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AN END OF LIFE ORIENTED FRAMEWORK TO SUPPORT THE TRANSITION TOWARD CIRCULAR ECONOMY

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Abstract

Circular economy is recognized as the most effective economic model to face issues related to waste management and resource scarcity. This requires to efficiently manage the End of Life (EoL) phase, which represents the joining link to close the product lifecycle. The objective of this paper is the definition of a framework to monitor product EoL during the most affecting phases. It is founded on the concept that it is better to prevent issues, by designing optimized products and creating favourable operative conditions, other than solve problems related to EoL. The EoL-oriented framework integrates three innovative resources: (i) a Design for Disassembly Tool to identify product criticalities, (ii) a Disassembly Knowledge Database to support the redesign phase and (iii) a Collaborative EoL platform for the sharing of relevant data and materials. The final aim is to provide companies with a set of integrated methodologies and tools able to support the decision-making process at different levels (from conception to EoL management), in order to design product with improved performances in terms of disassemblability, maintainability, de-manufacturing and EoL.

Keywords: Circular economy, Sustainability, Product Lifecycle Management (PLM), Design for X (DfX)

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1 INTRODUCTION

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 1970's we are using more resources than nature can regenerate and we are emitting more carbon dioxide into the atmosphere than forests can sequester (Global Footprint Network, 2016).

From the policy point of view, the European Union (EU) is facing these problems with increasing efforts, by issuing a series of legislations and long term programme with the objective to provide a strategic vision to reduce the environmental impacts caused by human activities. One of the nine pillars of the 7th Environment Action Plan (European Parliament and Council, 2013) is the transition to a resource-efficient, green and competitive low-carbon economy, which includes a special focus on turning waste into resources, through prevention, reuse, recycling and an efficient EoL management.

In a context where raw materials are limited and the economic growth cannot be interrupted, it is necessary to decouple these concepts. An effective solution is certainly the Circular 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 economic convenience of the transition to a circular business model strictly depends by different aspects, among them: possibility to efficiently take back products at the End of Life (EoL), cost of the reverse supply chain, product/component obsolescence, easy of disassembly of products, cost of EoL activities (e.g., disassembly, repair, cleaning, etc.), consumer awareness on green or remanufactured products, the legislative framework, etc. Both product design and waste management phases play a fundamental role to make products more durable, easier to repair, remanufacture or reuse, and to increase the rates of material recovery with the minimization of environmental impacts and economic losses (European Commission, 2015).

Considering the different lifecycle phases, EoL 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 paper is the definition of a conceptual framework to monitor the product EoL during the most affecting phases of the product lifecycle. 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. The final aim is to provide companies with a set of integrated methods and tools able to support the decision-making process at different levels (from conception to EoL management, from engineering to business activities, etc.).

2 RESEARCH BACKGROUND

End of Life is hard to monitor, since it involves many heterogeneous aspects and stakeholders.

Within the product EoL, disassembly is a preliminary but fundamental phase. Only reducing a product into its individual components (non-destructive disassembly) or constituent materials (destructive disassembly) it will be possible, for example, to reuse or remanufacture components (Mule, 2012). Design for Disassembly (DfD) is a class of target design methodologies to help designers in the early phase of product design (Dewhurst, 1993). The literature in the DfD field includes numerous topics, such as the Disassembly Sequence Planning (DSP) (Lee et al., 2001), the estimation of disassembly time (Germani et al., 2014), the evaluation of the economic feasibility of the different EoL scenarios (Bogue, 2007), etc. To make DfD approaches more efficient and less time-consuming, they should be integrated with 3D models to detect possible paths for the disassembly of a specific component (Santochi et al., 2002), to recognize liaison between components (Adenso-Díaz et al., 2007) and to derive optimal disassembly sequences (Cappelli et al., 2007). All these approaches and prototypal tools only focus on the disassembly phase, while the other EoL-related aspects are not considered.

With the diffusion of the Extended Producer Responsibility (EPR) paradigm, companies have been obliged to pay more attention to the EoL of their products, trying to determine the best EoL option for entire products and critical components, encouraging the implementation of EoL closed-loop scenarios (reuse, recycle and remanufacturing) (Zwolinski and Brissaud, 2008). Generally, target design methodologies about Design for EoL (DfEoL) emphasize single aspects or scenarios of the product EoL. Design for remanufacturing focuses on methods and tools for establishing the product properties with respect to remanufacturing (Zwolinski et al., 2006). Another common approach is design for material recycling, which aims to increase the recyclability of products at EoL, by using generic material compatibility charts (Le Pochat et al., 2007). Other more comprehensive DfEoL methods and tools are focused on integrating lifecycle considerations into the design process (Doi et al., 2010), improving modularity to maximize the recovery of parts or materials (Kwak and Kim, 2010) or selecting the best scenario for treating an EoL product (Bufardi et al., 2003). All of these approaches are also based on qualitative and subjective information, which reduces their effectiveness or limits the field of application, and do not give specific information on how to improve product characteristics.

Another key topic in the context of Circular Economy and EoL management is the knowledge capitalization and sharing (Tenopir et al., 2011). A forward (from design to EoL) product information sharing process positively impacts the recovery phase (Das and Naik, 2001; Parlikad and McFarlane, 2007). Concerning backward (from EoL to design) sharing to support design activities, DfD and DfEoL guidelines are commonly used, but they are too general and lack for precise recommendations (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. Different studies in this field demonstrated that quantitative data coming from the recovery phase can be used to significantly improve product design (Favi et al., 2016; Movilla et al., 2016) The final aim of these researches is the sharing of useful EoL information among the different lifecycle stakeholders.

Another aspect to consider is certainly the collaboration between the different actors, who contribute with competences and expertise to the realisation of a product and to the management of its life (Germani et al., 2015). Also in case of circular business models (e.g., reuse of components at EoL), the development of collaborative systems to support the decision-making process is recognized as a means to improve the overall performances of the entire network (Milovantseva and Fitzpatrick, 2015).

A general outcome of the presented literature review is the extreme complexity of issues related to product EoL management and Circular Economy. The high number of different approaches and methods proves that aspects to take into account are numerous and heterogeneous. Anyway, 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. DfD methods), EoL processes, EoL management, reverse supply chain, etc. An important step forward of this research work is the definition of an EoL-oriented framework 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 the most affecting phases of the decision-making process.

3 LIFECYCLE PHASES AND THE INFLUENCE ON PRODCUT END OF LIFE

To better understand which are the phases that mainly influence product EoL, an in-depth analysis of the product lifecycle, together with the EoL-related aspects, is presented in the following Figure 1.

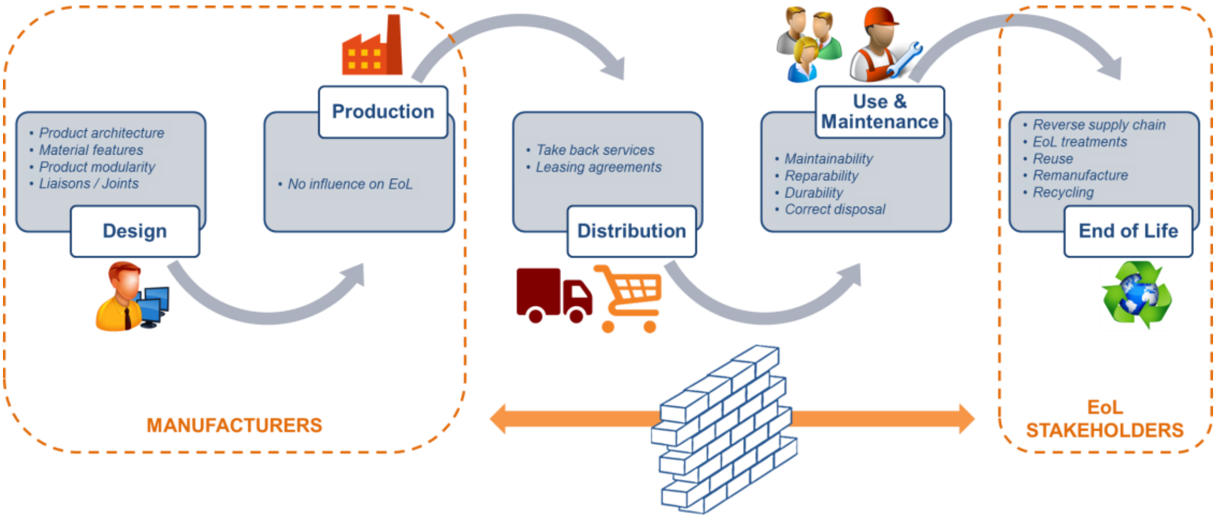

Figure 1. Product lifecycle phases and influence on product EoL

The product Beginning of Life (BoL) is generally managed "within the wall" of a manufacturer that conceives a new product idea (or a variant of 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 Middle of Life (MoL) phases, when retailers/distributors, consumers and service providers have a central role. Finally, the EoL can involve different actors, depending on the product typology, the geographical area or the existing regulations.

3.1 The key role of the Design phase

In general, the Design phase is a very complex problem solving process, influenced by a plurality of domains and by an high number of parameters (e.g., technical, social, strategic, economic, etc.), which allow reaching a feasible and satisfying solution.

According to the Systematic Approach (Pahl et al., 2007), the design process can be subdivided in four main phases: (i) the Planning and Task clarification, aiming at clarifying the requirements, (ii) the Conceptual Design, aiming at defining a preliminary solution (i.e. concept), (iii) the Embodiment Design, aiming at developing the overall product layout and (iv) the Detail Design, aiming at finalizing the design choices and generating the documentation for the successive phases.

Product design plays a critical role in the efficient management of product EoL and thus in favouring the viability of circular business models. 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 (Hatcher et al., 2011).

3.2 Production phase

The Production phase can be essentially viewed as the "concretization" of the product idea 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. Indeed, 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 involved.

However, 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. 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 closed-loop lifecycles.

3.3 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: (i) direct chains, in case of direct relationships between producers and consumers, (ii) short chains, in case of distributions realized by means of retailers, and (iii) 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-service 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.

3.4 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). 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. Moreover, the EoL scenario is a direct consequence of choices performed during the use phase (e.g., landfilling, disposal in recycling centres, repair, etc.). Stakeholders of the use and maintenance phases have to be necessarily involved to improve efficiency in product EoL management.

3.5 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 for the management of 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.
This complex environment requires the involvement of numerous and heterogeneous stakeholders. Each one is in charge of a specific phase: shippers for the transportation of wastes and EoL goods, authorized recycling centres for the disassembly and/or material recovering phases, remanufacturers for refurbishment activities, etc. The number and typology of stakeholders depends on the typology of products to treat. An EoL-oriented framework must consider all these aspects, the most important actors and their inter-relations.

4 THE END OF LIFE ORIENTED FRAMEWORK

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. However, also the other lifecycle stakeholders have strong influences on the EoL performances. Summarizing, 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;
- management of the stakeholders' network 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?).

A new configuration of the product lifecycle is thus needed to favour the implementation of circular business models, as depicted in Figure 2.

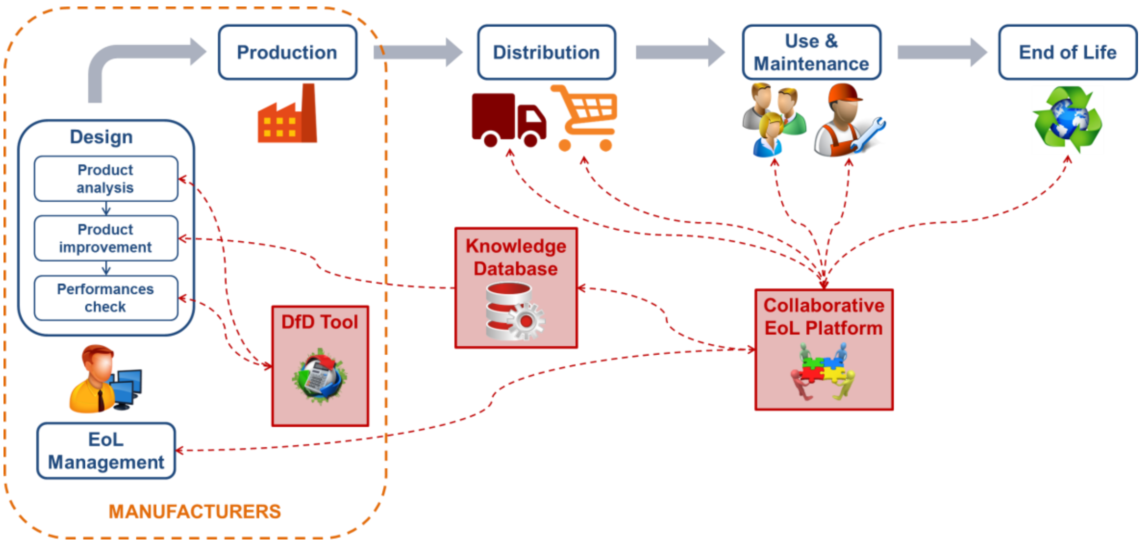

Figure 2. The proposed conceptual framework to manage product EoL

According to the proposed conceptual framework, the involved stakeholders are now supported, during key activities, by specific additional methodologies and tools, namely a DfD tool, a Disassembly and EoL Knowledge Database and a Collaborative EoL Platform. 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. The following sub-sections briefly explain the main features of the additional resources to efficiently monitor the product EoL.

4.1 A DfD tool to monitor product disassemblability

The first resource (DfD tool) included in the framework is dedicated to manufacturers, with the aim to manage the disassembly phase during the product design process (Favi et al., 2012a, 2012b). As stated in the Research Background section, disassembly is a preliminary but essential process toward product/component reuse or remanufacture, thus its influence on EoL performances is very high. The measure of product/component disassemblability during the design process allows identifying product criticalities, preventing potential issues and focusing the redesign strategy.

The DfD tool is based on three quantitative metrics: (i) the disassembly depth (i.e. number of operations to reach a target component), (ii) the disassembly time (i.e. estimated time to reach a target component within an assembly), and (iii) the disassembly cost (i.e. estimated cost to disassemble a target component by considering costs of labour and tools). These indicators can be analytically estimated, starting from the common product virtual representations (e.g. 3D CAD models, bill of materials, etc.), by using knowledge about liaisons (e.g., standard disassembly time, corrective factors to take into account liaison condition at the moment of the disassembly, etc.) (Germani et al., 2014). The availability of quantitative results during the design process is a key aspect to support the activities of the design team.

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 DfD 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. But, at the same time, detailed information are essential to perform the analyses, such as, shapes of components, materials or liaisons between components/parts.

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

Considering 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 any particular impacts in terms of additional project cost. Simulations about product disassemblability performed by using a DfD tool, integrated with Computer Aided Design (CAD) systems, are possible during the Embodiment Design phase, since the needed input data are available.

The use of a DfD tool that allows monitoring additional aspects (i.e. disassemblability and EoL performances) during the iterative process of analysis, change and check, usually performed by the design team to reach the final solution, is certainly an added value to have a more comprehensive view of the product lifecycle performances.

4.2 A Knowledge Based Methodology to guide the product improvement phase

The second methodology and repository (Knowledge Database) included in the framework aims to support design tasks of manufacturers (Favi et al., 2016).

As the DfD tool, also the Knowledge 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, disassembly cost, etc.), the DfD 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 DfD tool is an analytical system that provides quantitative assessments to identify weak points (e.g., components that require a higher disassembly time or an higher number of operations) and does not give any specific design suggestion on how to modify the product in order to solve the identified issues.

To overcome this lack a Knowledge Database is needed to provide practical and specific design suggestions based on knowledge coming from disassembly and EoL activities and processes. The stored EoL knowledge should derive from the collection, formalization and classification of the positive and negative knowledge and expertise about disassembly and EoL processes (e.g., cleaning operations) carried out by dismantlers and remanufacturing centres. In particular, the collection can be performed through surveys, interviews of the involved operators and direct observation/video recording of their activities. 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 for the formalization of specific design guidelines (Movilla et al., 2016). The best and worst design practices from the disassembly and EoL points of view can be then identified. In particular, best practices are those ones that allow operators to carry out the disassembly operations rapidly, while worst practices 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. The defined knowledge classification rules are based both on product characteristics (e.g., product families, target components to disassemble manually, assembly methods, etc.) and on other more general aspects (e.g., motivations of the disassembly, handling difficulties, etc.) (Favi et al., 2016). The Knowledge Database represents a concrete way to extend the producer responsibility, to close the current gap between manufacturers and dismantlers and to reduce complexity and cost of the disassembly and remanufacturing operations/processes.

By using the indications stored in the Knowledge Database, manufacturers can 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 during the product conception and design.

4.3 A Collaborative EoL Platform to "close the gap" between lifecycle stakeholders

The third proposed system (Collaborative EoL Platform) aims to favour the collaboration between the most important lifecycle stakeholders (Marconi et al., 2017).

On the basis of the analysis presented in the previous 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. In order to effectively implement closed-loop lifecycles, and thus to shift to circular business models, it is essential to facilitate the collaboration between the different lifecycle stakeholders (e.g., suppliers, manufacturers, consumers, service providers, etc.).

The basic idea of the Collaborative EoL Platform is to create a shared environment to favour the creation of additional physical (e.g., materials, components) and virtual (e.g., information) flows. The sharing of second-life components or products to be reused or remanufactured, the sharing of knowledge about best practices (i.e. Knowledge Database) and the support during the decision-making process at EoL are essential functionalities that this kind of platform should provide to the network of involved actors. The final aim is to support companies in choosing the best EoL scenario (e.g., reuse, remanufacture, selling to other companies, etc.) that allows maximizing economic convenience, while minimizing environmental impacts.

5 USE SCENARIOS

The use scenarios of the proposed conceptual framework to manage the product EoL could be different. The following Figure 3 illustrates some of the possible activities that can be performed by using the three included resources (i.e. DfD tool, Knowledge Database, Collaborative EoL Platform). The general idea is to favour the creation of additional flows of information (red dotted arrows in Figure 3) and materials (red continuous arrows in Figure 3), in order to practically implement closed-loop lifecycles.

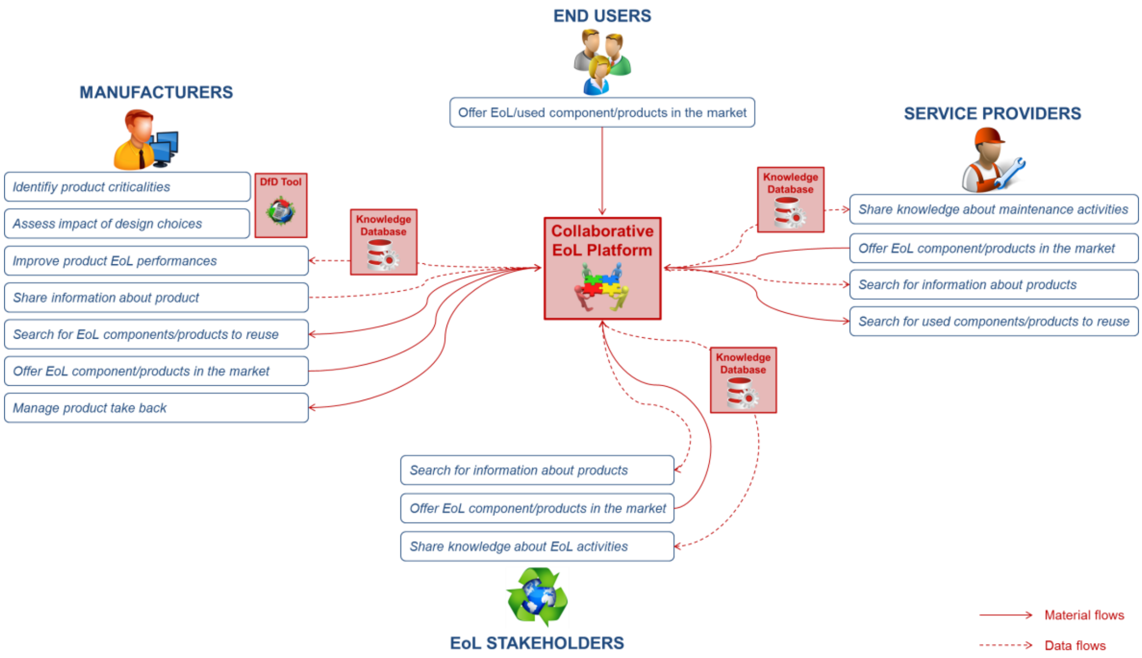

Figure 3. Framework use scenarios and flows of data and materials

First of all, *Manufacturers* can use the DfD tool during the design phase in order to identify potential EoL-related criticalities and correctly focus the improvement strategy toward more sustainable products and business models (e.g., remanufacturing). For the redesign phase, the Knowledge Database represents a useful means to make the most correct design choices and support also designers who do not have expertise in ecodesign themes. In addition, the DfD tool can be used to assess the impacts of design choices, in order to finally reach the most appropriate solution.
The collection and classification of data to be stored in the Knowledge Database requires the collaboration of *Service Providers* and *EoL Stakeholders*. They mainly act as information providers to share with *Manufacturers* their positive (i.e. best practices) and negative (i.e. common issues and problems) knowledge about maintenance and EoL activities. Anyway, they can also use the Knowledge Database as a repository of relevant information to standardize and make their processes more efficient and repeatable. The Collaborative EoL Platform is the virtual environment to practically realize this exchange of information, in order to close the gap between the different phases of the product lifecycle.
Another example of information sharing is the case of *Manufacturers* that want to make available to *End Users*, *Service Providers* or *EoL Stakeholders* specific information about the disassembly, maintenance or EoL of their products. This use scenario is completely compliant with the EPR concept and can be viewed as the lacking means 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 Collaborative EoL 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, all the information relative to the scheduled maintenance or the necessary product substitution can be stored and shared with *End Users*. In this way, *Manufacturers* and *End Users* can constantly collaborate to extend the product lifecycle and to guarantee an high quality service.
However, not only flows of information are possible, since the Collaborative EoL Platform can be also used as a public repository of second-hand components/products during the product useful life or at the EoL. Each item should 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

implementing closed-loop lifecycles, where the waste of a stakeholder (e.g., EoL consumer goods discarded by *End Users*) could become a precious resource for the same or another involved stakeholder (e.g., EoL components recovered from EoL goods can be reused by *Manufacturers*).

6 DISCUSSION AND CONCLUDING REMARKS

This paper deeply investigates issues and opportunities related to product EoL. It demonstrates that the product EoL, if opportunely managed with dedicated methodologies and tools included in a EoL-oriented framework, represents an important resource to exploit, instead of a problem to manage. This framework is founded on the concept that it is better to prevent issues, by designing optimized products and creating favourable operative conditions, other than studying and developing solutions to solve problems related to EoL (e.g., difficulties to recycle materials).

The proposed framework represents a 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.

An aspect to mention is that the proposed framework requires 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 Collaborative EoL platform is advantageous if different companies, involved in the lifecycle of a product, actively contribute to 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.

Future activities are needed to guarantee the integration and interoperability among the tools included in the framework and with company repositories and management systems. This will reduce impacts on traditional processes, but requires the study of standard procedures, to be followed by all the stakeholders, and standard exchange files, to be read/saved by all the interconnected resources.

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