g., Material Degradation Index) stored within the *Material DB* are used by the *Product Recyclability Module* for the assessment of the recyclability ratio (*RR*).

After the assessment phase, a decision on how to proceed must be made, defining target values (*C** and/or *RR**) that constitute the final objectives to reach through the redesign activity. The definition of these thresholds strictly depends on numerous aspects: (i) the characteristics of the product/component under analysis (e.g., value of component), (ii) the company strategy (e.g., interest in closed-loop scenarios, environmental objectives), (iii) cost-benefit analyses of the different EoL scenarios and (iv) normative compliance. For example, if a company is interested in implementing a remanufacturing business model, the target value C* could be fixed equal to the maximum disassembly cost that guarantees an economic benefit for this EoL scenario. Another example can be the threshold imposed by the normative EoL (e.g., WEEE or ELV) to fix the value of the RR*.

Once the target values are univocally established, the general strategy should consist in improving product features to minimize the disassembly time and cost and/or to maximize the potential recyclability ratio. In general, different situations can arise, and each is driven by different reasons. Table 8 illustrates the possible conditions deriving from the disassemblability and recyclability analyses, together with general redesign suggestions. An iterative process of redesign and checking is generally needed to finally reach the desired condition and obtain a product with optimized disassembly/EoL performances.

__Table 8.__ Redesign actions based on disassemblability and recyclability analyses.

Condition	Description	Results interpretation	Redesign suggestions
C > C*	The product under analysis does not reach the expected disassemblability performance	The disassembly sequences have a high number of operations. The issue is related to the product architecture and in particular to the positions of the target components	Modify the product structure
			Improve the accessibility of the target components
			Position target components in the external layers of the product
			Reduce the overall number of components
		Specific disassembly time for a particular operation is too long. The issue is related to the typologies of liaisons used to assemble the components.	Reduce the number of threaded liaisons
			Standardize screw typologies to reduce changes in disassembly tools
			Adopt snap-fits, particularly in the external parts of the product
			Reduce the number of same liaison typologies collected in a unique connection
RR < RR*	The product under analysis does not reach the expected recyclability performance	The contamination of certain components or materials is high.	Avoid the use of glues and adhesives to couple heterogeneous materials
			Avoid material contaminations such as varnishes

Condition	Description	Results interpretation	Redesign suggestions
		The materials used are not easy to separate and recycle at the EoL.	Adopt materials with a higher potential recyclability ratio
			Reduce the material variety
			Avoid the use of incompatible or partially compatible plastics
$C \leq C^*$	The product is compliant with the company's disassemblability targets	-	-
$RR \geq RR^*$	The product is compliant with the company's recyclability targets	-	-

6. DK: A Knowledge-Based methodology to improve product EoL performances

The proposed Target disassembly methodology and LeanDfD tool are mainly focused on supporting the identification of product criticalities related to EoL. Suggestions provided in the previous Table 8 are general indications on how to change product features in order to improve disassemblability of specific target components and/or the quantity of potential recyclable mass at the EoL. On one hand, this kind of suggestions have the advantage to be applicable in a large set of cases (e.g., different products, different criticalities, etc.). On the other hand, they are too general to effectively guide the redesign phase with the aim to solve specific problems.

For these reasons, this section presents a methodology to elicit, collect and classify knowledge coming from disassembly and EoL management activities. The final objective is to formalize it in specific design suggestions to be used during the design phase to improve product performances and preliminarily avoid disassembly and EoL issues

6.1. General framework

Generally, the manual disassembly of target components (see definition in Section 4) is crucial to establish the cost effectiveness of the EoL scenarios (reuse, remanufacturing and recycling) and the relative feasibility. Complex and time-consuming manual disassembly processes risk to reduce the percentage of components with a closed-loop lifecycle. Moreover, dismantlers are usually passive actors, subjected to choices made by other stakeholders (in particular designers). The gap between *Design Departments* and *Disassembly Plants* is dependent by the physical distance, but also by the temporal time lapse from the product design to the product EoL (product lifecycle). Disassembly and industrial waste treatment plants have a large knowledge and a huge quantity of data coming from experience. However, currently, the knowledge is not managed in structured way and particularly it remains enclosed within the disassembly plant boundary.

To overcome this lack, a design for disassembly approach, based on *Disassembly Knowledge (DK)*, is presented (Figure 20).

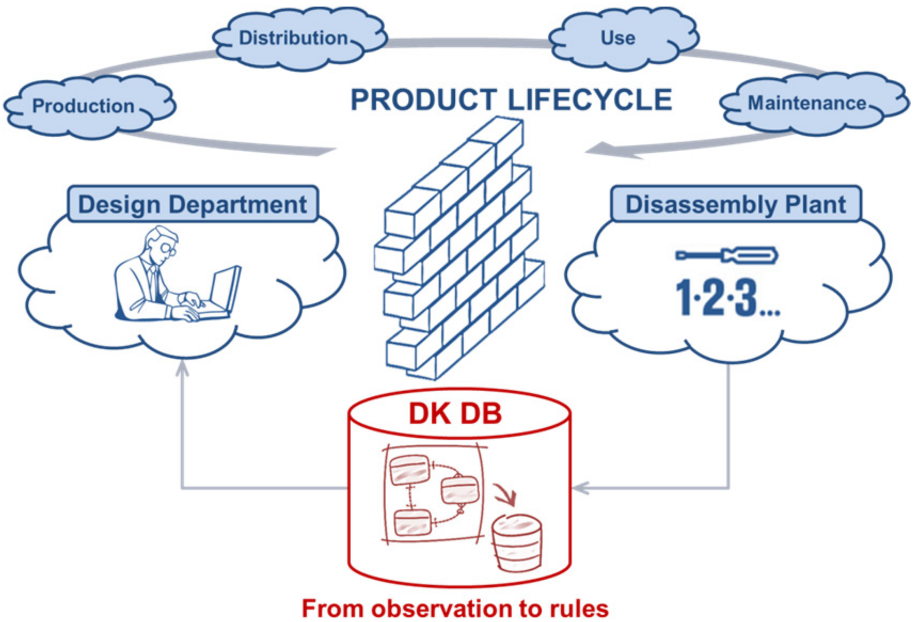


Figure 20. *General framework of the Disassembly Knowledge (DK) approach.*

The goal of the proposed methodology is to collect the knowledge, both positive and negative, coming from activities of the dismantling, remanufacturing and maintenance centres, and reuse it to create a repository for the Disassembly Knowledge management.

6.2. Methodology description

The general idea within this work is, firstly, to collect the knowledge of disassembly plants in a structured way and, secondly, to assemble a list of rules and guidelines for designers and engineers. This knowledge aims to support designers and engineers in the product development phase for the reduction of disassembly time and cost for both EoL and maintenance operations.

The DK repository has the purpose to support the disassembly knowledge management, in particular involving two main different end-users:

- operators at dismantling plants for the optimization of the de-manufacturing operations of industrial products;
- designers and engineers at design departments, involved in the design process of more sustainable products and goods.

The workflow adopted for the development of this repository is based on three main steps, as depicted in the following Figure 21. It starts with a *Classification of products* and relative standard components and parts. The key step is represented by the *Analysis of the observed disassembly problems*. Finally, the last step consists in the *Creation of the DK DB* before its application in the context of the design process. Full details on the three methodology steps are described in the following sub-sections.

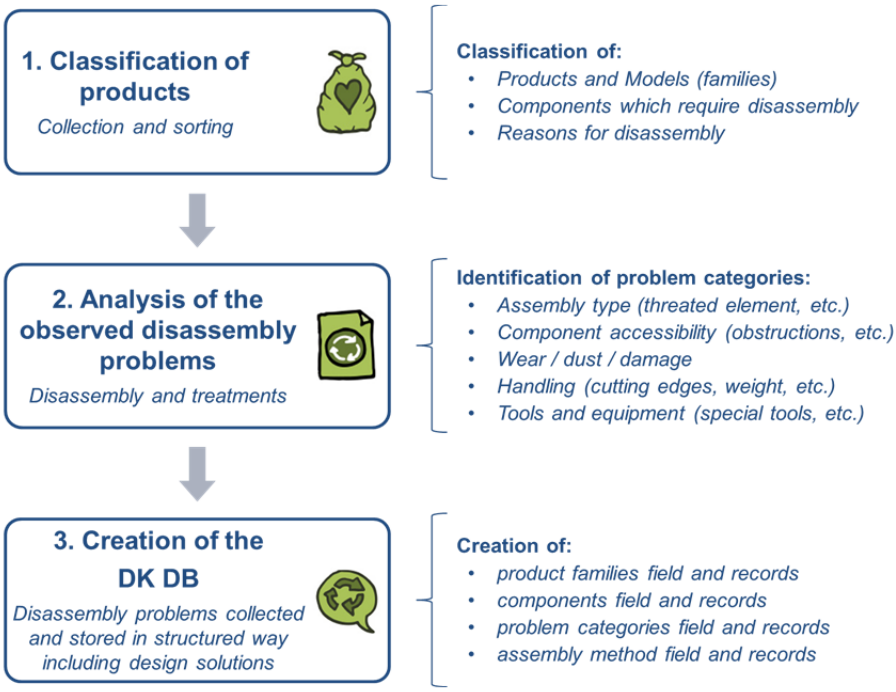


Figure 21. *Workflow for the DK repository building.*

6.2.1. 1st step: Classification of products

Considering the large variety of industrial products and models treated and disassembled at the different dismantling plants, the aim of this 1st step is the classification of products and goods. This means to group products in families, based on the EoL treatment to which they are subjected. Different product families have been identified, as for example: EEE, vehicle, industrial machinery, medical equipment, furniture, etc.

Each *Product family* contains a list of *Products*, and *Models* are the sub-classes of each *Product*. For example, car is a model of the product called road vehicles; road vehicles is a specific product class of the vehicle family. The following Figure 22 contains some example of the classified products and families.

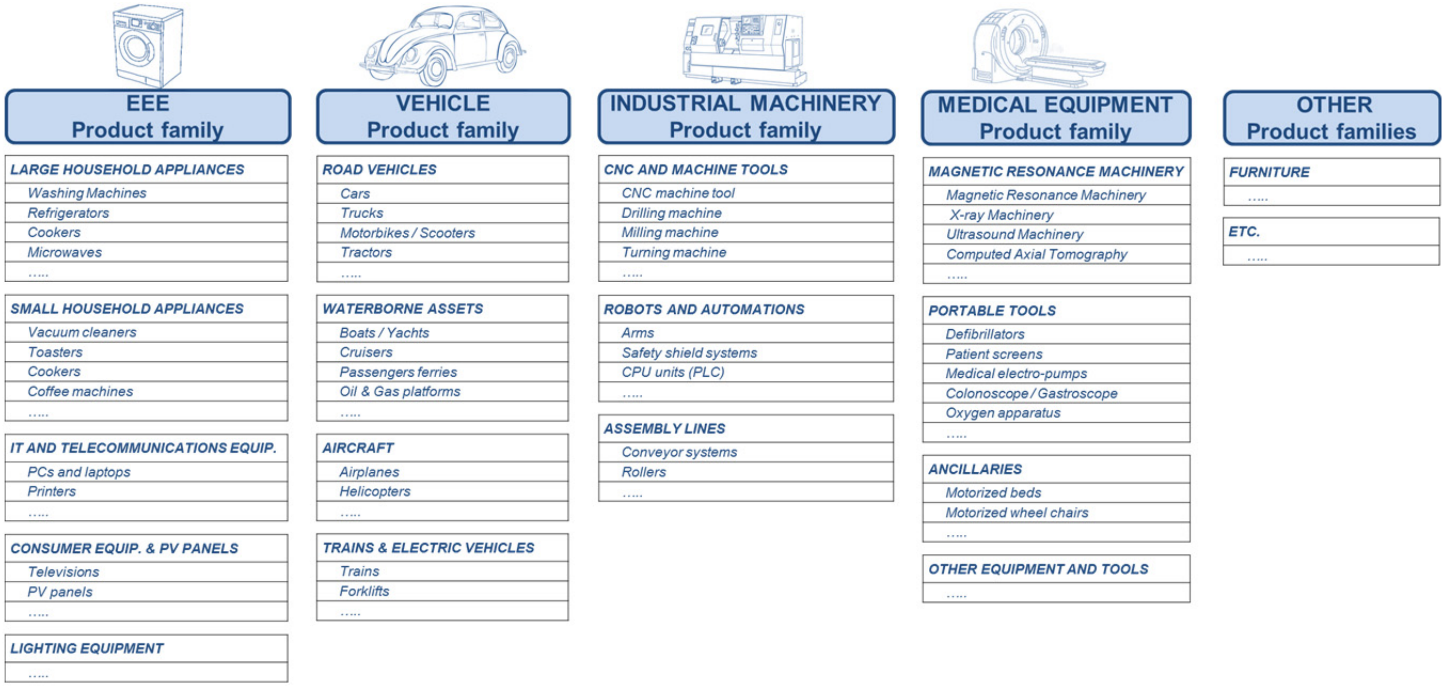
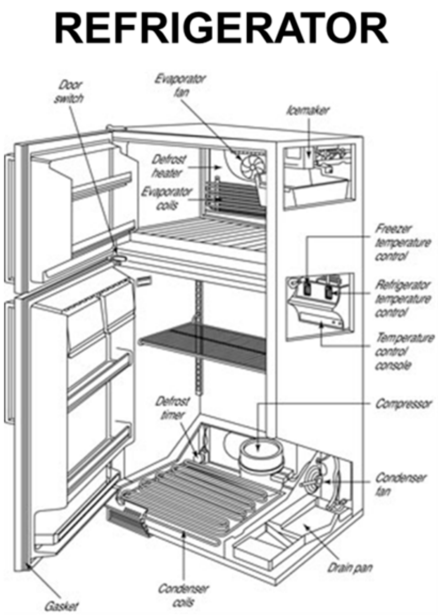


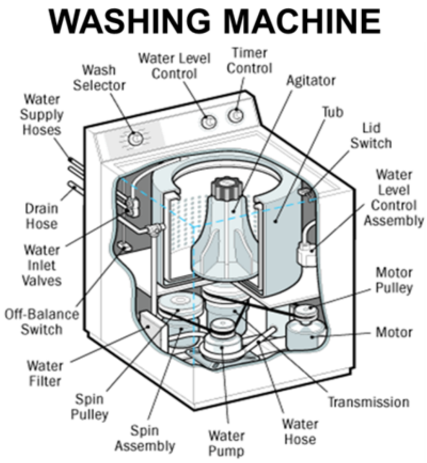
Figure 22. *Examples of classified products.*

This step also includes the classification of the main components, for each product (or product family), which require selective and non-destructive disassembly operations. As explained in Section 4, these components, called *Target Components*, are important during maintenance or at the EoL for different reasons (e.g., compliance with legislation/directives, valuable materials or parts, etc.). Most of the intrinsic knowledge of dismantling plants are relative to these components, thus their classification is essential to focus the successive phases of knowledge gathering (2nd step) and organization (3rd step). The following Figure 23 and Figure 24 report two representative examples of the classification carried out in the context of the EEE product family. Potential target components, which it is possible to find within a standard refrigerator and a standard washing machine are reported, together with the reasons that justify the need of a selective non-destructive disassembly.



Component	Disassembly Reason
Compressor	WEEE
Lamps	WEEE
PCB	WEEE
Display	WEEE
Electric motor (evaporator fan)	Remanufacturing
Electric motor (condenser fan)	Remanufacturing
Electric motor (no frost fan)	Remanufacturing
Thermostat	WEEE
Electric wires	WEEE
Evaporator	Remanufacturing
Condenser	Remanufacturing
Compressor relay	WEEE
Run capacitor	RoHS
Power transformer	WEEE
Switches	WEEE

Figure 23. *Potential target components for a refrigerator.*



Component	Disassembly Reason
Capacitor	RoHS
Electric motor (water pump)	WEEE
Electric motor (driver motor)	WEEE
Electric motor (drain pump)	WEEE
Electric motor (detergents & dispenser)	WEEE
PCB	WEEE
Display	WEEE
Electric wires	WEEE
Drum	Remanufacturing
Heating element	Remanufacturing
Power transformer	WEEE
Switches	WEEE

Figure 24. *Potential target components for a washing machine.*

6.2.2. 2nd step: Analysis of disassembly/EoL problems

This step essentially consists in the observation of disassembly, maintenance, remanufacturing and EoL activities, typical for each product or product family of interest. The goal is to classify issues and positive feedbacks observed during de-manufacturing operations.

The principal data collection methods are surveys, interviews of the involved operators and direct observation of their activities. This latter is recognized as the most effective mean for data collection, but direct observations need to be stored as video recordings to be really useful, since relevant details can be lost by only using instantaneous observations (Taylor-Powell and Steele, 1996). By using spreadsheets and/or video annotation software, useful data (e.g., duration of each operation, needs of special tools, difficulties on the disassembly or extraction operation, etc.) can be annotated and reused in the successive phase (3rd step) for the formalization of specific design guidelines (Movilla et al., 2016).

Regarding disassembly problems, for example, they can be originated from different aspects. An overall classification of disassembly problem categories is proposed below:

- assembly method (e.g., threaded element, welding, etc.);
- component accessibility (e.g., physical obstruction, limited accessibility, visual limitation, etc.);
- wear, dust and damage (e.g., rust formation, oil contamination, dust accumulation, etc.);
- handling (e.g., cutting edges, small parts, heavy parts, etc.);
- need of special tools and equipment (e.g., use of special equipment developed for the item disassembly purpose, etc.)
- material separation (e.g., necessity to separate different materials for recycling purposes)

Items in each category must be referred to the product family and the target component in which have been observed. Furthermore, each item of this classification has to be linked with:

- the materials involved;
- the adopted solution at the dismantling plant;
- the overall product condition (wear, dust, oil, etc.).

In this way, a comprehensive picture of the disassembly and EoL issues will be available as a baseline to prepare the design guidelines to solve each specific situation. More than one problem can be retrieved in this step and more than one solution can be adopted to solve them. The data collection should be able to take into account these relations and links.

6.2.3. 3rd step: Creation of the DK Database

The last step of the proposed workflow, concerns the definition of the repository (DK DB), for the storage of the knowledge (positive and negative), gathered in the previous steps. The best and worst design practices from the disassembly and EoL points of view are identified. Best practices are those ones that allow operators to carry out the disassembly operations rapidly. Worst practices, instead, are those ones that require high time, the use of special tools, etc. and thus should be avoided. The observation of disassembly and EoL operations allows correlating the design practices with products, components and assembly typologies. These are useful strategies to suggest to stakeholders involved in the design process, in order to optimize the product EoL performances.

The DK DB is organized in six main tables:

- Product family;
- Product;
- Target component;
- Disassembly reason;
- Observed disassembly problem;
- Suggestion (solution).

The overall structure of the repository has been created as broad as possible, in a way to store data related to different products and product families. The final objective is to define a common structure and, subsequently, to customize it on the basis of the product family features. In this way, designers can easily retrieve detailed information (using smart filtering systems) for the right development of specific target components and product structures. Furthermore, maintenance and EoL operators, who is interested in the de-manufacturing time reduction, can understand in which product each target component is used and which kind of assembly connections are involved.

The repository has been conceived to allow analysing the disassembly from different perspectives. The most general perspective is to consider the product as a whole and to analyse the general disassembly risks linked, for example, to standard EoL treatments and to regulations. General DfD guidelines help engineers in the definition of the product structure, the overall product architecture, the layout of product modules, the materials, the assembly methods and the components/materials which needs to be removed before final treatment.

Another perspective is the analysis of disassembly risks linked to the development of a specific component. In this case, the design rules are more detailed, specific and valid only for the analysed component. Specific component DfD guidelines support engineers and designers to avoid the use of forbidden materials and to choose the best assembly methods which guarantee a determined disassembly time. Furthermore, useful information about the specific position and layout of the component within the product can be highlighted, such as the rules to make easy the handling operations.

Another possibility is to shift the viewpoint from the component and focus on assembly methods and typologies (e.g., snap-fits, threated elements, welding, etc.). In this case, the DfD rules are valid both for the specific component and for all the parts which are assembled by using those assembly methods. For example, considering the threaded elements, it is possible to underline in which components threaded elements are commonly used, which kind of threaded elements are involved (e.g., screw, nut, bolt, etc.), together with drawbacks and advantages of each assembly type. Furthermore, considering that threaded elements are widely used, some useful information about the same assembly method can be retrieved from other products or product families.

An example of the DK DB structure is presented in Figure 25.

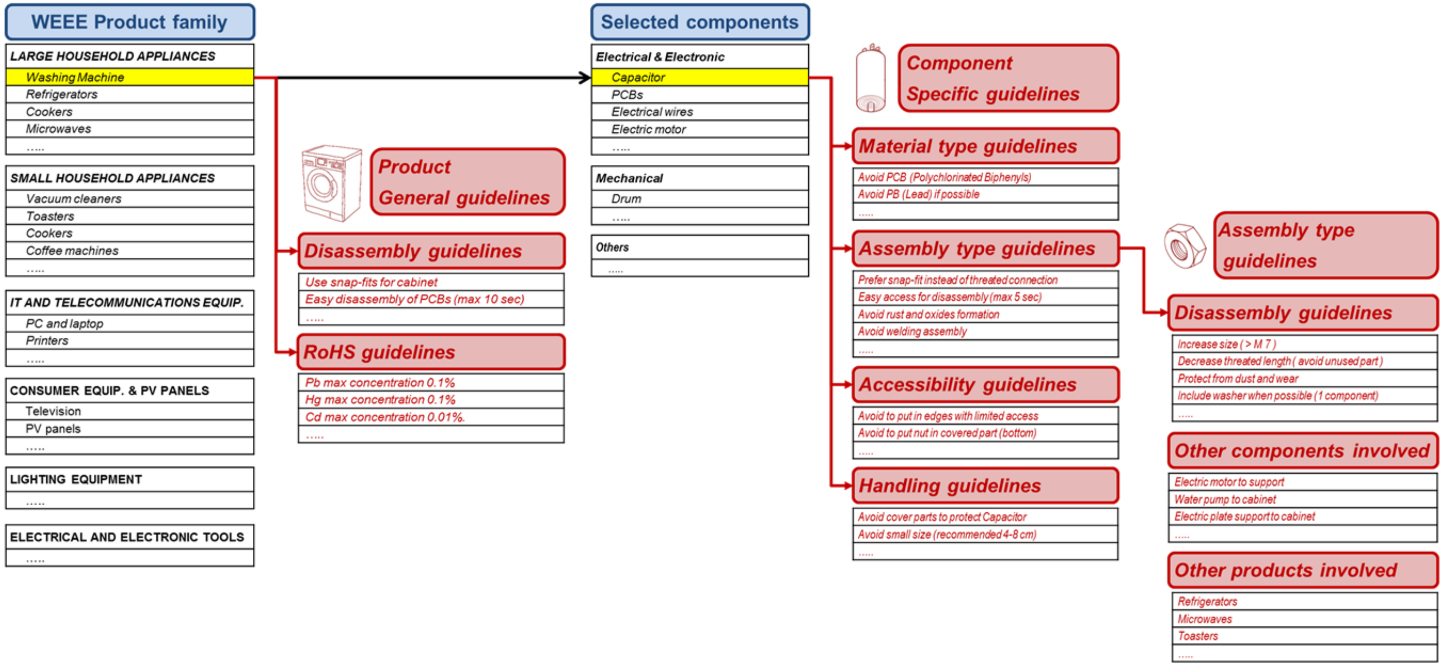


Figure 25. *Example of the structure of the DK DB for the Product family Washing Machine and the Component Capacitor.*

7. The EoL platform: A collaborative environment to “close the gap” between lifecycle stakeholders

Product lifecycle management is a responsibility shared between different stakeholders that collaborate to conceive and realize a product and successively manage its life. End of Life is the last phase, but it is strongly influenced by all the other phases (see Section 3 for details). An active collaboration between all the involved stakeholders is a key prerequisite to guarantee an efficient EoL management. The solution could be the creation of a shared environment where different active actors can interact in an effective way.

This section aims to define the features and functionalities of a *Collaborative EoL Platform* to favour the collaboration between different subjects. The final objective is to provide a mean for the practical implementation of the proposed EoL-oriented framework.

7.1. General idea

“Close the loop” for products means to “close the gap” between manufacturers and the other stakeholders involved in the product life. The idea of this work, illustrated in Figure 26, is to consider not only classical material flows (grey arrows), but also additional flows of information and materials (red dotted arrows), collected and shared through the implementation of the proposed platform.

Figure 26. *General idea of the Collaborative EoL platform.*

In general, there is a direct relationship and a flow of materials between *Manufacturers* and *End Users*. An intermediary subject (not represented in Figure 26) often has an active role (i.e. distribution). Through this direct and/or indirect relationship, *New* products are provided to end users and the use phase begins.

During the product useful life, *End Users* could need ordinary or extraordinary maintenance to restore product functionalities or to extend the product lifetime (e.g., change of motor oil in a motor vehicle, change of broken components in a domestic appliance, updating of functionalities in an electronic product, etc.). *End Users* and *Service* providers could have the necessity to communicate and exchange *Used* products more than one time during the use phase. In addition, *Service* providers could need *New Components* from *Manufacturers* in order to maintain *Used* products and restore their functionalities.

When a product (or one of its components) is *Damaged* and cannot be restored or the maintenance is not economically convenient, it is sent to EoL stakeholders, as *Dismantlers*, which are in charge of EoL treatments (e.g., disassembly, material separation, landfilling), *Recyclers*, which recover second-life materials or even *Remanufacturers*, which treat the product or its components in order to be resold and reused. A direct exchange of materials between *End Users* or *Service providers* and *EoL stakeholders* take place at the end of the use phase.

These are the "traditional" direct and indirect relationships and exchange of materials and information among the different stakeholders that share the management of the product lifecycle. By using traditional relationships (grey arrows in Figure 26) only open-loop lifecycles are possible, since none arrows come back to *Manufacturers*. After the production phase, *Manufacturers* "bow out" from the product lifecycle and after the product selling they are generally not in charge of other phases.

To practically implement closed-loop lifecycles, some additional relationships are missing. The proposed Collaborative EoL Platform aims to overcome this basic lack by creating a virtual environment to guarantee a "continuous" connection between all the most important stakeholders.

7.2. Platform main users and functionalities

The proposed platform consists in a framework linking the different stakeholders, to favour an easy exchange of materials and useful information. This solution allows creating additional direct relationships between the main users of the platform (red dotted arrows in Figure 26):

- *End Users* can offer *Used* products;
- *Service* providers can offer *Damaged* products;
- *EoL stakeholders* can offer or take *EoL* products or components;
- *Manufacturers* can offer or take *Second-life* products or components.

By using traditional (grey arrows in Figure 26) and new (red dotted arrows in Figure 26) relationships, made possible by the implementation of the proposed Collaborative EoL Platform, both open and closed-loop lifecycles are possible, since all the stakeholders have an active role during the different phases of the product lifecycle. In this way, second-life materials, components or even entire products can come back to *Manufacturers* to be reused or remanufactured with potential cost savings and certain benefits for the environment.

First of all, the platform can be used as a public repository of EoL second-hand components/products. Each item has to be classified according to distinctive parameters, useful to describe its features and to allow an easy filtering of the database. All the user categories can access the platform to offer components/products or to search in the public database. This platform functionality essentially allows creating a marketplace of second-hand goods (e.g., used products, second-life components, EoL materials, etc.). The creation of this cloud-based environment for an industrial sector allows the implementation of closed-loop lifecycles, where the waste of a stakeholder (e.g., EoL consumer goods discarded by *End Users*) could become a precious resource for another involved stakeholder (e.g., EoL components recovered from EoL goods by *Manufacturers*).

Besides the sharing of components and products between stakeholders, the platform allow sharing useful information. This is the case of *Manufacturers* that want to make available specific information about the disassembly, maintenance or EoL of their products. This public functionality is completely compliant with the EPR concept and can be viewed as the lacking mean toward the full implementation of the European Directives about product EoL. For example, a disassembly manual can be shared through the proposed platform by EEE manufacturers, in order to be compliant with the basic principles of the WEEE directive (European Parliament and Council, 2012), which encourages to provide all the necessary information to favour easy disassembly and EoL management.

The proposed platform can be also used by *Manufacturers* to monitor the lifecycle of their products. In cases of product-service selling, where *Manufacturers* are directly in charge of maintenance and EoL of their products, this private functionality allows tracing all the essential information relative to a product. For example, the platform is able to store and share all the information relative to the scheduled maintenance or the necessary product substitution. In this way, *Manufacturers* and *End Users* can constantly collaborate to extend the product lifecycle and to guarantee an high quality service.

The Collaborative EoL Platform is also the mean to link stakeholders involved in the beginning of life with those ones strictly related to the product EoL, according to the proposed DK methodology, described in the previous Section 6. The DK Database, which stores positive and negative knowledge about disassembly, maintenance and EoL issues of products, can be integrated within the platform. In this way, *EoL stakeholders* can easily share their knowledge about EoL activities and *Manufacturers* can reuse this knowledge as DfD rules and guidelines to improve performances of their product. At the end, both the user categories will have advantages (e.g., possibility to shift toward product-service or remanufacturing business models, reduction of time to manage EoL, increase of recovered materials/components, standardization of EoL activities, etc.), without the need of a "physical" time-consuming collaboration.

Finally, *Manufacturers* can use the private resources of the platform to efficiently manage the EoL of its products. This useful functionality is provided by implementing a decision-making algorithm, able to quantitatively evaluate the most convenient EoL scenario for each second-hand product or component. On the basis of input data provided by private (e.g., information about BoMs, component typologies, component costs, process costs, company internal rules and strategies, etc.) and public (e.g., product or component spent life, estimated component residual life, etc.) stakeholders, this algorithm can be used to calculate costs and revenues of the different choices (e.g., disassembly, remanufacture, discard, landfilling, etc.) and, as a consequence, economic and environmental benefits. Therefore, *Manufacturers* are supported in the EoL management of products and components that come back at the EoL, with the final aim to minimize costs and environmental impacts of their products, by implementing, where possible, reuse and remanufacturing scenarios. It is clear that parameters and formulas to be used by this kind of algorithm are strictly dependent by the product typology or, at least, by the considered sector. Since it is not possible to define a general purpose decision-making algorithm, this section does not report any description. An example on how this platform functionality can be exploited is detailed in Section 9, in the context of the electronics EoL management case study.

7.3. Platform architecture and modules

The general architecture of the proposed platform is represented in the following Figure 27. It is composed by four main modules that implement the functionalities previously anticipated and by three databases that store all the needed data.

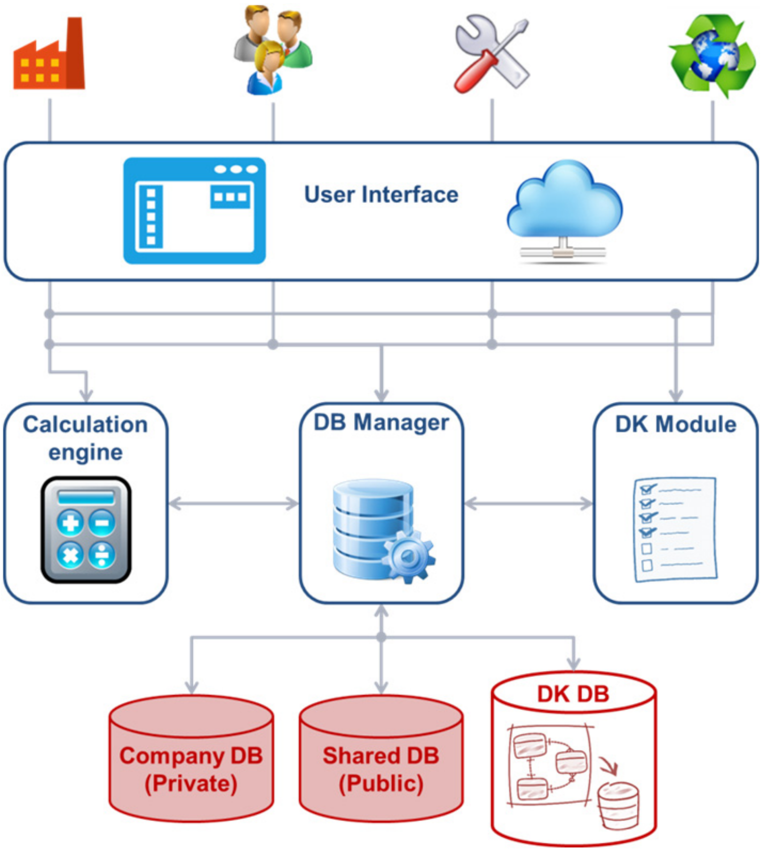


Figure 27. *Collaborative EoL Platform architecture.*

The first module is the *User Interface*, which allows accessing to all the platform functionalities. The web-based nature of the application guarantees an easy access to users located in different geographical areas. Since only authenticated user may gain access to the platform, personalized resources and functionalities (both public and private) are provided to each user typology.

The second module is the *DB Manager*, an interface between the users and the data stored within the platform repositories. It provides the functionalities to navigate and update the *Shared DB*, the *Company DB* and the *DK DB*. Filtering, intelligent searching, adding, removing, updating of public and private data are some examples of functionalities provided to the different platform users, on the basis of permissions set for each user typology.

The third module is the *DK Module* that essentially represents the implementation of the DK methodology detailed in Section 6. It is dedicated to *Manufacturers*, *Service providers* and *EoL stakeholders*, while *End Users* have not access to this platform functionality. On one hand, the *DK Module* can be used to update the information stored in the *DK DB*. This is the main task of *Service providers* and *EoL stakeholders*, which can share their knowledge about disassembly and EoL activities. On the other hand, *Manufacturers* can consult the stored knowledge during design activities, in order to prevent possible issues related to disassembly and EoL, with the aim to design more sustainable products and favour closed-loop lifecycles for a high percentage of components and materials.

The fourth module is the *Calculation engine*, which is the module running the decision-making algorithm (see Section 9 for a detailed example). This functionality is completely dedicated to *Manufacturers*, with the aim to support them in choosing the best and most sustainable EoL scenario for each component/product. On the basis of the information stored in the platform databases (in particular in the *Company DB*) and/or manually inserted by the platform user, the *Calculation engine* quantitatively evaluates the economic and environmental convenience of the different feasible scenarios. This module also operates in strict correlation with the *DB Manager* to update and modify the data and rules, stored in the private *Company DB*.

Concerning data storing, the first database is the *Shared DB (Public)* that stores all the used/damaged/EoL components or products shared by the involved stakeholders. These items have to be opportunely classified by using qualitative and quantitative parameters (e.g., component family, name, producer, spent life, estimated maximum life, etc.). This database can be accessed by all the platform users, to consult the stored information, in case of searching for components/products/information, or to add new items to share with another stakeholder or to offer them in the virtual marketplace.

Company DB (Private) maintains private information of *Manufacturers* (each manufacturer involved in the same network has its own database). The private data stored include: components/products which have to be used internally, private information about costs, specific internal rules and data, etc. These data are mainly used by the *Calculation engine* to perform the evaluations on the basis of the decision-making algorithm.

Finally, the *DK DB* stores the disassembly and EoL knowledge, directly coming from the involved *EoL stakeholders*, and organized according to the structure described in Section 6.

8. Application 1: Washing machine redesign

The proposed methodologies and tools have been tested in the context of product design oriented to improve EoL performances. In particular, the first case study regards a complete redesign of a commercial washing machine, with the final aim of avoiding disassemblability and EoL issues. The *LeanDfD tool* and the *DK methodology* have been provided to three typologies of stakeholders (dismantlers, expert designers, young designers) involved in this case study, to perform the different activities. On the basis of the indications obtained from physical and virtual analyses of the product, several redesign actions have been implemented to improve the product EoL performances and to validate the proposed methodologies and tools.

8.1. Product description and motivations

A washing machine has been selected to test the proposed methodology and tool, since this product represents a comprehensive and complete case study for different reasons.

First, this product is subjected to EoL regulations (European Parliament and Council, 2012), which impose an accurate separation of materials and components before proceeding with other destructive treatments. Capacitor, for instance, must be manually removed before the shredding phase and treated separately due to the potential presence of hazardous substances (e.g. lead or polychlorinated biphenyls). Printed Circuit Boards (PCBs) have to be separated to recover both hazardous substances and rare materials. These are strong incentives to optimize the product disassembly and dismantling in order to maximize the recovery rate.

Second, washing machines, as other household appliances, usually include components made from valuable materials, which can be recovered at the EoL to generate economic profits. This is the case, for example, of the drum fabricated using stainless steel, which has a higher value than the carbon steel commonly used to realize other washing machine components (e.g., external cabinet). For this reason, dismantlers are incentivized to disassembly and separate such kinds of materials and components before the product shredding.

Finally, a washing machine may need to be disassembled for maintenance or service reasons both during the useful life, to replace broken components, and at the EoL, to restore the product functionality in case of remanufacturing. Components that have a bigger chance to be replaced in a washing machine are the electric motor, the water pump or the heating element. These are opportunities to stimulate manufacturers to design products with improved EoL performances.

The analysed washing machine (Figure 28) is a consolidated model, produced for several years by an Italian firm and dedicated to the mid-market. This product is equipped with:

- an asynchronous single-phase motor (with capacitor) to guarantee the rotation of the drum;
- an electric pump for the discharge of water;
- a heating element to heat up the water;
- a simple electronic board for the control of the user interface and the main motor.

The external cabinet is fabricated from varnished carbon steel (AISI 1020), the front and top panels are respectively made from plastic (ABS – Acrylonitrile

Butadiene Styrene) and wood, and the drum is fabricated from stainless steel (AISI 430). The product under analysis had an estimated life of 15 years and had clear signs of rust both in the external cabinet and internal components (e.g., fasteners, etc.). This choice has been made in order to test the applicability and usefulness of the proposed methodologies and tools in realistic non-standard conditions.

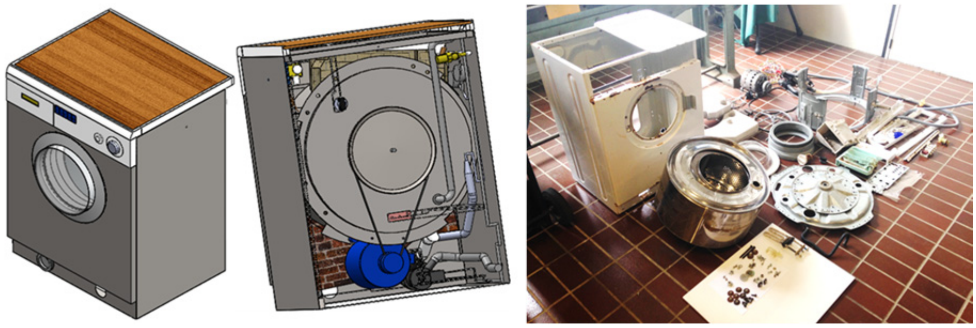


Figure 28. *Washing machine 3D model (left) and real disassembled product (right).*

8.2. Case study objectives and workflow

The general objective of this first case study is to verify the applicability, usefulness and reliability of the proposed methodologies and tools in supporting companies during the design of complex products, with the aim to obtain a new product version, easier to disassemble and to manage at EoL in comparison with the original version. Among the four methodologies and tools proposed in the context of this thesis, in this case study only the Target disassembly methodology, the LeanDfD tool and the DK methodology are used, while the experimentation of the Collaborative EoL Platform has been carried out in the context of the second case study, described in Section 9.

The specific objectives of the washing machine case study are:

- to demonstrate the ability of the Target disassembly methodology and LeanDfD tool in deriving the feasible and the best disassembly sequences for each chosen target component, starting from the product virtual models;
- to assess the disassemblability/recyclability performance of the original assembly model (recyclability ratio and disassembly cost) through the use of the LeanDfD tool;
- to verify the ability of the LeanDfD tool in identifying the product criticalities related to disassembly and EoL;
- to verify the ability of the DK methodology to gather and classify knowledge related to EoL treatments;
- to verify the usefulness of the LeanDfD tool and DK Database in supporting the redesign phase with the aim to improve the product disassemblability and EoL performances;
- to assess the consistency and the reliability of the estimated disassembly times in comparison with the measured ones.

To achieve all the aforementioned objectives, different activities were necessary and several stakeholders have been involved, as reported in Figure 29.

The *Product Disassembly* phase has been performed in collaboration with an Italian dismantling centre. The involvement of skilled operators is an essential feature of the proposed case study because it allowed guaranteeing the reliability of the validation activities. Only skilled operators have the sufficient experience to identify the effective disassembly issues due to the product characteristics. The involvement of not-skilled operators could introduce subjectivity and potentially lead to the definition of problems and difficulties due to the scarce experience. The operators had available a full-range of equipment (table, crane, electric screwdrivers, keys, hex keys, pliers, hammers, gloves, etc.) for the disassembly operations. Standard safety rules have been observed during the activities.

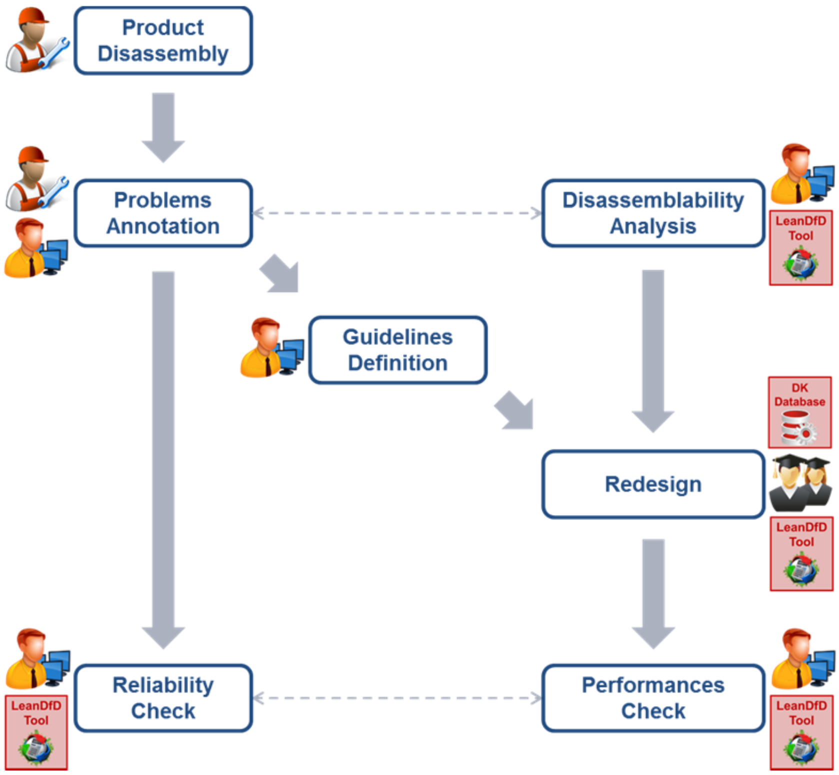


Figure 29. *Washing machine case study workflow.*

The *Problems Annotation* phase, together with the successive *Guidelines Definition*, have been performed in strict collaboration with the operators of the dismantling centre and the expert designers belonging to the manufacturing company. This choice has been made to guarantee that the positive and negative knowledge classified was correctly interpreted and that the defined design guidelines were effective and clear for the design team.

In parallel, a *Disassemblability Analysis* has been performed through the use of the Target disassembly methodology and LeanDfD tool, provided to expert designers of the manufacturing company. This step aims to discover the product criticalities and to verify if they are in line with the issues identified during the manual disassembly.

The *Redesign* phase, instead, has been performed in collaboration with non-expert stakeholders. Several groups of undergraduate students, enrolled in the last year of the Master of Science course in Mechanical Engineering, has been involved as young designers. They knew the basic rules of mechanical design as well as CAD tools, but they never followed courses about ecodesign, design for disassembly, design for EoL, etc.. The *DK Database* and the *LeanDfD tool* were provided to the young designers with the objective to configure a new product version with improved disassemblability and EoL performances. This was a preservative choice, which considered the worst scenario. In fact, if the design guidelines are effective with designers, that have no experience and that do not thoroughly know the product features, they can be considered definitively useful also for skilled designers with many years of experience.

Finally, the *Performances* of the new product version have been compared with those of the original design solution. Moreover, the *Reliability* of the analyses has been verified by comparing the estimated and measured disassembly times.

The following section describes all the activities in details.

8.3. Washing machine analysis and redesign

8.3.1. Disassemblability analysis

At first, five target components have been selected (1st step of the Target disassembly methodology) considering the specific purpose (Table 9):

- *Drum*: the constituent material of this component is stainless steel (AISI 430), thus it is convenient to separate it from the other carbon steel component before shredding.
- *Water pump*: it can be disassembled during the washing machine life for maintenance reasons or it can be recovered at EoL to remanufacture it and sell it as second-life component;
- *Electric motor*: it was selected as target component for legislation (WEEE), maintenance/service and also remanufacturing reasons;
- *Capacitor*: according to WEEE directive, it must be removed at EoL before proceeding with product dismantling or shredding, due to the potential presence of hazardous substances and materials (such as lead or polychlorinated biphenyl);
- *Electronic board*: it is a critical component identified by the WEEE directive.

Table 9. *Target components with the identified reasons for disassembly.*

	Reasons for disassembly			
Target Components	**Legislation**	**Maintenance**	**Remanufacturing**	**Material Recovery**
Drum				X
Water pump	X	X	X	
Electric motor	X	X	X	
Capacitor	X	X		
Electronic board	X			X

The *Virtual product model analysis* phase (2nd step of the Target disassembly methodology) was carried out to set *Precedencies, Disassembly levels and Liaisons between components* (3rd step of the Target disassembly methodology). The following Table 10 and Table 11 respectively illustrate the precedence relations (together with liaisons) defined to reach the Electric motor and the precedence matrix for the whole washing machine.

Table 10. *Precedence relations and liaisons needed to reach the Electric motor.*

Disassembly level	Component	Components with precedence relations	Joint components	Liaison Type
0	Back cover	-	Cabinet	6 Screws
	Top back cover	-	Cabinet	3 Screws
1	Wood panel	Cabinet Top back cover	Top guide DX	1 Guide
			Top guide SX	1 Guide
2	Top guide DX	Wood panel	Wood panel	1 Guide
			Cabinet	2 Screws
	Top guide SX	Wood panel	Wood panel	1 Guide
			Cabinet	2 Screws
	Concrete weight	Wood panel	Tank support	2 Screws
3	Top front cover	Top guide DX Top guide SX Concrete weight	Cabinet	2 Screws
			Control panel assembly	1 Snap-fit
4	Control panel assembly	Top front cover	Cabinet	3 Screws
			Top front cover	1 Snap-fit
5	Detergent box	Control panel assembly	Tank pipe	1 Pin
			Cabinet	3 Screws 1 Snap-fit 1 Pin
			Tank back cover assembly	1 Pin
	Electronic board assembly	Control panel assembly	Electric wires	30 Electric plugs
			Cabinet	6 Screws

Disassembly level	Component	Components with precedence relations	Joint components	Liaison Type
6	Electric wires	Detergent box Electronic board assembly	Tank back cover assembly	8 Electric plugs
			Electronic board assembly	30 Electric plugs
			Cabinet	13 Electric plugs 1 Pin
			Electric motor	5 Electric plugs
7	Cabinet	Electric wires	Top back cover	3 Screws
			Back cover	6 Screws
			Top guide SX	2 Screws
			Top guide DX	2 Screws
			Top front cover	2 Screws
			Control panel assembly	3 Screws
			Detergent box	3 Screws 1 Snap-fit 1Pin
			Electric wires	1 Snap-fit 1 Pin
			Tank support assembly	2 Pin 2 Snap-fit
			Tank	1 Snap-fit 1 Nut 1 Pin
			Electronic board assembly	6 Screws
8	Motor support	Cabinet	Electric motor	1 Nut

Disassembly level	Component	Components with precedence relations	Joint components	Liaison Type
9	Electric motor	Motor support	Motor support	1 Nut
			Tank support assembly	2 Screws
			Electric wires	5 Electric plugs
			Belt	1 Guide

Table 11. *Precedence matrix of the analysed washing machine.*

		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T		Disassembly depth
Tank pipe	**A**		1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	→	3
Top back cover	**B**	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	→	0
Motor support	**C**	0	1		0	1	1	0	0	1	1	0	1	0	1	1	1	1	0	1	1	→	12
Electric motor	**D**	0	1	1		1	1	0	0	1	1	0	1	0	1	1	1	1	0	1	1	→	13
Electric wires	**E**	0	1	0	0		1	0	0	0	1	0	1	0	1	1	1	1	0	1	1	→	10
Wood panel	**F**	0	1	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	1	→	2
Belt	**G**	0	1	1	0	1	1		0	1	1	0	1	0	1	1	1	1	0	1	1	→	13
Tank back cover	**H**	0	1	1	1	1	1	0		1	1	1	1	0	1	1	1	1	1	1	1	→	16
Cabinet	**I**	0	1	0	0	1	1	0	0		1	0	1	0	1	1	1	1	0	1	1	→	11
Top front cover	**J**	0	1	0	0	0	1	0	0	0		0	1	0	1	0	0	1	0	0	1	→	6
Tank support	**K**	0	1	1	1	1	1	0	0	1	1		1	0	1	1	1	1	0	1	1	→	14
Top guide DX	**L**	0	1	0	0	0	1	0	0	0	0	0		0	0	0	0	0	0	0	1	→	3
Tank + Drum	**M**	0	1	1	1	1	1	0	1	1	1	1	1		1	1	1	1	1	1	1	→	17
Top guide SX	**N**	0	1	0	0	0	1	0	0	0	0	0	0	0		0	0	0	0	0	1	→	3
Detergent box	**O**	0	1	0	0	0	1	0	0	0	1	0	1	0	1		1	1	0	0	1	→	8
Control panel assembly	**P**	0	1	0	0	0	1	0	0	0	1	0	1	0	1	0		1	0	0	1	→	7
Concrete weight	**Q**	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0		0	0	1	→	3
Pulley	**R**	0	1	1	1	1	1	0	0	1	1	0	1	0	1	1	1	1		1	1	→	14
Electronic board assembly	**S**	0	1	0	0	0	1	0	0	0	1	0	1	0	1	0	1	1	0		1	→	8
Back cover	**T**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		→	0

By using the LeanDfD tool, the evaluation of the disassemblability for the current design solution was not time-consuming. Due to the integration with the CAD systems, the user could import and visualize the product 3D model directly within the tool (Figure 30). The CAD viewer guided designers during the input of the needed information about precedencies and liaisons between components. The real conditions of the washing machine and related liaisons (e.g., dust and rust) have been considered by opportunely setting the liaison properties.

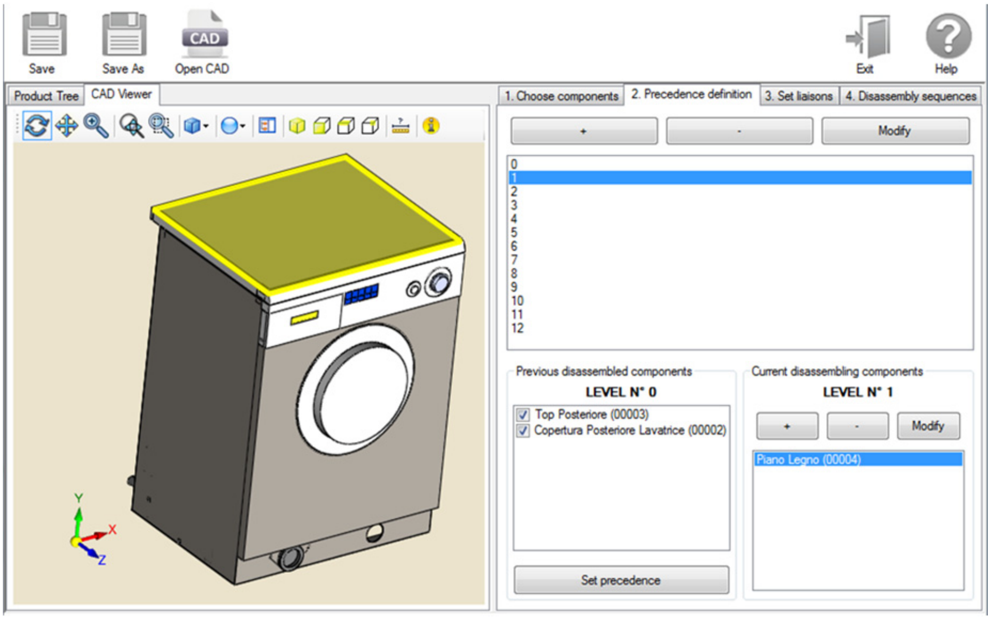


Figure 30. *LeanDfD user interface with the integrated 3D model viewer (washing machine case study).*

The definition of disassembly levels, the calculation of the precedence matrix, as well as the identification of liaison types allowed generating all the *Feasible disassembly sequences* for the five chosen target components (4th step of the Target disassembly methodology). After that, the *Best disassembly sequences* were derived by considering the disassembly paths which minimize the disassembly time, calculated on the basis of input information (Table 10 and Table 11) and data stored within the Liaison DB of the LeanDfD tool (5th step of the Target disassembly methodology). As highlighted before, since the analysed product is an EoL product, in some cases the conditions of liaisons at the moment of disassembly have been supposed different from the standard ones (e.g., rusted screws, oxidised electrical plugs, etc.). For this reason, corrective factors have been used to have a realistic estimation of the disassembly time. In addition, disassembly tools have been set for each liaison in order to estimate the disassembly costs.

Different results can be obtained with the use of the proposed Target disassembly methodology and LeanDfD tool. Firstly, the disassembly tree for each chosen target component (Figure 31) has been calculated by the use of LeanDfD. It allowed analysing the disassembly levels, the feasible disassembly sequences, the disassembly depth for each component (i.e. number of operations to perform) and clearly visualizing the connections to remove for each disassembly path.

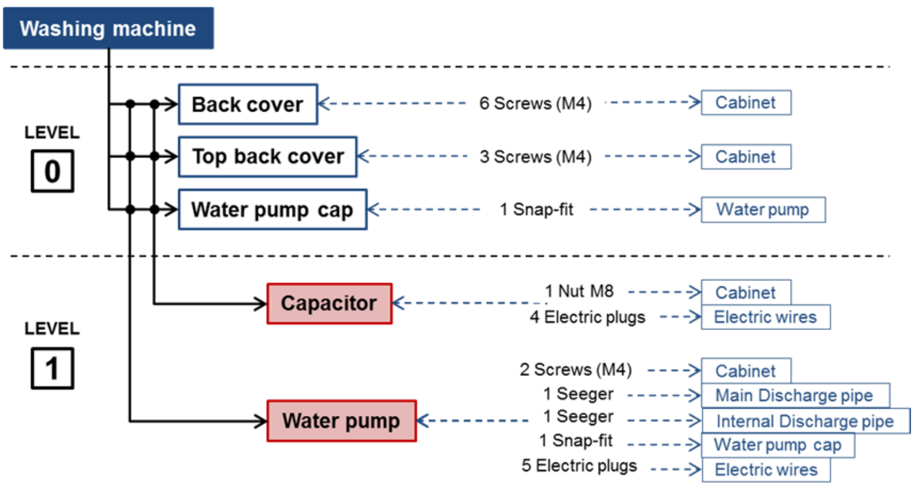


Figure 31. *Disassembly tree for the Capacitor and the Water Pump calculated by LeanDfD.*

Secondly, a cumulative disassembly time graph was automatically derived, considering the feasible disassembly sequences of each target component. The graph enables the univocal identification of the disassembly criticalities in terms of time-consuming operations, number of components to be disassembled, complex product structures and other parameters. Figure 32 reports the cumulative disassembly time graph calculated by LeanDfD for the electric motor. By observing the graph simple and rapid conclusions can be derived. For example, in the analysed case, the electric motor disassembly time (416,4 seconds) cannot be considered acceptable for maintenance reasons.

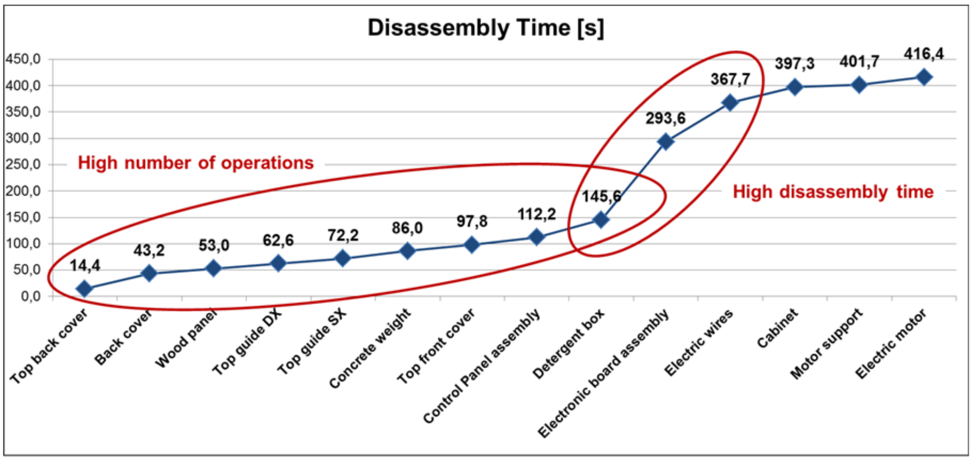


Figure 32. *Cumulative disassembly time for the electric motor calculated by using the LeanDfD tool.*

The following Table 12 reports the details relative to the best disassembly sequence estimated for the Electric motor.

Table 12. *Details of the best disassembly sequence for the Electric motor.*

Operation [N°]	**Removed component**	**Estimated disassembly time [s]**	**Estimated disassembly cost [€]**	**Disassembly tools**
1	Top back cover	14,4	0,08	Labour Screwer
2	Back cover	28,8	0,16	Labour Screwer
3	Wood panel	9,8	0,05	Labour
4	Top guide DX	9,6	0,05	Labour Screwer
5	Top guide SX	9,6	0,05	Labour Screwer
6	Concrete weight	13,8	0,08	Labour Screwer
7	Top front cover	11,8	0,07	Labour Screwer
8	Control panel assembly	14,4	0,08	Labour Screwer
9	Detergent box	33,4	0,19	Labour Screwer Pliers
10	Electronic board assembly	148,0	0,82	Labour Screwer
11	Electric wires	74,1	0,41	Labour
12	Cabinet	29,6	0,16	Labour Screwer
13	Motor support	4,4	0,02	Labour Screwer
14	Electric motor	14,7	0,08	Labour Screwer
Total		**416,4**	**2,3**	

This type of analysis has been performed for each target component with the aim of identifying the main features to be improved during the redesign phase. The following Table 13 reports a brief summary of the obtained results.

Table 13. *Results of the disassemblability analysis for the current product version.*

Target component	Components to remove [N°]	Liaisons to remove [N°]	Estimated Disassembly Time [s]
Drum	17	84	468,1
Water pump	2	16	66,8
Electric motor	13	75	416,4
Capacitor	1	11	44,0
Electronic board assembly	10	45	225,6

Different criticalities have been identified by analysing the results:

- high number of operations to disassemble the external cabinet before accessing the internal parts;
- difficulties to remove the different liaisons (screws and electric cables) used to assemble the electronic board assembly and the electric wire;
- necessity to disassemble an high number of components before reaching the electric motor (accessibility problems);
- high heterogeneity of the liaisons used.

Concerning the washing machine EoL performances, from the analysis performed by using the Recyclability module of the LeanDfD tool, a recyclability ratio of more than 70% has been estimated. This value was considered acceptable by the involved company, according to its long-term strategy. For this reason, the successive redesign phase has been only focused on improving the product disassemblability by facing the abovementioned criticalities.

8.3.2. Product disassembly and Problems annotation

Disassembly operations (Figure 33) have been carried out with particular care to not damage target components or other parts. During these activities, disassembly times have been registered, step by step, and each step has been documented in order to have a report of each disassembly operation regarding time, observed difficulties, notes, etc.. Particular attention has been posed on the annotation of disassembly sequences to reach each target component. In fact, they are strictly correlated with the product architecture and this is a key factor that could heavily influence the product disassemblability. Potential alternative disassembly paths have been evaluated during the washing machine dismantling to guarantee that the best one has been found in all the cases.

At the end of the disassembly process, all the information gathered by the expert operators has been used to define a list of the most important Problems observed. Concerning the analysed washing machine model, the main difficulties encountered for its correct treatment at EoL are the following ones:

1. high number of threaded joints (e.g., screws, nuts, etc.);
2. high number of screw typologies (e.g., M4, M6, M8, etc.);
3. high number of necessary disassembly tools (e.g., different typologies of screwdrivers);
4. high number of electric plugs with clear signs of rust;
5. long time to disassemble the main electric motor;
6. difficulties to access with two hands the long shank bolt that fixed the electric motor with the washing machine framework;
7. disadvantageous position of the heating element;
8. long time to disassemble the capacitor even if it was easily accessible;
9. internal parts are accessible only after the disassembly of several external components (e.g., top panel, rear panel, etc.).

It is worth to notice that the problems annotated during the disassembly campaign of the real washing machine, are fully in line with the criticalities identified with the disassemblability analysis, previously performed by analysing the washing machine virtual model through the LeanDfD tool. This confirms the usefulness of the proposed tool in supporting the identification of disassembly and EoL issues and the setting of the most appropriate redesign strategy.

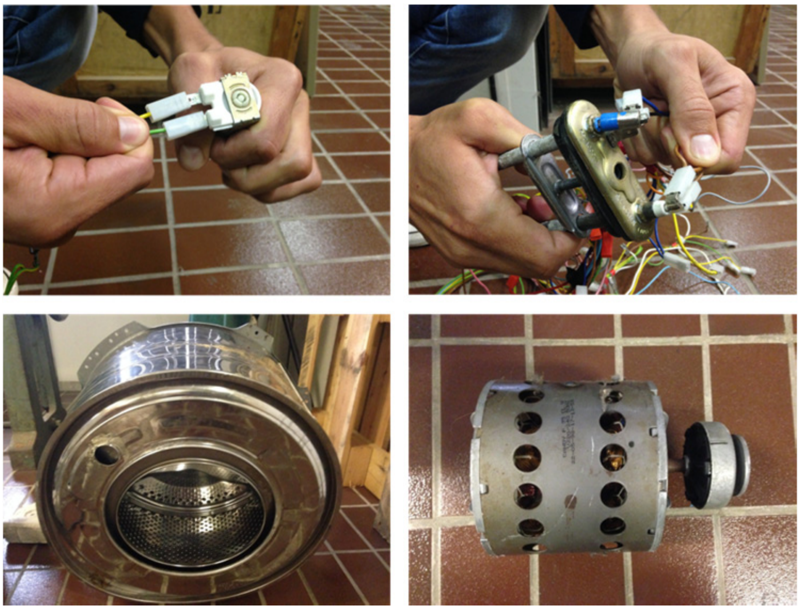


Figure 33. *Details of the disassembly operations for the capacitor, the heating element, the tank and drum and the electric motor.*

8.3.3. Design guidelines definition

The identified problems have been deeply analysed and used as a basis to define design guidelines, thus to create the DK DB. The following Table 14 contains an extract of the design guidelines defined and organized following the proposed DK DB structure.

__Table 14.__ Disassembly knowledge relative to washing machines.

Design guidelines	Related disassembly problem (N°)	Related Target Components
Use screws only when it is necessary for structural reasons. If possible, replace them with snap-fits	1 - 2	Entire Product
Reduce the number of screw typologies to minimize the needed disassembly tools	2 - 3	Entire Product
Use only standard screws to avoid the use of special tools	3	Entire Product
Increase the accessibility of target components. If possible arrange them in the external shells of the product or envisage windows in the external case to guarantee easy access	5 - 7 - 9	Entire Product
Prefer direct drive motors since they avoid the use of transmission belts and thus reduces the number of needed disassembly operations	5	Electric motor
Try to reduce the number of single electric plugs integrating more than one plugs together in a single integrated plug	4	Electric motor Capacitor Water pump Electronic Board
If possible protect the electric contacts from external agents (e.g., water) by using plastic shields to reduce the oxidation and thus the rust generation	4	Electric motor Capacitor Water pump Electronic board

Design guidelines	**Related disassembly problem (N°)**	**Related Target Components**
If possible avoid the use of bolts to fix electric motor in order to prevent accessibility problems	5 - 6	Electric motor
Design a dedicated window in the external case to reach the heating element for maintenance operations	7	Heating element
If possible avoid the use of capacitors through the adoption of alternative motor solutions (e.g., three-phase motors)	8	Capacitor Electric motor
If possible avoid the use of threaded joints to fix the capacitors in order to facilitate the disassembly operations	8	Capacitor
Reduce the number of components by integrating in particular those ones positioned in the external shells of the product	9	Entire Product
Avoid the use of threaded joints in the external case or in the aesthetic panels	1 - 9	Entire Product

8.3.4. EoL knowledge application: washing machine redesign

As anticipated before, five groups, each one composed by two students that acted as young designers, have been involved for the redesign phase. The initial material provided to each group were (Figure 34):

- the 3D model of the Original Design solution (OD) of the washing machine;
- a common CAD tool (*SolidWorks by Dassault Systèmes*) to be used for the modification of the washing machine virtual model;
- the full list of identified design guidelines to be used as suggestions to improve the product;
- the LeanDfD tool to be used for the assessment of design choices.

The final objective was to obtain a New design Solution (NS) of the washing machine, by implementing design alternatives in order to increase the disassemblability of target components.

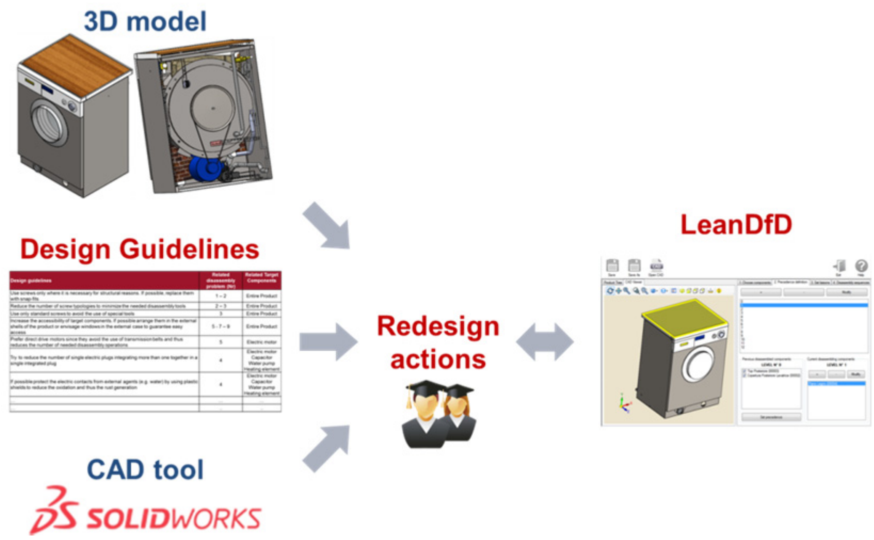


Figure 34. *Schematic workflow of the redesign step.*

Hereunder a summary of the most interesting solutions proposed by the different groups of young designers is presented.

Firstly, it is important to specify that the tank and all the related components of the oscillating group (e.g., concrete weights, etc.) have not been redesigned, since their modification would require a specific and complex structural study, which is out of scope of the present case study.

One of the proposed improvements is a broad action to solve the problem related to tool changes: the adoption of M4 screws with a hexagonal head with a notch. This screw typology has been chosen due to the support of the LeanDfD tool that, after different simulations, allowed the identification of the best solution in terms of minimum disassembly time.

The problem related to electric plugs and cables has been mitigated through the adoption of alternative electric connections. The concurrent use of the DK DB and LeanDfD tool suggested the adoption of electric terminals, shielded by plastic parts, to group together several electric plugs and thereby to reduce the number of necessary disassembly operations. This solution has been implemented for the electric motor, for the water pump and for the main electronic board, where several electric screw terminals can be potentially eliminated.

A series of redesign actions have been implemented to improve the geometry of the different external parts of the washing machine. The overall objective was to increase the accessibility of internal components, by reducing the complexity of the product architecture and the number of needed disassembly operations. In this case, at first the DK DB was used to understand the problems and the relative causes, as well as to set different potential alternative solutions. Then LeanDfD was used to rapidly compare the identified solutions, by assessing the disassemblability of each target component in terms of disassembly depth, disassembly time and disassembly cost. In particular, the following parts have been improved:

- the Top panel, originally made by four plastic parts and a plywood panel, has been redesigned as a single ABS component (Figure 35). Since this component has only an aesthetic rather than a structural function, the adoption of five snap-fits (two cantilever and three cylindrical), in substitution of the original seven screws, has been implemented to fix it with the front panel and the cabinet. Furthermore, the geometry and dimensions have been changed to adapt the new design solution with the general assembly;

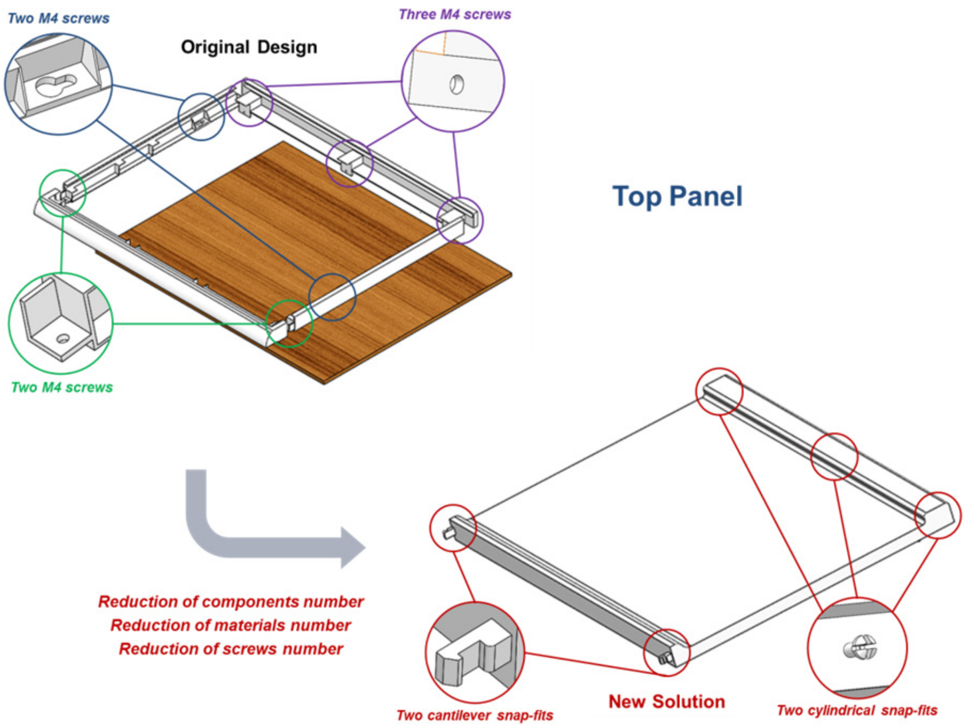


Figure 35. *Details for the Top panel redesign.*

- the Rear panel is a key component during the disassembly operations, since it guarantees access to the internal components of the washing machine. This was observed during the manual disassembly and this component is present in all the disassembly sequences calculated by using LeanDfD. Even if the rear panel has only a cover function, six M4 screws are used in the original design to fix it to the external cabinet. In this case, the redesign action (Figure 36) consisted in substituting the six original liaisons with only one rapid joint in the upper part and a guide in the lower part. This leads to a sensible reduction of the needed disassembly operations and disassembly time;

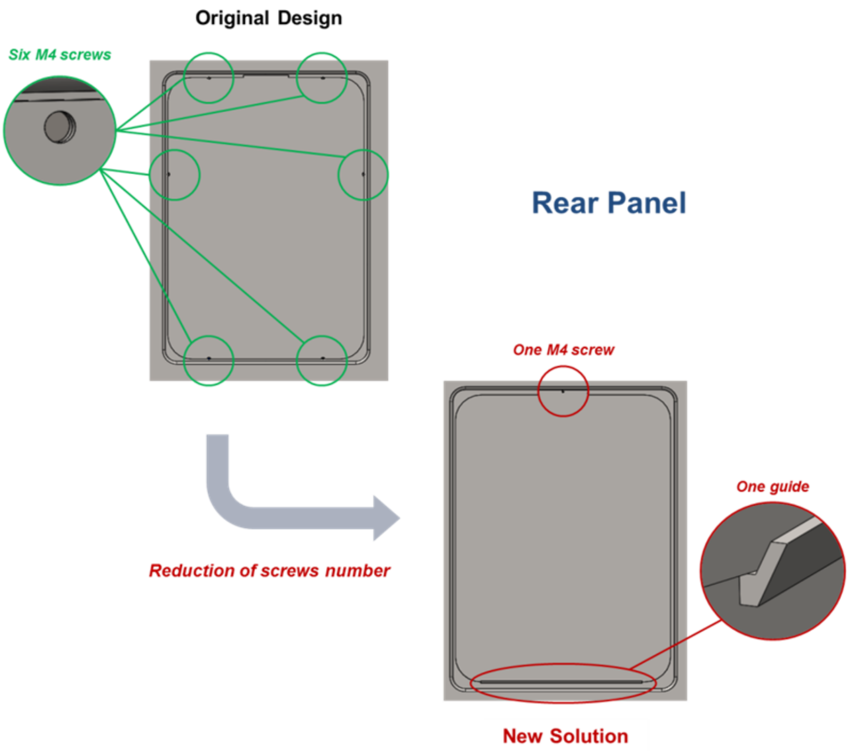


Figure 36. *Details for the Rear panel redesign.*

- the Front panel was originally composed by two different ABS components joint through three snap-fits and assembled to the washing machine external cabinet through five screws. Since these components have not structural functions, but only an aesthetic function, a single component has been designed (Figure 37). All the screws have been eliminated introducing two snap-fits on the border of the new component;

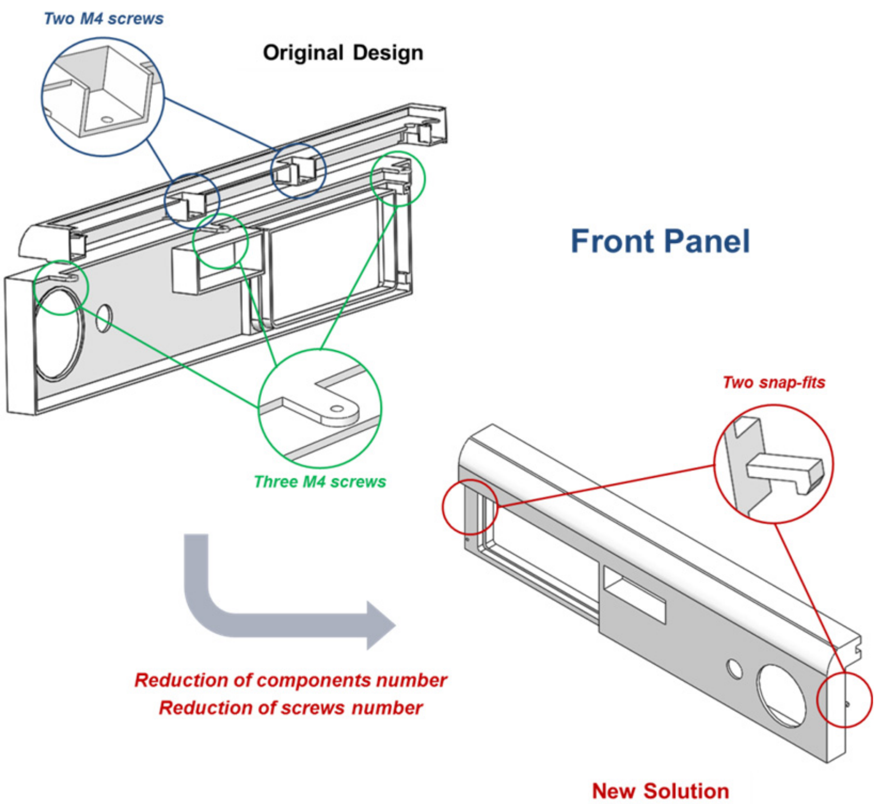


Figure 37. *Details for the Front panel redesign.*

- the Capacitor disassembly time has been reduced by changing the connection method: the threaded shank and the nut have been substituted by a cylindrical snap-fit (Figure 38);

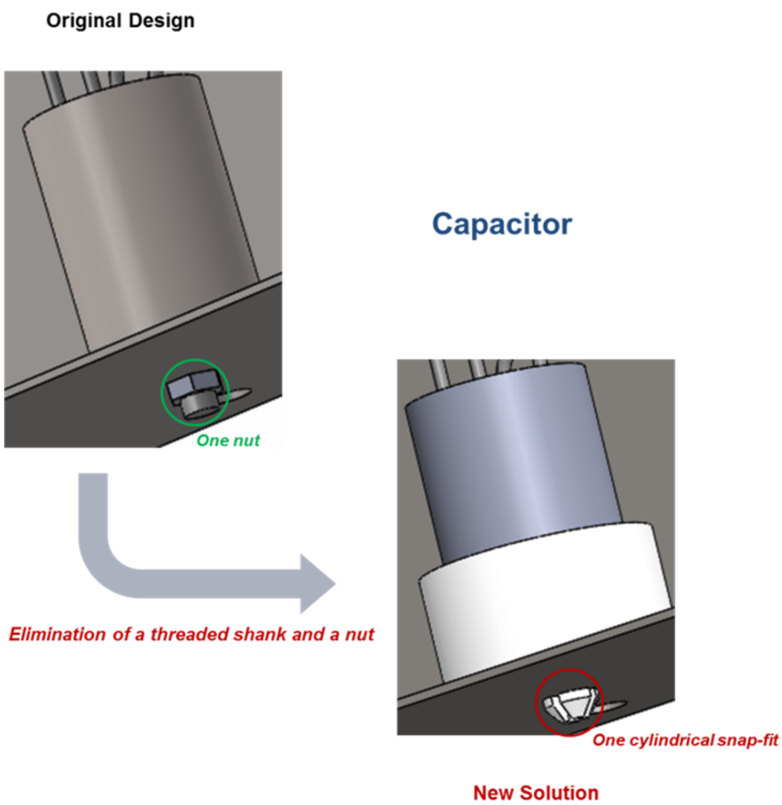


Figure 38. *Details for the Capacitor connection method redesign.*

- The Electric motor assembly has been improved to mitigate the problems related to accessibility. In the original design, the motor is fixed through two long shank bolts, which can be unscrewed only by using two hands. This led to the necessity of disassembling a large number of components before reaching the motor. This problem has been eliminated by realizing the thread directly in the metallic flange and using two screws (Figure 39). Moreover, to reach the electric motor immediately after the removal of the rear panel, two design solutions have been implemented: increasing the dimensions (height and width) of the rear panel and (ii) shifting the position of the motor;

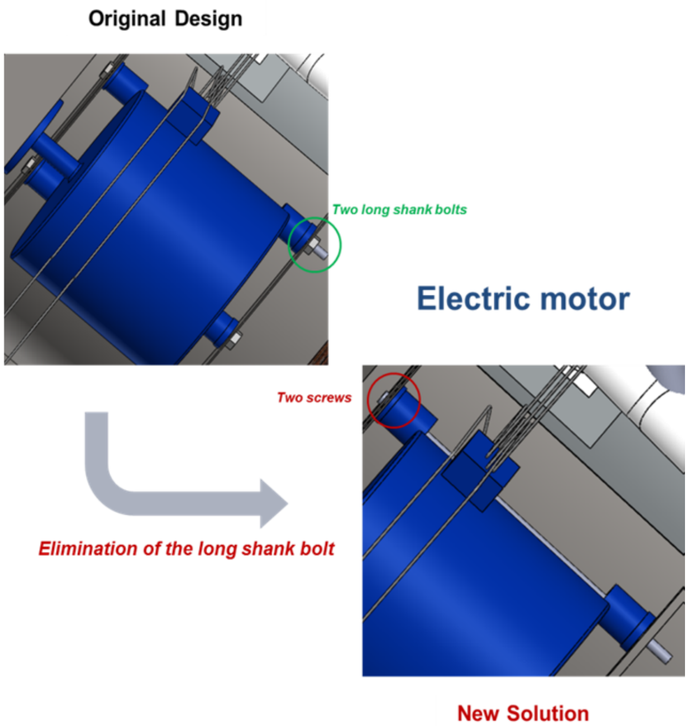


Figure 39. *Details for the Electric motor assembly redesign.*

- The last redesign action is related to the Electronic board support, which was originally fixed to the main framework using six screws. This latter has been reduced to only two, while two snap-fits have been added to obtain the necessary structural performance (as evaluated by a dedicated analysis) with improved disassemblability performance.

8.4. Results

As the last step of the washing machine case study, this section presents a critical review of the obtained results, considering two different aspects:

- the improvements of disassemblability performances obtained with the product redesign, to demonstrate the usefulness of the proposed methodologies and tools in supporting the product design process;
- the comparison between the estimated and the measured times, to demonstrate the reliability of the proposed Target disassembly methodology.

8.4.1. Quantification of the achieved benefits

The redesign process, allowed achieving tangible benefits for all of the considered target components. The obtained results are presented in Table 15, which compares the performances of the original design with the new washing machine solution, in terms of number of components and number of liaisons to remove before reaching the chosen target components. The disassembly time reduction (Figure 40), as well as the simplification of the disassembly sequences, are important results that favour maintainability, compliance with EoL regulations, recovery of the economic value of the EoL materials/components and increase of the quantity of materials with a potential closed-loop lifecycle.

Table 15. Comparison between Original Design (OD) and New Solution (NS) in terms of complexity of the best disassembly sequences.

Target component	Product Version	Components to remove [N°]	Liaisons to remove [N°]
Drum	OD	17	84
	NS	11	58
Water Pump	OD	2	16
	NS	2	9
Electric Motor	OD	13	75
	NS	1	6
Capacitor	OD	1	11
	NS	1	6
Electronic Board	OD	10	45
	NS	5	28

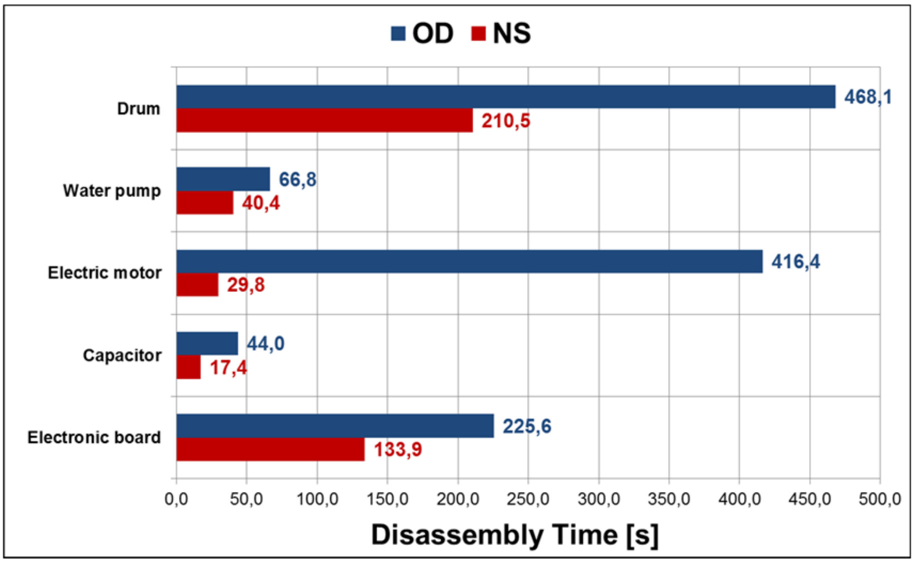


Figure 40. Comparison between Original Design (OD) and New Solution (NS) in terms of estimated disassembly time.

Examining the detailed results presented in Table 15 and Figure 40, the main improvement is related to the electric motor: a reduction in the disassembly time of 92.8% has been obtained. This unexpected result is mainly due to the elimination of the two long shanks originally used to fix the electric motor. In the new solution, the electric motor can be reached after the disassembly of only one component (the rear panel), while in the original design, thirteen components have to be removed to access the motor with two hands and disassemble the bolts.

Another tangible improvement is related to the drum disassembly time, reduced by approximately 55% after the implementation of the redesign actions. This significant result was achieved because the drum is positioned in the internal part of the washing machine framework and can be reached only after the disassembly of a high number of components or sub-assemblies. Thus, it benefits from almost all the described redesign actions that were implemented to reduce the disassembly time of the other chosen target components.

In conclusion, all the described solutions allowed reaching the prefixed objective to improve the disassembly and EoL performances of the analysed washing machine. Considering that young designers without any skill on DfD have carried out the redesign phase, it is clear that the DK methodology and the LeanDfD tool had a key role in reaching these interesting and promising results.

8.4.2. Reliability of the proposed methodologies and tools

In order to verify the reliability of the estimated disassembly times, a validation has been performed by comparing the disassembly times, estimated by using the proposed LeanDfD tool, and the experimental values, measured during the real product disassembly. Table 16 reports a summary of the obtained results, while in Table 17 details about the electric motor disassembly are illustrated.

Table 16. *General comparison between the estimated and the measured disassembly times.*

Target component	Estimated disassembly time [s]	Measured disassembly time [s]	Error [%]
Drum	468,1	496	-6,0%
Water pump	66,8	74	-10,8%
Electric motor	416,4	443	-6,4%
Capacitor	44,0	48	-9,1%
Electronic board	225,6	248	-9,9%

Table 17. *Detailed comparison between the estimated and the measured disassembly times for the Electric motor.*

Operation N°	Removed component	Estimated disassembly time [s]	Measured disassembly time [s]	Error [%]
1	Top back cover	14,4	14	2,8%
2	Back cover	28,8	27	6,3%
3	Wood panel	9,8	10	-2,0%
4	Top guide DX	9,6	9	6,3%
5	Top guide SX	9,6	9	6,3%
6	Concrete weight	13,8	12	13,0%
7	Top front cover	11,8	11	6,8%
8	Control Panel Assembly	14,4	16	-11,1%
9	Detergent box	33,4	36	-7,8%
10	Electronic board	148,0	160	-8,1%
11	Electric wires	74,1	85	-14,7%
12	Cabinet	29,6	33	-11,5%
13	Motor support	4,4	5	-13,6%
14	Electric motor	14,7	16	-8,8%
Total		**416,4**	**443**	**-6,4%**

The analysis of the results for each target component (Table 16) pointed out a small gap between the time measured during the experimental product de-manufacturing and the time estimated by using the proposed Target disassembly methodology. In general, for the target components of the washing machine, the estimation errors are approximately in the range from 6% to 10%. The differences could depend by two main reasons:

- the difficulty to effectively take into account the wear condition of some components and liaisons (the analysed product was a 15-years old washing machine);
- the inefficiencies in predicting accessibility problems due to components obstructions, product re-orientation or the use of large disassembly tools.

However, these error rates can be certainly considered as acceptable during the design process, when the objective is to univocally identify the most important criticalities and correctly focus the corrective actions.

9. Application 2: Electronics EoL management

The second case study regards the EoL management of electronic boards for industrial applications. The *Collaborative EoL Platform*, and in particular a specific decision-making algorithm, has been implemented and validated, with the aim to find the most convenient (both from the economic and environmental points of view) EoL scenario for each analysed electronic board or component. An Italian SME directly participated in the validation activities with different figures (design, marketing and purchasing departments).

9.1. Product description and motivations

Electronic wastes (e-wastes) are one of the most critical flows to manage. Waste of Electrical and Electronic Equipment constituted about 8% of the world municipal wastes in 2004 (Widmer et al., 2005), with an increase of 3-5% per annum (Rahimifard et al., 2009). If on one hand, the electronics industry has become one of the world's largest and fastest growing manufacturing industry (Gu et al., 2016), on the other hand, the use of electronic devices leads to rapid product obsolescence and decrease of lifetime, which intensifies the e-wastes problem (Mazon et al., 2012).

Currently, only a very small percentage of e-wastes are properly recovered (about 15-20%), while the majority has a non-traced EoL. A significant quantity of e-wastes is exported from developed to underdeveloped countries where they are processed in unsafe and unhealthy conditions (Long et al., 2016).

In general, e-wastes contain a mixture of different substances and materials: heavy metals (e.g., lead, cadmium, mercury, barium, etc.), precious and valuable metals (e.g., copper, gold, silver, palladium, etc.), oxides (e.g., SiO_2, Al_2O_3, etc.), rare earths, halogenated compounds, chlorinated compounds, etc. (Devika, 2010). For this reason, the EoL management of PCBs is problematic, but high economic value can be recovered from this mixture (Song and Li, 2014).

Material recycling is the most common EoL scenario for electronics. Recycling treatments are quite simple but not very efficient. They consume high quantity of energy and release emissions to air and water. The traditional methods to recycle metals from e-wastes are essentially (Zhang and Xu, 2016): (i) incineration, where e-wastes are burned to recover copper, (ii) hydraulic shaking bed separation used to obtain crude copper, and (iii) acid leaching to recover metals by using leaching solvents (e.g., HNO_3, HCl, $HClO_4$, etc.). More advanced and complex technologies in this field are pyrometallurgy (Cui and Zhang, 2008) and hydrometallurgy (He and Xu, 2014). This latter can be also used to recover Rare Earth Elements (REEs) from EoL products (Tunsu et al., 2015). Currently, also electrochemical technologies are emerging methods to recover base and precious metals with high environmental compatibility, high energy efficiency and reduced use of chemicals (Kim et al., 2011; Lister et al., 2014; Diaz et al., 2016).

All the aforementioned technologies guarantee economic sustainability. However, they certainly do not represent the best option. Despite several researches are focusing on improving the environmental performances of these processes, they are still impactful for the natural environment and hazardous for the humanity. Several studies confirmed that the regions where an intensive processing of e-wastes is carried out are characterized by consistent environmental impacts (Duan et al., 2016) and present a high concentration of heavy metals in surrounding air, dust, soils, sediments and plants (Song and Li, 2014). In addition, the pond water used for irrigation are often seriously acidified and contaminated by heavy metals (Wu et al., 2015). These polluted environments can lead to an increment of different diseases compared with the global situation, such as sex ratio deviations of offspring (Liu et al., 2010) and male genital diseases (Xu et al., 2014b).

In order to mitigate these problems, while keeping the economic value of electronics at EoL, a shift toward reuse or remanufacture of electronic products and components is needed. These scenarios potentially represent a new business opportunity for manufacturers, since their implementation leads to a reduction of costs for virgin materials and components supply, and to relevant benefits from the environmental point of view.

The case study refers to an Italian manufacturer of display and electronic control boards for industrial applications. In particular, they are specialized in supplying parts to escalators and lifts manufacturers. This specific application is particularly suitable for the implementation of reuse and remanufacturing scenarios, since in this sector the technological obsolescence, typical of other electronic products (in particular mobile phones), is not very rapid. These electronic boards are used to control simple operations (e.g., open the lift door, turn on the lights in the cabin, stop the movement of the escalator, etc.), thus the required computational power is not particularly high. Many of the components (e.g., microprocessors, regulators, etc.), bought by the involved company to realize its boards, are standard and used in different products from dozens of years. In addition, these electronic boards have a mean life of about 8 years, while the estimated maximum life of several components is generally major. At the electronic board EoL, several components have a residual life and thus a relevant residual economic value. Finally, the involved manufacturer directly manages the maintenance and EoL of their products. All these considerations justify the implementation of a reuse or remanufacturing scenario in this industrial case study.

9.2. Case study workflow and objectives

The general objective of the second case study is to verify the effectiveness of a specific decision-making algorithm in supporting the implementation of reuse and/or remanufacturing scenarios for EoL electronics, by assuring economic and environmental benefits.

The specific objectives of the electronics case study are:

- to demonstrate the applicability of the developed EoL decision-making algorithm in real industrial contexts;
- to verify the ability of the developed EoL decision-making algorithm in finding the most convenient EoL scenario for electronic components;
- to quantify the economic and environmental benefits of reuse and remanufacturing scenarios.

To achieve all the aforementioned objectives, different activities were necessary, as reported in Figure 41.

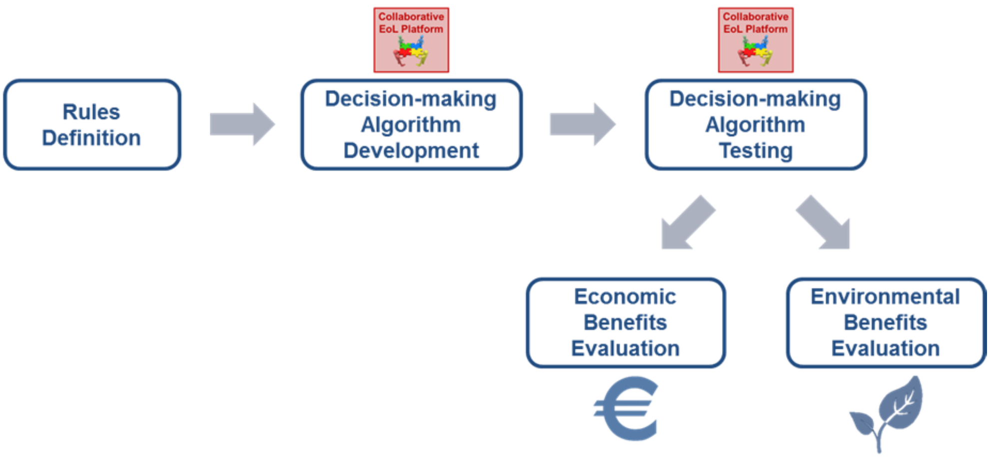


Figure 41. *Electronics case study workflow.*

During the *Rules Definition* phase the involved company defined all the basic principles and rules, needed for the successive implementation of the algorithm. For example, all the products and components candidate to be remanufactured have been identified and characterized by using specific parameters. In addition, basic rules to be used during the decision-making process have been formalized.

The *Decision-making Algorithm Development* phase focused on the implementation of the algorithm, by considering previously gathered rules and data. A detailed procedure, and the relative mathematical formulas, have been defined in order to consider all the possible cases for the considered products and components.

The successive *Decision-making Algorithm Testing* phase aimed to verify the ability of the developed procedure in identifying the most convenient EoL scenario for each analysed EoL board or component. The algorithm has been tested by considering different electronic board typologies. In addition, several lifetime scenarios were considered in order to deeply validate the developed formulas.

Finally, the *Economic & Environmental Benefits Evaluation* phases allowed quantifying the potential benefits that the involved company could obtain by practically implementing each suggested EoL scenario.

The following section describes all the activities in details.

9.3. How to efficiently manage EoL electronics?

9.3.1. Rules definition

At the beginning, an in-depth analysis of all the components used by the involved company to realize its electronic boards have been performed. The 654 components have been classified by using several specific parameters, needed for the decision-making algorithm implementation. The considered parameters are the followings:

- Component identification code;
- Description;
- Category;
- Sub-category;
- Assembly technology (e.g., Surface Mounted Devices – SMD, etc.);
- Supplier;
- Unitary cost [€];
- Mean Time Between Failure (MTBF) [years];
- Maximum useful life [years];
- Disassembly time [s];
- Disassembly cost [€].

In addition, other secondary data have been considered:

- Total number of items bought in a year for each component;
- Total cost in a year for each component (derived from the number of items bought and the unitary cost) [€];
- Incidence of disassembly operations (derived from the disassembly cost and the unitary cost) [€/€];
- Added value for the disassembly (derived from the unitary cost and the disassembly cost) [€].

On the basis of the produced boards mean life, maximum useful life, purchasing volumes and cost per component, about 110 components have been preliminarily selected as candidate for reuse, from the 654 components bought by the company from its suppliers. Only these items are considered in the case study (see an extract of the selected components in the following Figure 42).

Description	TOT v	TOT q	Cost 2015	MTBF [years]	Useful life [years - cycles]	TSM [s]	CSM [€]	Added value [€]
Display TFT 5,7" 320240-96-E LQ057AC113A/LQ057AC111A	84.460,00	2231	37,857	884	10	10	0,061	37,796
Display TFT 7" WVGA 800X480 TM070RDH10-20	61.480,00	2693	22,830	884	10	10	0,061	22,768
TRASFORMATORE TOROIDALE E06 + kit Mod. 438VEG0030	1.768,00	80	22,100	7660	30	50	0,306	21,794
TRASF.TOROID 438VEG0040-1 160VA 0-230/24Vac con cablaggio + dischi fissaggio	23.029,35	1311	17,566	7660	30	40	0,244	17,322
Display TFT 4,3" modulo RGB 4.3" resolution 480x272 WQVGA - DLC: DLC0430EZG-2	18.000,00	1924	9,356	884	10	10	0,061	9,294
microprocessore mcimx286cvm4b	6.651,52	936	7,106	1436	25	30	0,183	6,923
Display TFT 2,8" (ER-TFT028-4 (EAST RISING)	12.659,00	1893	6,687	884	10	10	0,061	6,626
LCD 3 icone - fondo nero icone colorate	7.200,00	770	9,351	2089	20	500	3,056	6,295
microprocessore dsPIC33FJ256MC710-I/PT	24.014,81	4135	5,808	3482	20	30	0,183	5,624
microprocessore PIC24FJ256GB110-I/PF 16 BIT TQFP100	15.525,04	2770	5,605	3482	25	30	0,183	5,421
Microcontrollore RENESAS Electronics 32bit LQFP144 SMD R5F56218BDFB	6.025,80	1117	5,395	1436	25	30	0,183	5,211
microprocessore PIC18F452-I/L (27)	11.555,82	2224	5,196	3482	25	10	0,061	5,135
MAX1243BCSA+ MAXIM - 10BIT ADC, SMD, 1243, SOIC8 (100)	760,00	154	4,935	2498	25	20	0,122	4,813
microprocessore PIC18F4620-I/P DIP 40 pin (10)	15.482,25	3231	4,792	3482	25	10	0,061	4,731
Antenna GSM lunghezza cavo 3 [m] - CE-CG016	1.152,00	247	4,664	28725	30	10	0,061	4,603
16 pin trasformatore switching ET39 ferrite core flyback converter	239,25	43	5,564	6759	30	160	0,978	4,586
LCD QVGA GRAPHIC CONTROLLER TQFP100	10.447,98	2254	4,635	2498	25	20	0,122	4,513
microprocessore DSPIC33FJ128GP804-I-PT	11.714,46	2585	4,532	3482	25	30	0,183	4,348
SD CARD 2 GIGA - SANDISK SDSDJ-2048-814-J	5.319,00	1231	4,321	2946	25	3	0,018	4,303
Microprocessore PIC18F4525 I/P	15.326,40	3616	4,238	3482	25	10	0,061	4,177
dsPIC30F4013-30I/PT	25.015,21	5970	4,190	1436	25	30	0,183	4,007
microprocessore DSPIC33EP128MC506-I/PT	2.574,00	693	3,714	1436	25	30	0,183	3,531
LCD-MON - LCD 2 ico. DTN BLU	7.000,00	1539	4,548	2089	20	200	1,222	3,326
ic dvr octal low side soic-24	657,20	191	3,441	2498	25	30	0,183	3,258
LCD-TRI - LCD 3 icone DTN BLU	27.040,78	6233	4,338	2089	20	200	1,222	3,116
microprocessore PIC16C62B-04 I/SP	254,00	77	3,299	3482	25	30	0,183	3,115
Integrato smd LM2576-HVS-ADJ	7.560,00	2354	3,212	2873	15	20	0,122	3,089
LCD 3 icone verticale - STN Blue	7.345,00	1231	5,967	2089	20	500	3,056	2,911
Integrato smd LM2577S-ADJ - TO- 263 (45)	1.215,00	416	2,921	2873	15	20	0,122	2,798
Microprocessore ARM MCU 16/32 Bits LQFP-48	169,46	57	2,973	3482	25	30	0,183	2,790
LCD Alfanumerico fondo nero con digit bianchi ed icone colorate	4.822,00	1231	3,917	2089	20	200	1,222	2,695
Microprocessore PIC24FJ128GA006-I/PT 16 BIT 64TQFP	6.131,70	2147	2,856	3482	25	30	0,183	2,673
Driver per motore DC 5-A H-Bridge TLE5205-2G (1000)	6.450,00	2308	2,795	2498	15	20	0,122	2,672
TAS5602DCA - Audio Power Amplifier IC	809,20	297	2,725	2089	15	20	0,122	2,602
MICRO SD CARD 4 GIGA (AP4GMCSH4-RA)	15.456,00	6000	2,576	2445	20	3	0,018	2,558

Figure 42. *Extract of the 110 components candidate to reuse.*

The involved company also defined a set of rules to be considered by the decision-making algorithm. The following initial hypotheses have been made:

- If the residual life of a component, disassembled from a EoL or used board, is major than 10 years, the component can be reused in a board sold as New. These products are considered comparable with boards produced by only using new components, thus can be sold without any discount rate. This choice has been made by considering that the mean life of the produced board are generally 8 years, thus a safety factor (+20%) has been considered, to guarantee the correct functioning of the board for the entire life;
- If the residual life of a component, disassembled from a EoL or used board, is minor than 10 years but major than 3 years, the component can be reused in a board sold as Remanufactured. These products have an estimated maximum life minor than boards produced by only using new components, thus have to be sold by applying a discount rate;
- If the residual life of a component, disassembled from a EoL or used board, is minor than 3 years the component cannot be internally reused, thus can be sold to other companies for reuse or material recycling. This choice has been made by considering that the company guarantees a warranty of 3 years for all the sold boards (sector requirement);
- The discount rate for Remanufactured boards is set to -20%. This value has been chosen by the commercial department of the involved company, by essentially considering the price of repaired boards;
- The maximum useful life of each component can be retrieved from literature studies or estimated on the basis of company experience or even using data, such as the MTBF, coming from technical manuals, (Telcordia Technologies, 2016).

- The disassembly time and cost of each component have been estimated considering manual operations, currently performed by expert operators in the case of broken boards.

9.3.2. EoL decision-making algorithm development

When a *used or EoL electronic board comes back* from the market, the first needed activity is the *estimation of the Effective Life of the board* (EL_b). In case of boards produced by the same company that manages the EoL, this data can be estimated by considering the production date or the production batch and making a realistic hypothesis on the use profile. If, instead, the board or component comes back from another producer, the univocal way to estimate the spent life is to use literature data or public information provided by the manufacturing company that can be shared by using the *Shared DB* of the proposed *Collaborative EoL Platform*. This second option provides a less accurate data which is managed and accounted by the algorithm. The spent life is then used to estimate the *Residual Life of each interesting component* (RL_i) installed in the board (components belonging to the list of 120 "candidates" preliminarily identified during the Rules Definition phase), according to the following equation (8):

$$RL_i = MaxL_i - EL_b \tag{8}$$

where EL_b is the estimated effective life of the board and $MaxL_i$ is the maximum life of the *i-th* component (retrieved from literature or estimated by using data coming from technical manuals).

At this stage it is necessary to establish if the *i-th* component can be re-installed in other boards or has to be discarded. This decision depends by two different thresholds defined according to the company strategy:

- $MinL_{i,new}$: the minimum value of residual life for the *i-th* component to be reused in new boards. This threshold varies for different companies and for different applications. As said before, in this case study this value has been set to 10 years;
- $MinL_{i,reman}$: the minimum value of residual life for the *i-th* component to be reused in remanufactured boards. Since the mean life and the warranty for remanufactured boards are generally less than the corresponding values for new boards, $MinL_{i,reman}$ can be set as a fraction of $MinL_{i,new}$. As said before, in this case study this value has been set to 3 years.

The following conditions can arise:

$$\begin{cases} RL_i \geq MinL_{i,new} \rightarrow NEW \\ MinL_{i,reman} \leq RL_i < MinL_{i,new} \rightarrow REMAN \\ RL_i < MinL_{i,reman} \rightarrow DISCARD \end{cases} \quad (9)$$

The first condition of equation (9) is the most favourable one, since the component under analysis can be reused in new boards in substitution of a new one to buy from suppliers. From the economic point of view the first condition ($RL_i > MinL_{i,new}$) is always beneficial, since the new board equipped with second-life components can be sold at the same price of a board completely equipped with new components. It is also convenient from the environmental point of view, since the reuse of a second-life component allows avoiding the production of a new component with savings of virgin materials. In order to maximize the environmental and economic benefits, it is recommended to use an high number of second-life components in place of new ones.

The second condition of equation (9) is not always convenient from the economic point of view. Manufacturers need to consider that the selling price of a remanufactured board (equipped with second-life components) has to be less than the price of a new board (because the guaranteed life is less than the mean life of a new equivalent board). The scenario convenience directly depends from the disassembly cost and the applied discount rate. From the environmental point of view, there is always a benefit because of the avoided production of components.

Finally, the third condition listed in equation (9) is the most unfavourable one. In this case the component cannot be reused neither in new boards nor in remanufactured boards. Possible scenarios are the sale to other companies that can reuse these components for other applications or even the sale to material recyclers.

The economic benefits (*EcoBen*$_i$) related to the reuse of the *i-th* component can be calculated by using the following equation (10):

$$\begin{aligned} EcoBen_i &= C_{b,new} - C_{b,second} = \\ &= C_{b,new} - (C_{b,new} - C_{c,new} + C_{d,i}) = C_{c,new} + C_{d,i} \end{aligned} \tag{10}$$

where $C_{b,new}$ is the production cost of a new board with only new components, $C_{b,second}$ is the production cost of a new board with a component recovered from an EoL board (the *i-th* component), $C_{c,new,i}$ is the cost of a new *i-th* component and $C_{d,i}$ is the disassembly cost of the *i-th* component.

Concerning environmental benefits (*EnvBen*$_i$), instead, they can be simply derived by considering the avoided impacts due to the avoided production of new components, according to the following equation (11):

$$EnvBen_i \approx -EnvL_i \tag{11}$$

where $EnvL_i$ is the environmental load (i.e. impact) related to the production of the *i-th* component.

As a summary, the following Figure 43 illustrates all the steps of the of the proposed algorithm, dedicated to electronics EoL management.

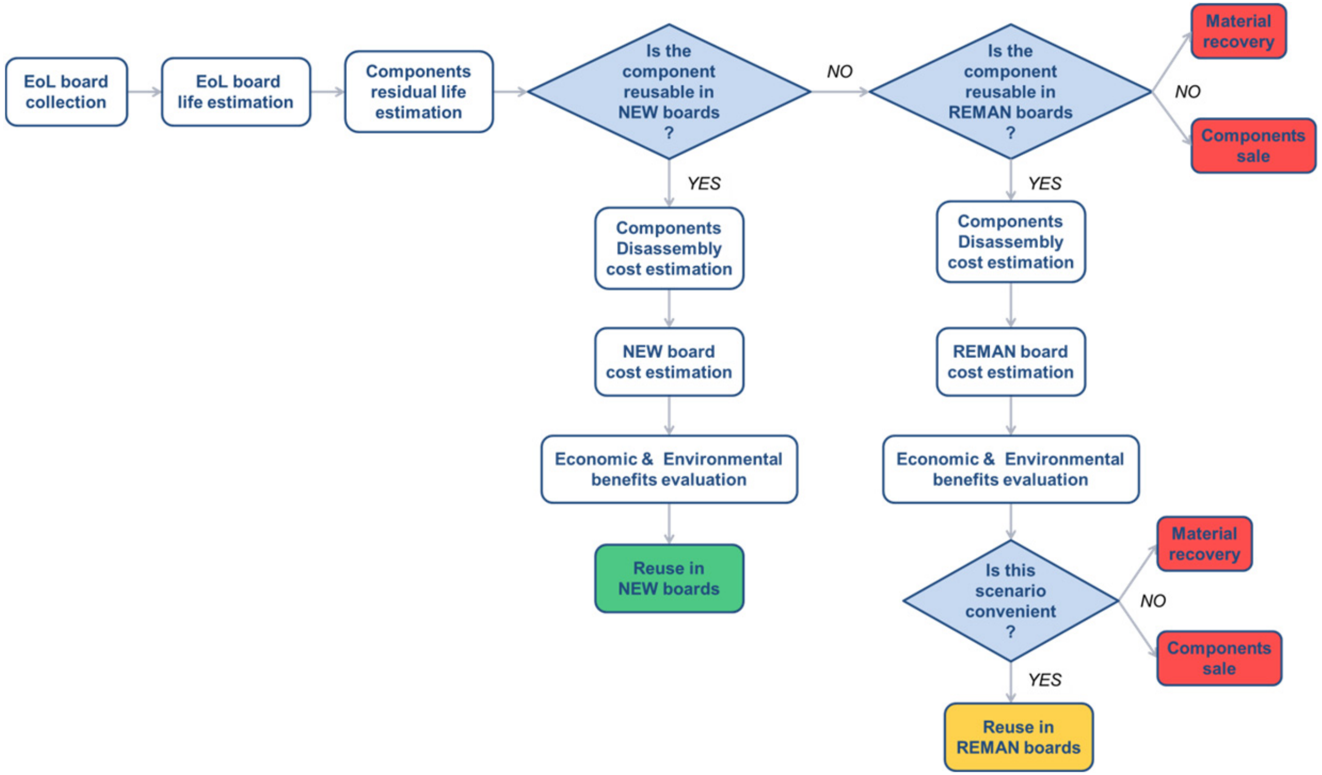


Figure 43. *EoL decision-making algorithm.*

9.3.3. *Algorithm testing*

The algorithm has been tested by using 5 different electronic boards: 4 display boards and 1 control board (see details in the following Table 18).

Table 18. *Details of the 5 analysed boards.*

Board code	Board Type	Components candidate to reuse [N°]	Board production cost [€]	Board selling price [€]
TFT555_V9	Display board	7	39,00	92,74
TFT701-A_V5	Display board	4	76,50	150,80
LCD510-OT_V1	Display board	5	18,00	46,50
LCD610-OT_V6	Display board	2	11,60	24,13
VEG2000_V6	Control board	2	47,00	102,23

Each board is equipped with different components belonging to the list of 110 components candidate for reuse at EoL, as well as with other components which are not considered in the algorithm application. These latter were not interesting for reasons related to purchasing volumes and/or cost and/or residual value at the board EoL.

The following Table 19 reports the details for each component candidate to reuse in the 5 analysed boards. Relevant data, needed for the algorithm application, as the purchase price, estimated maximum life and disassembly cost are also showed in the table.

Table 19. *Details of components candidate to reuse in the 5 analysed boards.*

Board code	Component code	Component Type	Price [€]	Maximum life [years]	Disassembly cost [€]
TFT555_V9	DISP TFT 4.3"	Display	9,36	10	0,061
	LM22676MR-ADJ	Regulator	1,82	15	0,122
	LM3410XMF	Regulator	1,24	15	0,122
	MICRO SDCARD-4G	Memory	2,58	20	0,018
	PCA2129T	Controller	2,17	20	0,122
	R5F56218BDFB	Microprocessor	5,39	25	0,183
	SN65HVD1780D	Controller	2,27	25	0,183
TFT701-A_V5	LM3410XMF	Regulator	1,24	15	0,122
	SGTL5000XNLA3/R2	Controller	1,49	25	0,122
	PCA2129T	Controller	2,17	20	0,122
	DISP TFT 7"	Display	22,83	10	0,061
LCD510-OT_V1	DSP-BACKLIGHT-SMD	Display	1,91	10	0,367
	DSP-LCD-VEL	Display	4,55	20	1,222
	LM22676MR-ADJ	Regulator	1,82	15	0,122
	PIC16F1947-I/PT	Microprocessor	1,92	25	0,183
	SN65HVD1781D	Controller	1,95	15	0,122

Board code	Component code	Component Type	Price [€]	Maximum life [years]	Disassembly cost [€]
LCD610-OT_V6	PIC16F1947-I/PT	Microprocessor	1,92	25	0,183
	SN65HVD1780D	Controller	2,27	25	0,183
VEG2000_V6	PIC18F4620-I/P	Microprocessor	4,79	25	0,122
	LM2576T-ADJ	Regulator	1,19	15	0,306

9.4. Results

As the last step of the electronics EoL management case study, this section presents the results obtained with the algorithm application to all the 5 considered boards. The aim was to establish the economic and environmental convenience of the reuse of EoL components in new and/or remanufactured boards.

9.4.1. Definition of scenarios

Before proceeding with the presentation of results, it is necessary to clarify that several scenarios have been defined to cover all the possible cases. As reported in Table 19 not all the considered components candidate to reuse have the same maximum life. This parameter varies in the range between 10 years and 25 years. In addition, even if the mean life of the analysed electronic boards is 8 years, it is necessary to consider that the real spent life can be different. Electronic boards can come back before 8 years, due to broken components or due to particular requests of customers. It is also possible that some electronic boards come back after 8 years, in cases where all the components are not broken and customers do not require product updates. Depending on the considered electronic board and on the considered range of years, components to be reused in new boards, components to be reused in remanufactured boards and components to discard are variable. As a consequence, economic and environmental benefits assume not fixed values.

For the aforementioned reasons, the simulations have been iterated by varying the number of years of spent life for the electronic board that comes back at EoL. In particular, for each analysed electronic board the considered range of spent life spans from 1 year till to 12 years (maximum value for board spent life according to company historical data). To better clarify the procedure followed to define the scenarios, Table 20 reports the details for the board TFT555_V9.

Table 20. Procedure to derive scenarios to consider for the board TFT 555_V9.

Spent life [years]	**Components candidate to reuse in NEW boards** (residual life)	**Components candidate to reuse in REMAN boards** (residual life)	**Components to DISCARD** (residual life)
1	LM22676MR-ADJ (14) LM3410XMF (14) MICRO SDCARD-4G (19) PCA2129T (19) R5F56218BDFB (24) SN65HVD1780D (24)	DISP TFT 4.3” (9)	-
2	LM22676MR-ADJ (13) LM3410XMF (13) MICRO SDCARD-4G (18) PCA2129T (18) R5F56218BDFB (23) SN65HVD1780D (23)	DISP TFT 4.3” (8)	-
3	LM22676MR-ADJ (12) LM3410XMF (12) MICRO SDCARD-4G (17) PCA2129T (17) R5F56218BDFB (22) SN65HVD1780D (22)	DISP TFT 4.3” (7)	-
4	LM22676MR-ADJ (11) LM3410XMF (11) MICRO SDCARD-4G (16) PCA2129T (16) R5F56218BDFB (21) SN65HVD1780D (21)	DISP TFT 4.3” (6)	-
5	LM22676MR-ADJ (10) LM3410XMF (10) MICRO SDCARD-4G (15) PCA2129T (15) R5F56218BDFB (20) SN65HVD1780D (20)	DISP TFT 4.3” (5)	-

Spent life [years]	**Components candidate to reuse in NEW boards** (residual life)	**Components candidate to reuse in REMAN boards** (residual life)	**Components to DISCARD** (residual life)
6	MICRO SDCARD-4G (14) PCA2129T (14) R5F56218BDFB (19) SN65HVD1780D (19)	DISP TFT 4.3” (4) LM22676MR-ADJ (9) LM3410XMF (9)	-
7	MICRO SDCARD-4G (13) PCA2129T (13) R5F56218BDFB (18) SN65HVD1780D (18)	DISP TFT 4.3” (3) LM22676MR-ADJ (8) LM3410XMF (8)	-
8	MICRO SDCARD-4G (12) PCA2129T (12) R5F56218BDFB (17) SN65HVD1780D (17)	LM22676MR-ADJ (7) LM3410XMF (7)	DISP TFT 4.3”
9	MICRO SDCARD-4G (11) PCA2129T (11) R5F56218BDFB (16) SN65HVD1780D (16)	LM22676MR-ADJ (6) LM3410XMF (6)	DISP TFT 4.3”
10	MICRO SDCARD-4G (10) PCA2129T (10) R5F56218BDFB (15) SN65HVD1780D (15)	LM22676MR-ADJ (5) LM3410XMF (5)	DISP TFT 4.3”
11	R5F56218BDFB (14) SN65HVD1780D (14)	MICRO SDCARD-4G (9) PCA2129T (9) LM22676MR-ADJ (4) LM3410XMF (4)	DISP TFT 4.3”
12	R5F56218BDFB (13) SN65HVD1780D (13)	MICRO SDCARD-4G (8) PCA2129T (8) LM22676MR-ADJ (3) LM3410XMF (3)	DISP TFT 4.3”

In the case of TFT555_V9 board, the ranges to be considered for the economic and environmental analyses are the following: (i) 1 – 5 years, (ii) 6 – 7 years, (iii) 8 – 10 years and (iv) 11 – 12 years. Within each range, the situation remains fixed, with the same components candidate for reuse in new boards, for reuse in remanufactured boards and to discard, thus the benefits remains unvaried.

Ranges of spent life for the other 4 analysed electronic boards have been derived by following the same procedure detailed above.

9.4.2. Economic analyses

Results obtained with the economic analyses are summarized in Table 21. They highlight that not all the possible scenarios are convenient from the economic point of view. In particular, the reuse of components in new boards leads to economic profits in all the considered cases. In general, the less is the value of spent years by the EoL board and the higher is the economic profit, since more components are appropriate for reuse in new boards.

Moreover, the economic profit is higher in case of complex electronic boards, equipped with many precious components. In this case a high number of second-life components can be used in substitution of new virgin components to buy from suppliers. This is the case of the board TFT555_V9 which is equipped with 7 components belonging to the list of 110 candidates to reuse. Considering, a spent life of 8 years (typical mean life of the analysed boards) the economic profit is €11,90, a relevant value in comparison with the standard production cost of €39,00 (see Table 18). If the company will decide to implement a reuse scenario for this board typology, the savings will be more than 30% of the production cost.

Table 21. Results of the economic analyses.

Board code	Range of spent life [years]	Economic profit for reuse in NEW boards [€]	Economic profit for reuse in REMAN boards [€]
TFT555_V9	1 - 5	14,72	-9,25
	6 - 7	11,90	-6,44
	8 - 10	11,90	-15,73
	11 - 12	7,30	-11,13
TFT701-A_V5	1 - 5	4,54	-7,39
	6 - 7	3,42	-6,27
	8 - 10	3,42	-29,042
	11 - 12	1,38	-27,00
LCD510-OT_V1	1 - 5	7,99	-7,76
	6 - 7	4,69	-4,46
	8 - 10	4,69	-6,00
	11 - 12	1,36	-2,67
LCD610-OT_V6	1 - 7	4,00	-3,76
	8 - 10	4,00	-4,33
	11 - 12	3,51	-4,33
VEG2000_V6	1 - 5	5,62	N/A
	6 - 12	4,73	-19,56

The reuse of components in remanufactured boards, instead, is always inconvenient, independently from the spent life of the EoL board that comes back. This is essentially due to the chosen discount rate applied by the company (-20%). An in-depth analysis has been made to understand which could be the maximum discount rate to apply in order to guarantee economic profits in case of reuse of EoL components in remanufactured boards (Table 22).

Table 22. Analysis of the discount rate for REMAN boards.

Board code	Range of spent life [years]	Maximum Discount Rate to get Economic profit for reuse in REMAN boards
TFT555_V9	1 - 5	10%
	6 - 7	13%
	8 - 10	3%
	11 - 12	8%
TFT701-A_V5	1 - 5	15%
	6 - 7	16%
	8 - 10	1%
	11 - 12	2%
LCD510-OT_V1	1 - 5	3%
	6 - 7	10%
	8 - 10	7%
	11 - 12	14%
LCD610-OT_V6	1 - 7	4%
	8 - 10	2%
	11 - 12	2%
VEG2000_V6	6 - 12	1%

From results reported in Table 22 it is not possible to establish an univocal value of discount rate that can be conveniently applied to all the 5 boards. In some cases (e.g., TFT701-A_V5) an acceptable percentage can be set (about 10%-15%), while in other ones the reuse of components in remanufactured boards seems to be not applicable. Possible improvements to make this scenario convenient, could be the enlargement of the list of 110 components candidate to reuse or the adoption of optimized assembly/disassembly technologies to reduce the disassembly cost (e.g., use of connectorized components, use of automatic disassembly equipment).

It is worth to notice that all the results presented only consider costs relative to components purchasing, assembly and disassembly operations, but do not consider other costs, as transportation or warehouse, which could have a relevant influence. By considering these additional items, the real economic profits will be minor than the value presented in the previous tables.

Another aspects not considered in this case study is the possibility to get revenue from the sale of EoL boards or components to other companies or to recyclers. Future implementation of the algorithm should include these possibilities in order to have a wider view of all the possible EoL scenarios.

In conclusion, the application of the decision-making algorithm allows company discovering that the only economically sustainable scenario is the reuse of EoL components with a residual life of more than 10 years to be reused in boards sold as new, without any discount rate. Contrary to what is established by the marketing department, the algorithm experimentation allowed discovering that the discount rate of 20% applied to remanufactured board is not economically sustainable. This confirms the usefulness of the proposed algorithm in supporting the decision-making process regarding EoL management activities.

9.4.3. Environmental analyses

The environmental analyses have been realized by applying the standardized Life Cycle Assessment (LCA) methodology (ISO, 2006a; ISO, 2006b). The scope was to compare the current open-loop scenario (taken as baseline), where EoL boards are discarded and sent to material recyclers, with the closed-loop reuse scenarios, where several components are disassembled from EoL boards and reused as second-life components in new or remanufactured boards. As reported in Figure 44, two consecutive lifecycles have been considered in the analyses to quantify the environmental benefits related to the reuse of components.

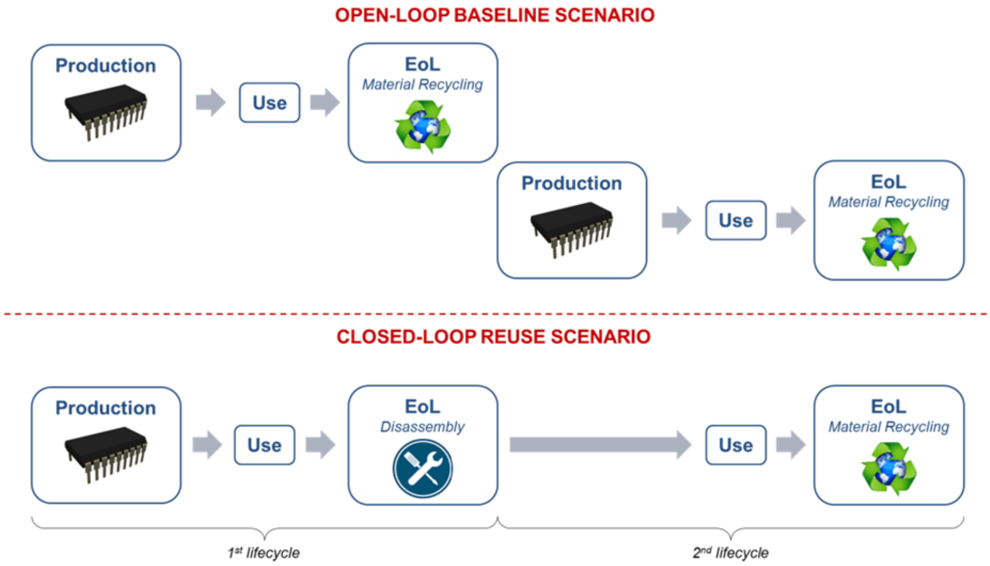


Figure 44. *System boundaries for the LCA analyses.*

As in the case of economic analyses, also for the environmental assessments different simulations have been carried out in order to measure the advantages in all the possible cases, according to scenarios previously defined (e.g., EoL board that comes back after 5 years, after 8 years, etc.).

For each analysed board (listed in Table 18) the developed LCA model only includes the production, disassembly operations and dismantling of components candidate to reuse (details in Table 19). This choice is justified by the fact that the scope of the environmental assessments is to quantify the advantages of reuse scenarios in comparison with the baseline scenario (Figure 44). The other phases (e.g., production of the other components, board use, etc.) remains fixed, thus can be neglected in a purely comparative analysis, without losing significance.

Concerning the Life Cycle Inventory (LCI), the estimation of the weight for each component has been made in collaboration with the involved company by using technical manuals and literature data. The disassembly have been modelled by considering the electric energy consumed during these operations for each component. In particular, the energy values have been derived considering the use of a de-soldering tool with a nominal power of 40 W and the disassembly times estimated during the first phase of the case study. The component EoL (i.e. material recycling) has been modelled in a simplified way by using a WEEE dismantling process. Details about the LCI data, are reported in Table 23.

Table 23. *Life Cycle Inventory data.*

Life cycle phase	Item	Input data	EcoInvent dataset
Production	DISP TFT 4.3"	89,0 g	Liquid crystal display, unmounted
	LM22676MR-ADJ	0,2 g	Integrated circuit, logic type
	LM3410XMF	0,2 g	Integrated circuit logic type
	MICRO SDCARD-4G	8,0 g	Integrated circuit, memory type
	PCA2129T	0,3 g	Transformer, low voltage
	R5F56218BDFB	6,2 g	Integrated circuit, logic type
	SN65HVD1780D	0,1 g	Integrated circuit, logic type
	DISP TFT 7"	262,0 g	Liquid crystal display, unmounted
	SGTL500XMLA3/R2	100,0 g	Integrated circuit, logic type
	DSP-BACKLIGHT-SMD	0,1 g	Backlight, for liquid crystal display
	LM22675MR-ADJ	0,2 g	Integrated circuit, logic type
	SN65HVD1781D	0,1 g	Integrated circuit, logic type
	DSP-LCD-VEL	130,0 g	Liquid crystal display, unmounted
	PIC16F1947-I/PT	2,2 g	Integrated circuit, logic type
	PIA-BACKLIGHT-SMD	0,1 g	Backlight, for liquid crystal display
	PIA-LCD-IG-VEG	150,0 g	Integrated circuit, logic type
	LM2576T-ADJ	0,2 g	Integrated circuit, logic type
	PIC18F4620-I/P	2,2 g	Integrated circuit, logic type

Life cycle phase	Item	Input data	EcoInvent dataset
Disassembly	Disassembly operations	-	Electricity, low voltage {IT}| market for
EoL	Material Recycling	-	Waste electric and electronic equipment {GLO}| market for

Table 23 also reports the mapping with the *EcoInvent 3.1 – allocation, default – system* datasets (Wernet et al., 2016) , used for the Life Cycle Impact Assessment (LCIA). Due to the impossibility to find very specific datasets relative to the production of single electronic components, the most similar available EcoInvent datasets have been used. This choice certainly reduces the degree of accuracy of the obtained results, but for comparative analyses it can be considered as acceptable. In addition, this was the univocal way to proceed, since it was not possible to directly involve producers of electronic components (e.g., *Motorola*, *ST Microelectronics*, etc.) to collect relevant LCI data.

Two different indicators have been chosen for the assessments:

- Climate change [kg CO2 eq] (Goedkoop et al., 2013), which is the most common indicator to consider the influence of activities on climate changes as the global warming;
- ReciPe Endpoint [EcoPt] (Goedkoop et al., 2013), a damage-oriented indicator, simple to understand and useful to compare different scenarios in a detailed way.

Results obtained with the LCIA of the 5 analysed boards are reported in the following Table 24.

__Table 24.__ Results of the environmental analyses.

Board code	Scenarios	Range of spent life in the 1st lifecycle [years]	Climate change [kg CO2 eq]	ReciPe Endpoint [EcoPt]
TFT555_V9	Baseline scenario	-	30,68	6,07
	Reuse of components in NEW boards	1 – 5	20,65	3,84
		6 – 10	20,96	3,94
		11 – 12	25,77	4,53
	Reuse of components in REMAN boards	1 – 5	15,35	3,03
		6 – 7	15,35	3,03
		8 – 12	20,65	3,84
TFT701-A_V5	Baseline scenario	-	187,43	53,47
	Reuse of components in NEW boards	1 – 5	109,33	29,11
		6 – 10	109,49	29,16
		11 – 12	109,49	29,16
	Reuse of components in REMAN boards	1 – 5	93,72	26,73
		6 – 7	93,72	26,73
		8 – 12	109,33	29,11
LCD510-OT_V1	Baseline scenario	-	19,42	3,58
	Reuse of components in NEW boards	1 – 5	9,72	1,79
		6 – 10	9,95	1,86
		11 - 12	9,95	1,86
	Reuse of components in REMAN boards	1 – 5	9,72	1,79
		6 – 7	9,72	1,79
		8 – 12	9,72	1,79

Board code	Scenarios	Range of spent life in the 1st lifecycle [years]	Climate change [kg CO2 eq]	ReciPe Endpoint [EcoPt]
LCD610-OT_V1	Baseline scenario	-	21,47	3,84
	Reuse of components in NEW boards	1 – 10	10,74	1,92
		11 – 12	19,68	3,28
	Reuse of components in REMAN boards	1 – 7	10,74	1,92
		8 – 12	10,74	1,92
VEG2000_V6	Baseline scenario	-	3,74	1,16
	Reuse of components in NEW boards	1 – 5	1,87	0,58
		6 – 12	2,02	0,63
	Reuse of components in REMAN boards	6 – 12	1,87	0,58

Reuse of components, both in new and remanufactured boards, always leads to environmental benefits. The avoided production of new components "cover" the energy consumption related to disassembly, thus the environmental balance is always positive. This is the main difference between the economic and the environmental analyses. Reuse in remanufactured boards is more advantageous than reuse in new boards, since a higher number components (i.e. all the components with a residual life of at least 3 years) can be reused for the second lifecycle, thus the production of an higher number of new components can be avoided. Benefits are even major in case of complex boards equipped with a high number of components candidate to reuse or equipped with complex components.

10. Discussion and Concluding Remarks

The present research work deeply investigated issues and opportunities related to product EoL. It allowed demonstrating that the product EoL, if opportunely managed with dedicated methodologies and tools, represents an important resource to exploit, instead of a problem to manage.

The major contribution to the state of the art is the definition and development of a set of methodologies and tools, integrated in a single framework, to support the decision-making process. This EoL-oriented framework is founded on the concept that it is better to prevent issues, by designing optimized products and creating favourable operative conditions, other than study and develop solutions to solve problems related to EoL management (e.g., difficulties to recycle materials, complex reverse supply chains, etc.). The proposed framework overcomes the numerous literature works in the field of DfD, DfEoL and EoL management, which are generally focused on supporting single aspects, such as the design process in case of design for disassembly methods or the EoL activities in case of recycling technologies, but lacks of a holistic view. The most important step beyond the state of the art is certainly the possibility to favour the collaboration between all the most important lifecycle stakeholders with the aim of constantly monitoring the EoL performances throughout all the most affecting lifecycle phases.

Taken together, the proposed methodologies and tools represent a quantitative support for companies to take informed decisions and prevent possible future issues relative to EoL management. In this way the EPR principle can be actually applied and, as a consequence, new circular business models (e.g., remanufacturing, product retirement, etc.) can be conveniently implemented by manufacturing companies. This switch toward circular economy can lead to environmental benefits, due to minimization of energy and virgin materials consumption, and to economic savings, due to the recovery of the residual value contained within products after the end of their first useful life.

In particular, the main results obtained with the thesis activities can be summarized as follows:

- an integrated approach to monitor disassemblability and EoL performances of products throughout the whole product lifecycle;
- three metrics (i.e. disassembly depth, disassembly time, disassembly cost) to quantitatively measure the product and component disassemblability;
- a database containing quantitative data about liaisons, to be used to calculate the disassembly time and costs of target components;
- a target disassembly methodology to derive the feasible and best disassembly sequences for target components, in case of selective disassembly simulations carried out during the design process;
- a DfD tool to support the implementation of the target disassembly methodology and assess the impacts of design choices in terms of product disassemblability and recyclability performances;
- partial integration of the DfD tool with the most largely used design tool (i.e. CAD tool), in order to limit the impacts in terms of required additional time and efforts for design activities;
- a framework to "close the gap" between design departments and EoL stakeholders;

- a KB methodology, based on positive and negative knowledge gathered by observing disassembly/remanufacturing/EoL activities, to support redesign phase toward the implementation of closed-loop lifecycles for most of the components in a product;
- an EoL-oriented platform to favour the active collaboration and exchange of materials and relevant data among stakeholders involved in the management of the different product lifecycle phases.

Concerning the Target disassembly methodology to quantitatively measure the product/component disassemblability, it is a structured workflow which integrates already known (e.g., precedence matrix) and novel (e.g., Liaison DB) items. The main novelty in comparison with the state of the art is certainly related to the development of the database and to the definition of the procedure to estimate the disassembly time. This latter is largely considered as a key indicator for DfD activities, since it is directly correlated to disassembly and EoL management costs. However, a structured procedure for its estimation during the design process has been not already defined in other literature studies. The presented applications (combustion engine in Section 4 and washing machine case study in Section 8) demonstrated that the Target disassembly methodology is robust and not dependent from the product complexity, since it can be applied both in the case of simple products, with few components, or in the case of complex products, with a product architecture composed by several components and sub-assemblies. The applicability of the proposed method is guaranteed by the fact that almost all the required input information can be derived from the product virtual models, which are usually available during the product development process (i.e. embodiment design phase). As previously explained, the starting point is represented by the analysis of 3D models and BoMs, documents largely used during the design process and well-known by the design team.

Concerning the proposed LeanDfD tool, it can be viewed as the needed resource to guarantee the implementation of DfD actions in real design contexts. First of all, the tool is able to identify criticalities through the calculation of the disassembly sequences and the estimation of the disassembly time and cost for each target component. Then, it helps in rapidly evaluating the impact of the design choices, in terms of disassemblability and recyclability performances. In this sense, an essential feature is the partial integration with CAD systems that allows importing 3D models in standard exchange format (i.e. STEP). The availability of the 3D CAD model and related attributes is very important to limit the needed time to perform a complete product disassemblability analysis and to minimize the impact on the traditional design workflow, in comparison with a manual application of the Target disassembly methodology. The washing machine case study proved that the developed tool is able to estimate the disassemblability indicators with a good reliability (errors in disassembly time estimations are in the range 8% - 10% in comparison with measured times). The monitoring of these indicators during the design process, when there are available degrees of freedom to optimize the product characteristics (e.g., geometry, materials, architecture, and liaisons), facilitates the normative compliance and contributes to improve EoL performances. In this sense, the tool can be viewed as a necessary mean to evaluate new business models based, for example, on remanufacturing or product service, where the easy disassembly or easy maintainability of specific components are key factors in guaranteeing the economic feasibility.

The main limitation of the proposed Target disassembly methodology and LeanDfD tool is related to the feedbacks given to designers. Sometimes, the disassembly time and cost are not sufficient to fully support designers during the product redesign phase (this is especially valid for inexperienced engineers). For this reason, the DK methodology has been developed in order to find an effective way to support designers during the product improvement phase. Indeed, it is well known from literature studies that general ecodesign guidelines are not sufficient to effectively support the product improvement phase. The final aim is to create an eco-knowledge repository for aiding designers during the definition of alternative product solutions. The gathering of experiences from dismantlers, remanufacturers and EoL stakeholders represents a mean to preliminarily avoid EoL issues, thus to reduce the complexity of the EoL management processes. The effectiveness of the DK methodology has been confirmed by the good results obtained by the undergraduate students who acted as inexpert designers in the redesign of the analysed washing machine (the disassembly time of the considered target components of the washing machine has been reduced of at least 40%).

The exploitation of the abovementioned methodologies and tools in industrial companies is possible only through a dedicated EoL collaborative platform for the sharing of materials (e.g., EoL products or components) and relevant information (e.g., knowledge on disassembly and EoL activities). The idea beyond is to create a collaborative environment, involving all the relevant stakeholders that have a role in the product lifecycle (e.g., suppliers, manufacturers, recyclers, remanufacturers, etc.), in order to close the gap between the BoL, the MoL and the EoL stages. The proposed platform can be used as a public/private repository where relevant information and EoL products/components, opportunely characterized, can be offered to other stakeholders to be reused in a second-life scenario. In addition, the platform can host a decision-making algorithm able to support companies in the evaluation of the economic and environmental convenience of reuse scenarios. The implementation of the platform in the context of the electronics sector, demonstrated the possibility to preserve the residual value of components, minimizing production costs (up to 44%) and environmental impacts (up to 50%).

Besides the positive results obtained, some general weak points of the proposed methodologies and tools have to be highlighted. First of all, the adoption of them in the industrial context, requires a deep change of mentalities, in particular for what regard Small and Medium Enterprises (SMEs). The advantages that can be obtained through the implementation of a circular business model, are often not immediate. Therefore, it is necessary to set a long-term strategy, but SMEs have usually difficulties to have a long-term view, due to day-by-day problems (e.g., new product development, supplier management, product delivery).

Another aspect to mention is that the proposed methodologies and tools are founded on the collaboration of internal (i.e. different company departments) and external (i.e. partner companies) stakeholders. For example, the gathering of EoL knowledge is only possible by involving EoL stakeholders. The EoL platform is advantageous if different companies, involved in the lifecycle of a product, share materials and information. Companies need to be willing to actively collaborate, by overcoming classical issues, such as privacy, data confidentiality, worry for potential competitors, etc.

We also should not forget that the use of additional tools could lead to possible negative impacts on company processes. Even if, the proposed methodologies and tools have been developed by firstly analysing the traditional processes and tools, the adoption of new methods and tools potentially requires additional activities (e.g., disassemblability analyses, management of EoL components, etc.) to be performed by different subjects within a company (e.g., designers, managers, etc.). To date the two case studies allowed separately verifying the usefulness of the thesis outcomes (target disassembly methodology, LeanDfD tool and DK methodology in the washing machine case study and EoL collaborative platform in the electronics case study). Anyway, the whole framework was not yet exploited in any industrial application. This is an essential future work to better evaluate the needed extra-efforts (in terms of time, cost and additional human resources) and thus to understand the net benefits in each case.

Another barrier that could limit the diffusion of this kind of methodologies and tools is certainly the absence of mandatory standards and regulations related to the management of the product EoL, to be applied already during the product conception and design. As stated before in the Introduction (Section 1), different EoL regulations exist, such as the European WEEE directive, but they only force manufacturers to organize the product EoL and the waste collection and treatment, while indications related to the design phase are only suggestions: *"... Member States shall [...] encourage cooperation between producers and recyclers and measures to promote the design and production of EEE, notably in view of facilitating re-use, dismantling and recovery of WEEE, its components and materials ..."* (European Parliament and Council, 2012). Policy makers should force on a mandatory base the consideration of EoL aspects, by setting minimum thresholds for disassemblability and/or other EoL performance indicators to be respected by manufacturers during the development of new products. In the long term this kind of measures will contribute to mitigate the environmental problem, to reduce the quantity of wastes to manage, to limit the resource consumption and, as a consequence, to preserve the natural environment and the human wellbeing.

Future work are needed to improve the quality and significance of the obtained results, as well as to overcome some of the abovementioned weak points. To effectively reduce the negative impacts on traditional processes, it will be necessary to work on integration and interoperability of the proposed methodologies and tools. For example, only a "soft" integration has been developed for the LeanDfD tool which is able to interoperate with the most common CAD tools, by reading 3D models in standard interchange formats (i.e. STEP). Anyway, to increase the tool usability, a "hard" integration is probably needed, integrating the tool as a plugin within the CAD environment. In this way, end users will be able to assess the design choices in a "familiar" environment and in real time. Moreover, a step forward will consist in the implementation of algorithms for the automatic identification of disassembly levels based, for example, on collision analysis or Gaussian spheres. By implementing algorithms for the automatic disassembly sequence calculation from a 3D model (Cappelli et al., 2007), manual inputs can be drastically reduced, as well as the time required for the analyses.

Another relevant improvement could be obtained by guaranteeing a complete interoperability and a "transparent" exchange of information among the different methodologies and tools developed in the context of this thesis work. To date, the holistic framework has been defined on the basis of the identified industrial needs, and some resources included in the framework have been developed. Anyway, to make the proposed framework fully operative, it is necessary to work on tool integration and interoperability. For example, the LeanDfD tool could be used to derive useful data (e.g., indications on how to disassemble a product, etc.) to share through the Collaborative EoL Platform. The integration of these tools each other and with company repositories and management systems (e.g., PDM, PLM, etc.) will lead to an optimized flow of information and to a reduction of needed efforts for their use. However, this requires consistent research efforts to study common procedures, to be followed by all the involved stakeholders, and standard exchange files, to be read/saved by all the interconnected software tools.

A wider future work could be focused on studying how to effectively involve lifecycle stakeholders already during the product design process. Currently, the developed methodologies and tools dedicated to the design phase (i.e. Target disassembly methodology, LeanDfD tool, DK methodology) do not directly involve other stakeholders than the manufacturing company. Only the DK methodology aims to collect knowledge and expertise coming from other lifecycle stages. However, the external stakeholders only act as information providers and do not directly collaborate to the product development and/or improvement.

Collaborative design for EoL methods and tools could be very useful in case of design/redesign of new products or product variants, with the aim to maximize EoL performances and, at the same time, guarantee economic savings for the different lifecycle stakeholders.

Another direction of research could be the study of simplified techniques to conceive products with the "EoL on mind". The developed methodologies and tools are based on assessment of quantitative indicators. If, on one hand, this guarantees a high reliability, on the other hand, this necessarily requires the use of detailed information (e.g., geometry, material choices, etc.) that are usually available only during the embodiment and detail design phases. In order to guarantee their applicability in the early design stages (e.g., product conception), the study and development of innovative Conceptual design for EoL techniques, based on a limited and not definitive set of data about the product features, is thus needed.

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Appendix A. Liaison Database

Table 25. *Full details of the Liaison DB.*

Liaison Class	Liaison Type	Standard disassembly time [s]	Class Property	Type Property	Condition	Corrective Factor
Threaded	-	-	Wear	-	Not worn	1,0
					Partially worn	1,3
					Completely worn	2,0
	Screw	4,0	-	Head Type	Hexagonal	1,2
					Hexagonal with notch	1,0
					Cylindrical	1,2
					Cylindrical with notch	1,0
					Cylindrical with hex notch	1,1

Liaison Class	**Liaison Type**	**Standard disassembly time [s]**	**Class Property**	**Type Property**	**Condition**	**Corrective Factor**
				Unscrewing tool	Screwer	1,0
					Spanner	1,2
					Screwdriver	1,4
				Length	≤ 20 mm	1,0
					> 20 mm, ≤ 40 mm	1,1
					> 40 mm	1,2
				Diameter	≤ 4 mm	1,2
					> 4 mm, ≤ 12 mm	1,0
					> 12 mm	1,2
	Threaded rod	4,0	-	Unscrewing tool	Electric puller	1,0
					Manual puller	1,2
					Manual	1,1

Liaison Class	Liaison Type	Standard disassembly time [s]	Class Property	Type Property	Condition	Corrective Factor
				Length	≤ 20 mm	1,0
					> 20 mm, ≤ 40 mm	1,1
					> 40 mm	1,2
				Diameter	≤ 4 mm	1,2
					> 4 mm, ≤ 12 mm	1,0
					> 12 mm	1,2
	Nut	4,0	-	Head type	Common	1
					With cap	1,1
					With wings	1,2
				Unscrewing tool	Screwer	1,0
					Manual	2,0
					Spanner	1,3
					Pliers	1,9

Liaison Class	Liaison Type	Standard disassembly time [s]	Class Property	Type Property	Condition	Corrective Factor
				Length	≤ 3 mm	1,0
					> 3 mm, ≤ 10 mm	1,1
					> 10 mm	1,2
				Diameter	≤ 4 mm	1,2
					> 4 mm, ≤ 12 mm	1,0
					> 12 mm	1,2
Shaft-hole	-	-	Wear	-	Not worn	1,0
					Partially worn	1,3
					Completely worn	2,0
			Length	-	≤ 10 mm	1,3
					> 10 mm, ≤ 300 mm	1,0
					> 300 mm	1,4

Liaison Class	Liaison Type	Standard disassembly time [s]	Class Property	Type Property	Condition	Corrective Factor
			Diameter	-	≤ 10 mm	1,6
					> 10 mm, ≤ 100 mm	1,0
					> 100 mm	1,4
			Grooves	-	No	1,0
					Yes	1,3
			Play	-	≤ 0,1 mm	1,2
					> 0,1 mm, ≤ 1 mm	1,1
					> 1 mm	1,0
			Extraction tool	-	Manual	1,0
					Pliers	1,2
					Shaft puller	1,5
	Pin	3,0	-	Conicity	No	1,0
					Yes	1,2

Liaison Class	Liaison Type	Standard disassembly time [s]	Class Property	Type Property	Condition	Corrective Factor
			-	Notch	No	1,0
					Yes	1,2
	Linchpin	3,0	-	Knurling	No	1,0
					Yes	1,2
Rapid joint	-	-	Wear	-	Not worn	1,0
					Partially worn	1,3
					Completely worn	2,0
			Disassembly tool	-	Manual	1,0
					Pliers	1,2
					Shaft puller	1,3
	Dap joint	2,0	-	Play	Yes	1,0
					No	1,3

Liaison Class	Liaison Type	Standard disassembly time [s]	Class Property	Type Property	Condition	Corrective Factor
	Snap-fit	2,0	-	Geometry	Cylindrical	1,0
					Rectangular	1,1
					Spherical	1,05
					Other	1,2
	Guide	3,0	-	Length	≤ 300 mm	1,0
					> 300 mm	1,2
				Typology	T	1,2
					L	1,0
					U	1,05
					Dovetail	1,1
Electric	-	-	Wear	-	Not worn	1,0
					Partially worn	1,3
					Completely worn	2,0

Liaison Class	Liaison Type	Standard disassembly time [s]	Class Property	Type Property	Condition	Corrective Factor
	Coaxial cable	4,0	-	Connected with	Rigid frame	1,0
					Cable	1,2
				Disassembly tool	Manual	1,0
					Other tools	1,2
	Electric plug	2,0	-	Connected with	Rigid frame	1,0
					Cable	1,2
				Disassembly tool	Manual	1,0
					Other tools	1,2
	Screw terminal	2,0	-	Screw head type	With notch	1,0
					Hexagonal	1,2
				Screw diameter	≤ 4 mm	1,4
					> 4 mm, ≤ 10 mm	1,0
					> 10 mm	1,2

Liaison Class	Liaison Type	Standard disassembly time [s]	Class Property	Type Property	Condition	Corrective Factor
				Disassembly tool	Screwdriver	1,0
					Manual	1,1
					Other tools	1,2
	Ribbon cable	2,0	-	Width	≤ 200 mm	1,0
					> 200 mm	1,1
				Typology	Simple dap joint	1,0
					With clip	1,1
					With screw	1,3
				Disassembly tool	Screwdriver	1,0
					Manual	1,0
					Other tools	1,3

Liaison Class	Liaison Type	Standard disassembly time [s]	Class Property	Type Property	Condition	Corrective Factor
Prevent extraction	-	-	Wear	-	Not worn	1,0
					Partially worn	1,3
					Completely worn	2,0
	Circlip	4,0	-	Shaft diameter	≤ 20 mm	1,4
					> 20 mm, ≤ 80 mm	1,0
					> 80 mm	1,2
				Disassembly tool	Seeger puller	1,0
					Manual	1,3
	Split pin	4,0	-	Diameter	≤ 5 mm	1,0
					> 5 mm	1,4
				Disassembly tool	Pliers	1,0
					Manual	1,3

Liaison Class	Liaison Type	Standard disassembly time [s]	Class Property	Type Property	Condition	Corrective Factor
Not removable	-	-	Wear	-	Not worn	1,0
					Partially worn	1,2
					Completely worn	1,4
	Nail / Rivet	6,0	-	Material	Steel	1,2
					Aluminium	1,0
				Disassembly tool	Rivet puller	1,0
					Pliers	1,2
Motion transmission	-	-	Wear	-	Not worn	1,0
					Partially worn	1,3
					Completely worn	2,0
	Tang / Key	3,0	-	Length	≤ 40 mm	1,3
					> 40 mm, ≤ 100 mm	1,0
					> 100 mm	1,2

Liaison Class	Liaison Type	Standard disassembly time [s]	Class Property	Type Property	Condition	Corrective Factor
				Shape	Straight	1,0
					Rounded	1,2
					With snug	1,1
					Disk shaped	1,3
				Length	≤ 40 mm	1,3
					> 40 mm, ≤ 100 mm	1,0
					> 100 mm	1,2
				Disassembly tool	Manual	1,0
					Pliers	1,3
	Spline profile	3,0	-	Groove number	≤ 3	1,0
					> 3, ≤ 10	1,1
					> 10	1,3

Liaison Class	Liaison Type	Standard disassembly time [s]	Class Property	Type Property	Condition	Corrective Factor
				Disassembly tool	Manual	1,0
					Pliers	1,3
Magnetic	Magnetic	2,0	-	-	-	-
Washer	-	-	Wear	-	Not worn	1,0
					Partially worn	1,05
					Completely worn	1,1
	Washer	2,0	-	Thickness	≤ 2 mm	1,3
					> 2 mm	1,0
Bearing	-	-	Wear	-	Not worn	1,0
					Partially worn	1,1
					Completely worn	1,3

Liaison Class	Liaison Type	Standard disassembly time [s]	Class Property	Type Property	Condition	Corrective Factor
	Bearing	5,0	-	Typology	Radial	1,0
					Axial	1,4
				Diameter	≤ 20 mm	1,3
					> 20 mm ≤ 100 mm	1,0
					> 100 mm	1,2
				Disassembly tool	Bearing puller	1,0
					Manual	2,0
Obstruction	Visual obstruction	1,0	-	-	-	-

Appendix B. LeanDfD User Manual

B.1. Introduction

Figure 45. *LeanDfD logo.*

B.1.1. Primary function of tool and the lifecycle phase it addresses

The main objective of the LeanDfD tool is to understand the economic and environmental consequences related to (manual) disassemblability of the product and the product End of Life (EoL) performance. The tool addresses the EoL phase of the product life cycle and its improvement with regard to environmental and economic parameters.

B.1.2. Primary users of tool

The main user of the tool would be a design engineer.

B.1.3. Step-by-step process of operation from CAD/PLM/Web

The LeanDfD tool is composed of two modules, the first for the analysis of the manual disassembly time and cost (known as the Disassembly module), the second for the analysis of product EoL performance in terms of recyclability (known as the EoL module). In the following paragraph, the description of the main steps the user has to perform to undertake an analysis is presented.

When the user opens the tool, he can:

- import an XML BOM file (that can be used in both the Disassembly and EoL modules);
- import a LeanDfD native file (that can be used in both the Disassembly and EoL modules, if the native file is derived from an XML file);
- import a CAD file (in this case only the Disassembly analysis can be performed).

After the user has completed one of the previous operations the main interface will be displayed (Figure 46). It is composed of 2 sections: the left section in which the product structure is shown, and the right section in which a summary of previous analysis is shown (relative to product or specific components).

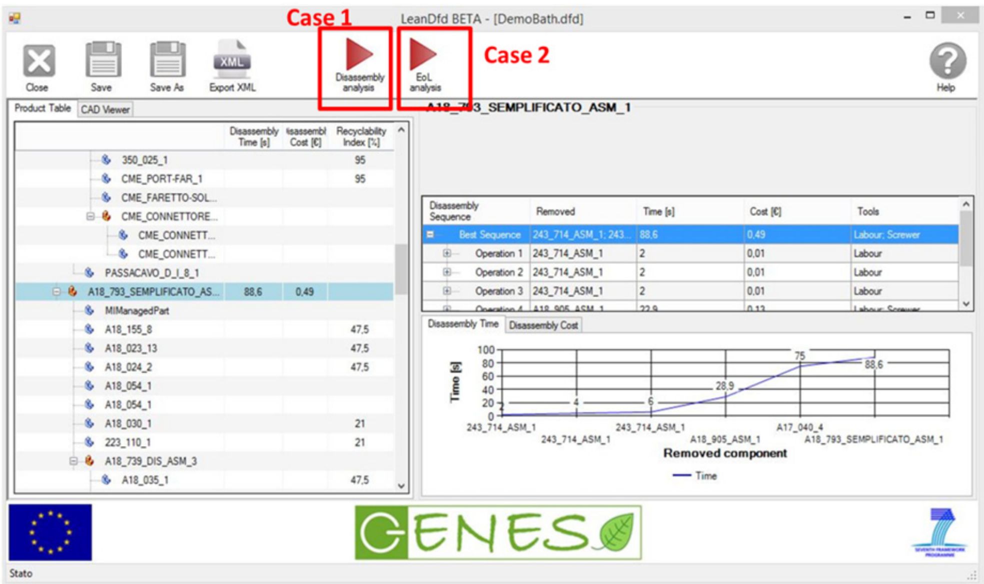

Figure 46. *Main interface.*

B.2. Workflow

From the main interface, the user has to choose from the following modules:

- Disassembly analysis (Case 1);
- EoL analysis (Case 2).

B.2.1. Case 1

If the user chooses to use the Disassembly Module, he can analyse the disassemblability (feasible sequences and related cost and time) of a specific component/sub-assembly; he opens the specific module by clicking on the "Disassembly Analysis" icon in first tool screen and follows the Workflow of the Disassembly module (Figure 47).

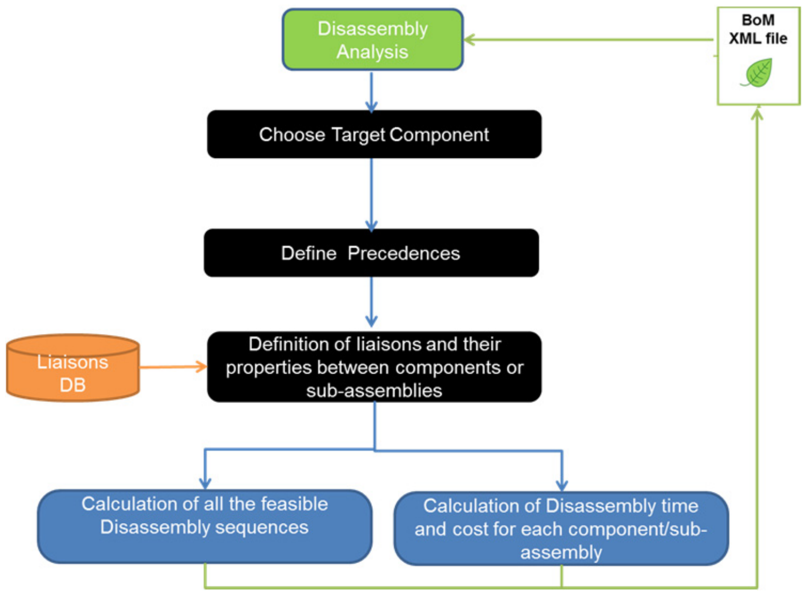

Figure 47. *Disassembly module workflow.*

To perform the disassembly analysis, 4 steps need to be undertaken:

- **Choose one or more target Components**. These are the components the user wishes to analyse with the tool and for which he wants to calculate the related manual disassembly time and cost. The user has to select a component from the product structure and click on the icon "Add component". This operation is repeated until he has inserted all the desired target components. The target components are highlighted in the product structure and added in the right section of the interface (Figure 48).

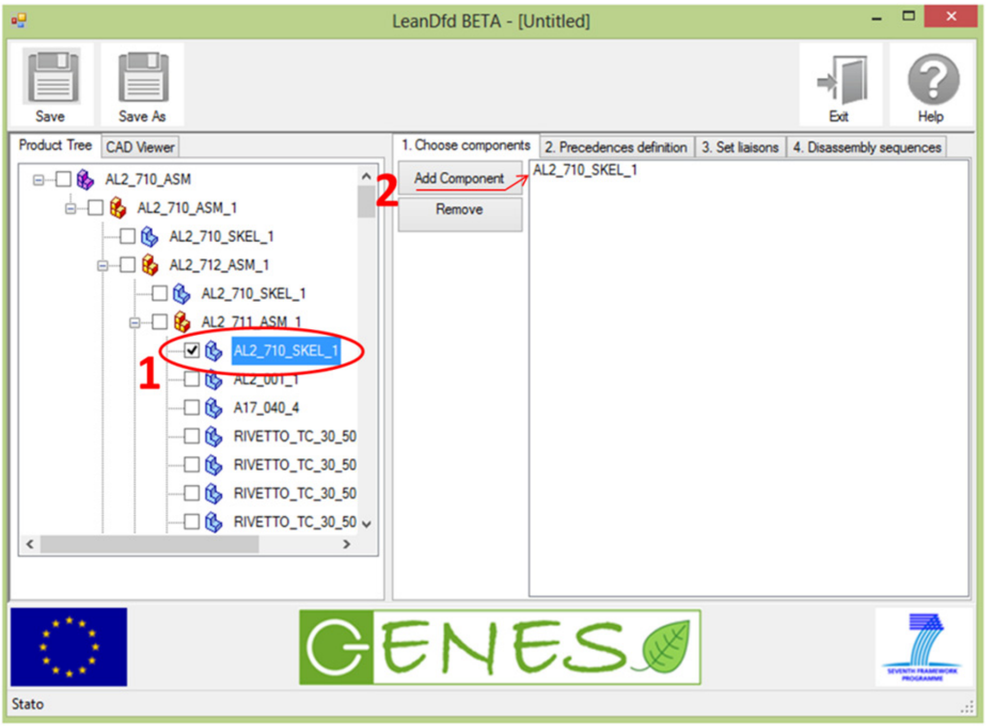

Figure 48. *Choose target components.*

- **Define the precedence between components.** In this step the user has to define the hierarchy (the level in the interface) of each component in the product structure (Figure 49). Then for each component at each level, he has to specify which components need to be disassembled before the selected one. In Figure 5 below for instance, we have the component A17_040 that belongs to the Level 2. And in order to disassemble the components A17_040 the user has recorded that it is necessary to disassemble the component A18_905_AMS that belongs to the Level 1.

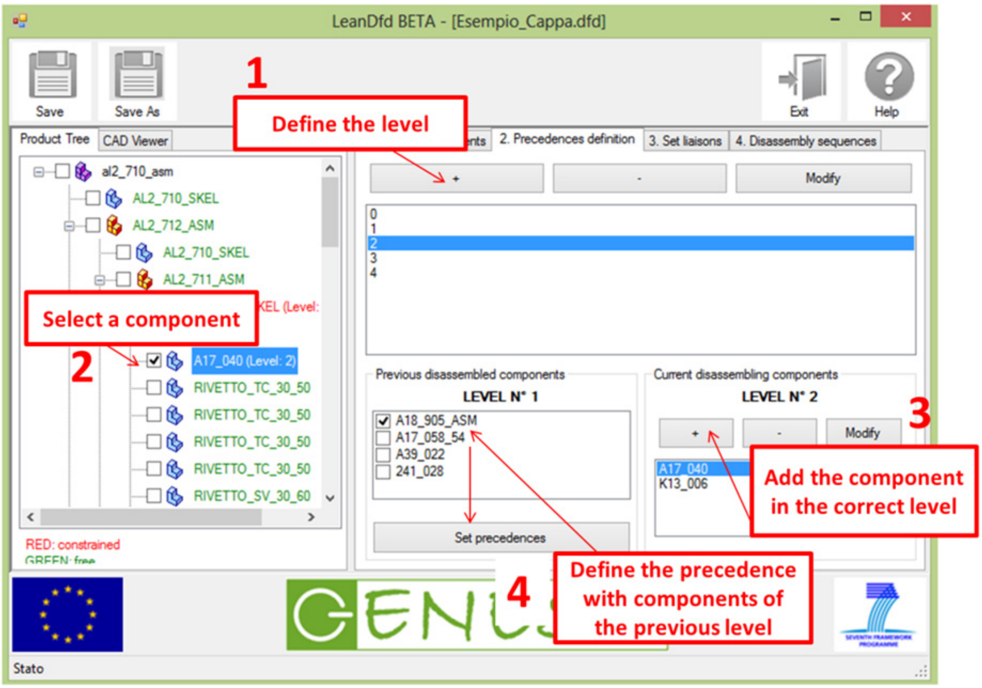

Figure 49. Define the precedence between components.

- **Define connections and describe the connection type and properties.** The user has to select a component from the product structure on the left hand side and then select the linked components from the table in the right side of the interface, by ticking each component box. Then, he has to click on the "Set liaison" icon (Figure 50). Finally, he has to specify the liaison type and the liaison properties (Figure 51).

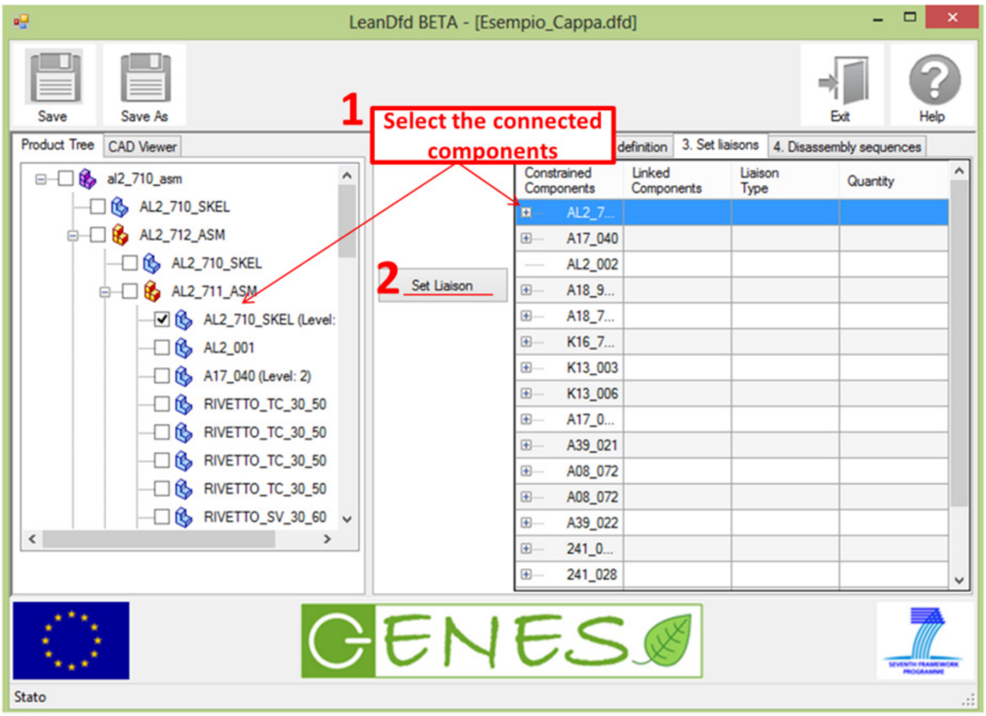

Figure 50. *Set Liaisons.*

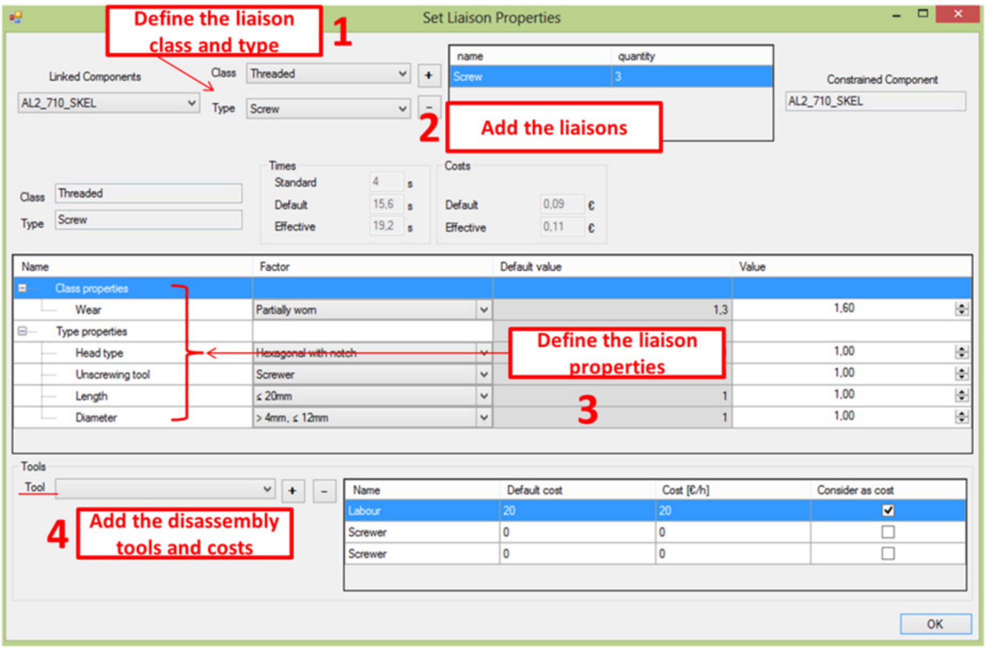

Figure 51. *Set liaison properties.*

- **Disassembly sequences**. In the final sheet, the user has to choose one of the previously defined target components and view the disassembly analysis results. The tool will show all the feasible disassembly sequences, and by double clicking on a specific sequence, the user can view the results (disassembly time and cost) in graphic form (Figure 52).

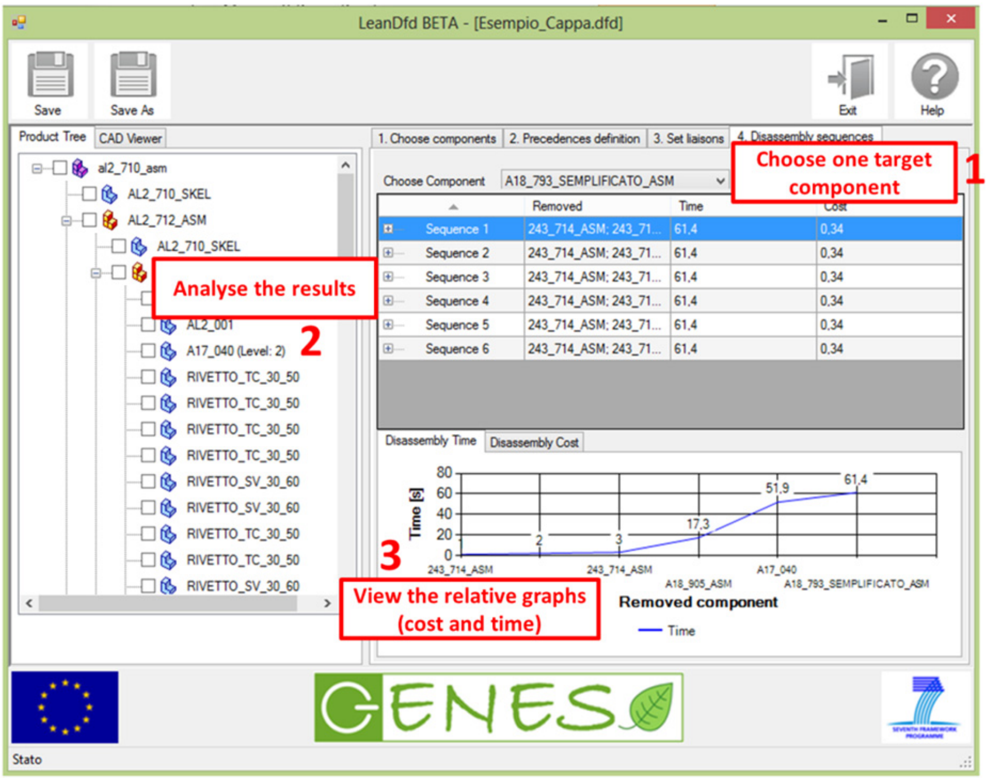

Figure 52. *Disassembly sequences.*

B.2.2. *Case 2*

If the user wants to analyse the EoL performances (in terms of recyclability level) of the product, he has to click on the icon "EoL analysis" of the tool main interface (Figure 46). The following section presents the main steps which the user will follow to undertake the EoL analysis. This module is able to calculate outputs from an XML file (the XML file is used by the G.EN.ESI tools to store product properties and contains all the material information).

When the user has selected "EoL analysis", the first interface he will see, is the "Material Properties" sheet that has the same structure as the main interface of the Disassembly module. It is in fact composed of 2 sections: the left section in which the product structure is shown, and the right one in which a summary of product properties is shown (Figure 9). In the left section the user can see for each component:

- the material (if a material is associated with the component in the XML file);
- the mass (if a mass is associated with the component in the XML file)
- information about EoL properties:
    - Hazardous (if YES, the material cannot be sent to landfill)
    - Incinerable (if YES, the material is suitable for incineration)
    - Biodegradable (if YES, the material is biodegradable)

In the right section the user will see four tables:

- a summary of the percentage in the total product mass of Hazardous, Incinerable and Biodegradable materials contained in the entire product (section A in Figure 53);
- the icon to consult the "Incompatibility Matrix" for plastics (useful to understand what the main incompatibilities for the plastic recycling process are) (section B in Figure 53);
- a summary of the "Non-recyclable plastics" contained in the product and the possibility to indicate if they are manually separated (section C in Figure 53);
- a summary of the "Partially compatible plastics" contained in the product and the option to indicate if they are manually separated (section D in Figure 53);
- a summary of the "Incompatible plastics" contained in the product and the option to indicate if they are manually separated (section E in Figure 53).

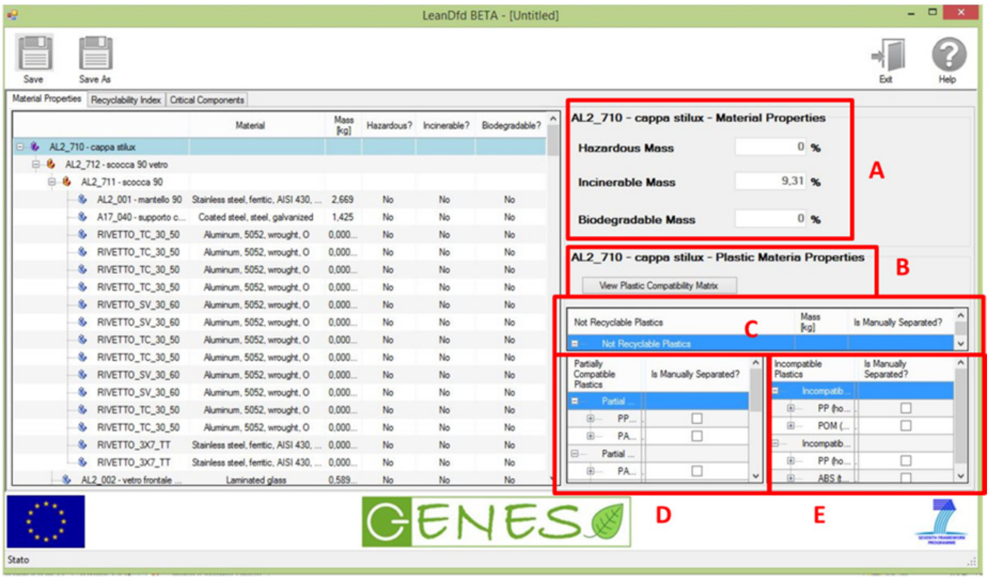

__Figure 53.__ Material Properties sheet.

The tool automatically inserts the components (on the basis of the material from which they are composed and on the basis of information stored in its Data Base) in the table "Non-recyclable plastics", "Partially compatible plastics" or "Incompatible plastics". Then, the user has to specify if a manual separation of these materials is required before shredding, when the product at its EoL will be recycled. The requirement for manual separation of these "critical for recycling" components, will influence the recyclability level of the entire product, so it is necessary that the user specifies this information.

After the user has inserted the information on manual disassembly/separation for those components that the tool has identified as belonging to the category "Non-recyclable plastic", "Partially compatible plastics" or "Incompatible plastics", he can proceed to the Recyclability Index sheet. The first step is to to insert data on the "Material contamination" section in the right section of the interface (Figure 54).

In this section, the user has to insert information on material contamination, by answering two questions. If contaminants are present, the user has to answer YES to the two questions and then specify the contaminated components, by selecting them from the product structure and by clicking on the icon "Add contaminated component". Then he has to specify the contamination type for the specific components selected. This operation need to be completed for metal components (question one) and for those components contaminated by acoustic foam, glues, paint and coatings, etc (question two).

After he has inserted the contaminant information, he can move on the "Recyclability Index" section (Figure 55). In this section the user can see the Recyclability Index of the entire product (as a percentage) at the top of the section, and the recyclability index in graphical form for each product component at the bottom.

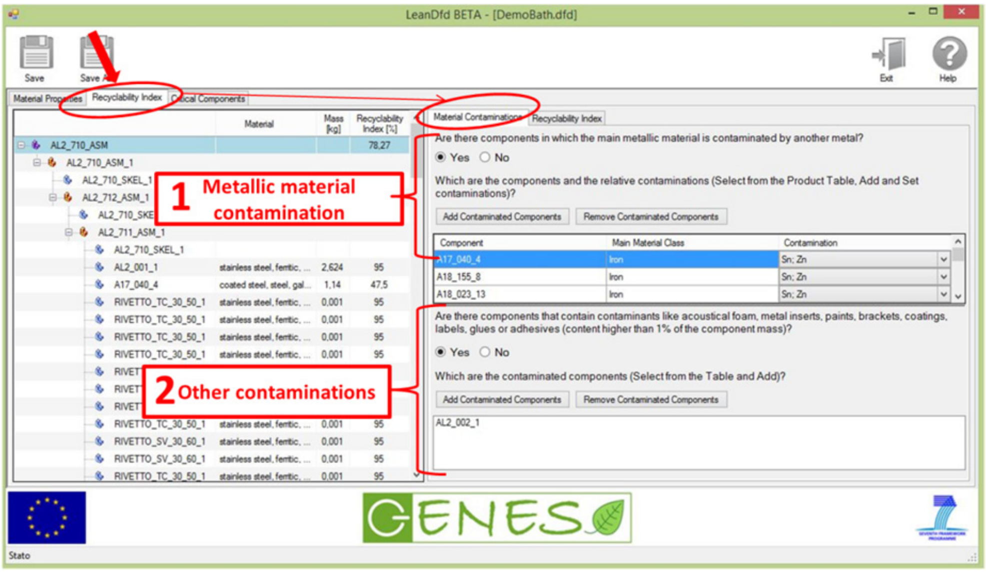

Figure 54. *Material Contamination section.*

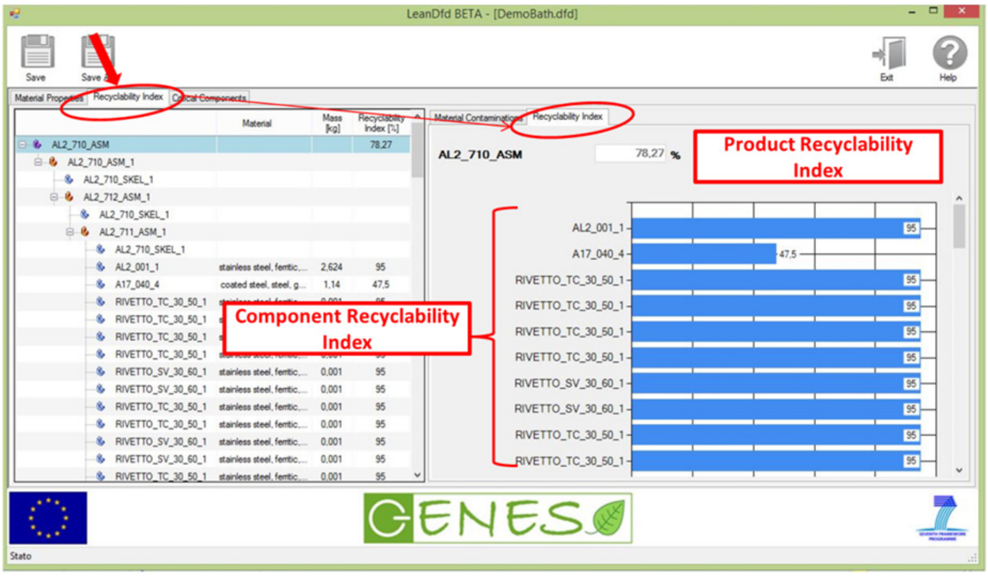

Figure 55. *Recyclability Index section.*

The final sheet the user can consult is the "Critical component" sheet (Figure 56). In this sheet, the user has to choose the product typology to which the analysed product (cooker hood, washing machine, refrigerator, etc…) belongs. After he has selected one of the possible product typologies, the tool automatically retrieves the related critical components for this typology,. Critical components are all those components that cannot be recycled, due to the fact that they contain hazardous or dangerous material and need to be manually disassembled before mechanical shredding. These critical components are shown to the user in the critical component combo box at the right of the product typology icon.

The next stage is to associate the critical components in the product structure with general critical components. This operation is undertaken by:

- selecting a component from the product structure;
- selecting the corresponding critical component from the "Critical Component" combo box;

- clicking on the icon “Set Critical component”;

After the association is made, the tool creates a row to indicate:

- the component name;
- the corresponding critical component;
- an attachment which contains information on EoL treatments specific to that critical component (in .pdf format);
- the option to select the critical component as a target component of the disassembly analysis module of the LeanDfD tool and directly launch the disassembly analysis by clicking the “Launch Disassembly analysis” icon.

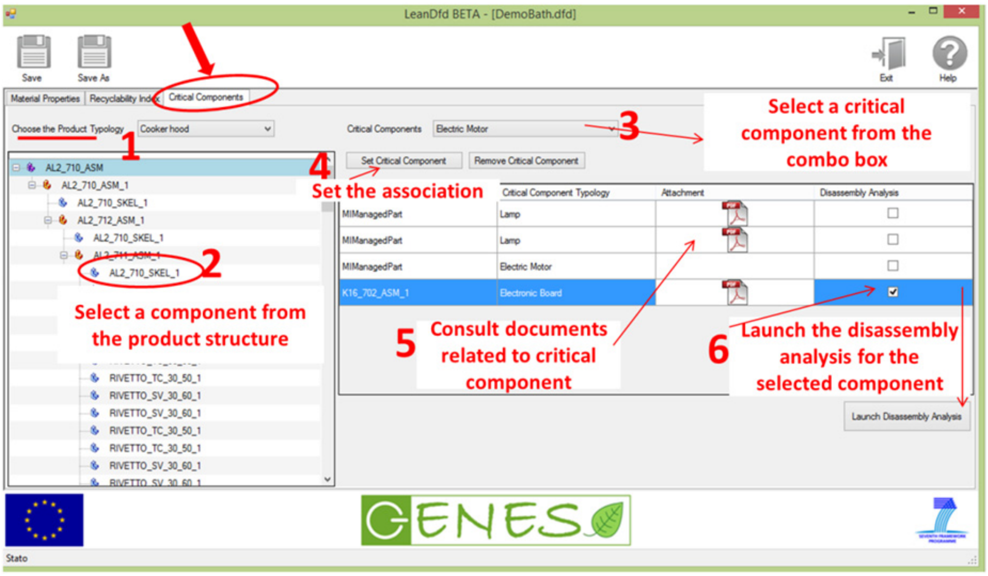

Figure 56. *Critical component sheet.*

The user can finally save the completed analysis, and exit to return to the main tool interface. Here the user can see all the analyses previously undertaken using Disassembly or EoL analysis in the summary section.

Once the user has completed the analysis and has exited from the analysis sheet (Disassembly or EoL), he can save the analysis in .dfd format or Export the analysis in XML format by selecting the relevant icons (Figure 57).

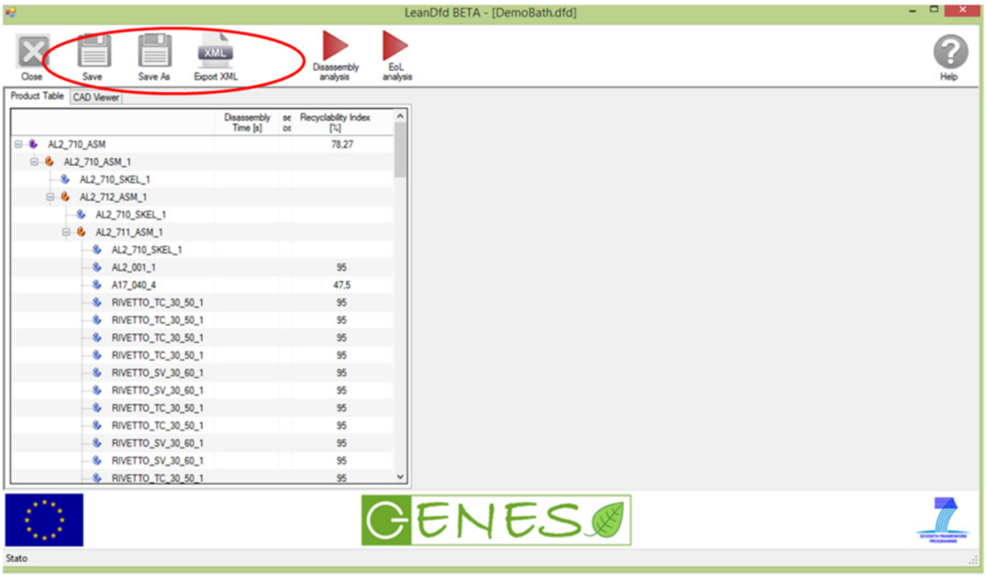

__Figure 57.__ Options to save the analysis.