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A design for disassembly tool oriented to mechatronic product de-manufacturing and recycling

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Abstract

The easy disassembly of certain product components is a prerequisite to guarantee an efficient recovery of parts and materials. This is one of the first step in the implementation of circular economy business models. Design for Disassembly (DfD) is a particular target design methodology supporting engineers in developing industrial products that can be easily disassembled into single components.

The paper presents a method and a software tool for quantitatively assessing the disassemblability and recyclability of mechatronic products. The time-based method has been implemented in a software tool, called LeanDfD, which calculates the best disassembly sequences of target components considering disassembly precedencies, liaisons among components, and specific properties to model the real condition of the product at its End-of-Life (EoL). A dedicated repository has been developed to store and classify standard times and corrective factors of each disassembly liaison and operation. This knowledge feeds the two LeanDfD tool modules: (i) product disassemblability module, which allows to carry out the time-based analysis and to improve the disassemblability performance of target components, and (ii) product recyclability module, which estimates the quantities of materials that could be potentially recycled at the product EoL. The LeanDfD tool functionalities have been defined starting from the means of the user stories and the developed tool framework, data structure, databases and use scenarios are described.

A group of designers/engineers used the tool during a re-design project of a washing machine, considering the disassemblability as the main driver. The case study highlights how the proposed DfD method and tool are able to support the implementation of re-design actions for improving product de-manufacturability and EoL performance. The LeanDfD features aid engineers in making a quick and robust assessment of their design choices by considering quantitative disassemblability and recyclability metrics.

Keywords

Design for Disassembly tool; Disassembly Time; Disassembly Sequence Planning; Recyclability.

1 Introduction

The final disposal of goods and products is a critical issue that must be considered to reduce the amount of wastes and to save resources. For these reasons, the end-of-life (EoL) management of industrial products and components has become a topic of rapidly growing interest for manufacturers and dismantling centers. Concerning the management of EoL wastes, three main perspectives drive the new generation of designers/engineers: (i) the compliance with legislation/regulations, (ii) the reduction of the environmental impact considering the whole product lifecycle, and (iii) the possibility of making profits through the implementation of circular business models (e.g. remanufacturing) [1].

Product design plays a critical role in obtaining such benefits. Product design features, such as material, shape and dimensions, product architecture, functionalities and modularity, should be evaluated considering the entire lifecycle, with a focus on its usage and final disposal. Improving the product maintainability means considering the disassembly features for those target components subjected to scheduled maintenance and service, with the aim to develop new sustainable business models (e.g. product-service) [2][3]. Improving and upgrading the product recyclability, to facilitate the efficient recovery of components and materials from the product, requires considering several aspects (e.g., reverse logistics and disassembly) in the early design stage [4].

Design for Disassembly (DfD) is a particular target design methodology (DfX) supporting engineers in developing industrial products that are easily dismountable into single components. Briefly, DfD entails: (i) the simplification of de-manufacturing operations, (ii) the reduction of disassembly time/cost, and (iii) the recovery of relevant quantities of components and materials. DfD involves different design tasks, such as the material selection, component design, and product architecture definition, as well as the correct selection and use of joints, connectors and fasteners [5]. Existing DfD approaches suffer from practical limitations to their implementation in technical design departments. These tools usually consider disassembly time as an input parameter and do not focus on the calculation of effective disassembly time. Real conditions of the product at the time of disassembly are generally not accounted, as well as their effect on the disassembly operations. In addition, most of the DfD tools seem complicated for a daily use and lack in supporting designers and engineers during the setting of decision-making strategies for the improvement of complex products [6]. The mentioned issues have been the main drivers for the development of this research work.

The paper aims to propose a design for disassembly framework and software tool (called LeanDfD), which can be used by technical departments during the product development process. The research context is related to complex mechatronic products, which includes appliances, vehicles, machines, etc. The approach is based on the calculation of the disassembly sequence and the effective disassembly time by using simple equations, robust data and the aid of a 3D CAD viewer. An important novelty of the proposed tool is related to the knowledge repository, called Liaison DB, which properly classifies and links mechanical liaisons with features and standard disassembly times. A time-based analysis permits robust disassembly estimations in terms of disassembly paths and time to reach a target component ("effective" disassembly time). The tool is able to assess different metrics, such as the disassembly time of target components, cost and recyclability ratio. The disassemblability and recyclability analyses represent an essential prerequisite for identifying criticalities (e.g., components with low accessibility and critical materials not easily recycled) and guiding the re-design stage with specific suggestions properly developed considering the identified criticality. The final goal of LeanDfD is to link three main aspects related to the product de-manufacturing and recycling: (i) the "effective" disassembly time for a specific target component, (ii) the identified criticalities and (iii) the re-design suggestions.

The paper is structured as follows: Section 2 reports a literature review of DfD frameworks and tools, highlighting the current limitations to implement them in technical design departments. Section 3 describes the methodology developed and used for the definition of the DfD tool (described in Section 4). A case study in the context of mechatronic products is proposed in Section 5. The study's results and conclusions, including pros and cons, are presented in Section 6.

2 DfD methods and tools review

The first studies on design for disassembly topic started in the early 1990s when the problems related to the waste of industrial products became a new world challenge [7]. The literature is particularly broad in this field, and it includes several topics, such as: (i) the application of rules and guidelines to design easily disassemblable products [8][9][10], (ii) the generation and optimization of disassembly sequence planning (DSP) [11][12][13], (iii) the mathematical problem solutions for disassembly line balancing [14][15], and (iv) the classification and formalization of disassembly knowledge [16][17][18].

2.1 DfD rules and guidelines

Preliminary studies conducted by Ishii et al. [19] aimed to consider the disassembly as part of a more complex scenario (the product EoL) and to provide qualitative information about the management of components and sub-assemblies for product retirement and disposal (e.g. recycling). For this reason, an overlapping among different EoL oriented target design methodologies have been observed in the literature (e.g., Design for Remanufacturing, Design for Recycling) [20][21][22][23]. This is the case for the approach defined by Rose and Ishii [24], who developed a tool able to guide product designers in the specification of appropriate EoL strategies. According to Bogue [10], a list of rules and guidelines can be adopted during the design phases to facilitate de-manufacturing operations. These rules can be managed by expert engineers who know the product features and characteristics. A possible organization of DfD rules has been proposed by Favi et al.[25], with the aim of suggesting design improvements (material selection, liaison type, etc.) based on the possible EoL scenarios. The rule and guideline application during the design process allows reaching a high level of product disassemblability. The final goal is to encourage the implementation of EoL closed-loop scenarios (reusing, remanufacturing and recycling) [26].

2.2 DSP methods

DSP is a fundamental task to judge the component or sub-assembly accessibility and to assess the disassembly paths, giving a quantitative measurement of the product disassemblability [27]. DSP can be considered as the starting point for the disassembly analysis and thus the first step in the definition of a DfD methodology. Several research activities focus on the development of algorithms and procedures to find the best disassembly sequence for target components in an industrial product. Two main categories of DSP methods can be defined as reported in Table 1: (i) exact methods (EM), and (ii) heuristic and metaheuristic methods (HM).

Research works based on EM guarantee finding the global optimum in a disassembly problem. EMs are time-consuming and of limited feasibility when the number of product components or sub-assemblies increases, because of the combinational nature of the problem. Research works based on HM have been investigated with the aim of decreasing the computational time. Indeed, HMs seem beneficial in terms of computational time, but they do not overcome the issue of manual inputs required for the analysis.

Table 1. Research works on exact methods (EM) and heuristic and metaheuristic methods (HM)

	Dewhurst [7]	De Ron, Penev [28]	Gungor and Gupta [11]	Srinivasan et al.[29]	Ong, Wong [30]	Srinivasan and Gadh [31]	Gungor and Gupta [32]	Mascle, Balasoiu [33]	Zhang, Zhang [34]	Galantucci et al.[35]	Kongar and Gupta [36]	Giudice and Fargione [37]	Hui et al.[38]	Smith et al.[39]	Xia et al.[40]	Kheder et al.[41]	Meng et al.[42]	Tseng et al.[13]
EM	X	X	X	X	X	X	X	X	X									
HM										X	X	X	X	X	X	X	X	X

To make DSP methods more efficient and less time-consuming, the required designers' inputs can be minimized by extrapolating data from the product structures (3D CAD models) [43][44]. The liaison type recognition and the arrangement of modules and components in the general assembly can be automatically retrieved from the CAD model [12][45]. Although the link with design tools (e.g., CAD) is particularly interesting to overcome the problem of manual data input, the presented methods aim to solve the path optimization problem, through the minimization of disassembly operations number or the minimization of items to remove. Literature analysis of DSP methods highlights a lack in methods that aim to solve the problem of disassembly time estimation and minimization. Preliminary studies on the estimation of disassembly time have been proposed with the aim to use disassembly time as target of DSP optimization problem [46][47]. Anyway, some aspects are not generally accounted and require further in-depth analyses, such as the relationship between the estimated disassembly time and liaisons features, and the re-design actions to improve the product disassemblability or recyclability performance.

2.3 DfD tools

DSP is only a specific aspect of the DfD that does not consider, for example, the way to improve the product. DfD requires a holistic approach, which includes, moreover, design and re-design aspects, definition of metrics to assess sustainability, comparison of alternatives, etc. Most of the available researches on this aspect provide an insight about specific models (e.g.; ontology, Case Based Reasoning) to determine recycling strategy and performance of disassembly operation [48] and/or to provide a decision-making system for disassembly [49].

Herrmann et al. [50] 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. Go et al. [51] define a set of modules that need to be developed to build a disassembly tool. The modules are software programs 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 remanufacturing. Issaoui et al. [52] 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 that minimizes the number of disassembly operations. The approach suffers of poor performances when a large quantity of components is connected to the target one. Another interesting DfD framework was proposed by Harivardhini et al. [53]. The tool proposed by the authors is oriented to support designers in evaluating some of the most important factors influencing disassembly (effort, ergonomic risk, profit, efficiency and environment). Currently, each disassembly task has to be entered manually by the designer. This certainly leads to a time-consuming and error-prone activity.

2.4 Outcomes of the literature review

In conclusion, looking into the literature, it emerges that DSP is the first step to define a structured and holistic DfD framework and tool. Several algorithms (both exact and heuristic) have been developed to solve the DSP problem. Even if all these proposed methods are very interesting, they are still on the level of research studies and far from practical implementation in the industrial/production context. Current approaches for DSP optimization mainly consist in the minimization of the disassembly paths (or tasks) rather than minimizing the "effective" disassembly time. In addition, DSP methods generally consider the disassembly time as input, while this parameter is the most important metric (output) used for the disassemblability evaluation and the implementation of design for disassembly strategies. The implementation of a time-based DSP approach into a design for disassembly tool has not investigated yet. In addition, another lack has been noticed in the current literature and it concerns the way to correlate the "effective" disassembly time calculated by a time-based DSP method and a set of structured guidelines for the improvement of disassemblability and recyclability aspects.

3 Methodology

The optimization of the product disassemblability and EoL performances necessarily require their estimation during the design process, when only product virtual representations are available. This section describes the theoretical frameworks for the evaluation of the disassemblability for selected target components and the recyclability ratio of the products.

3.1 Component disassemblability assessment

The analytical estimation of the disassembly time and cost of a selected target component is the result of the proposed four-step methodology (Figure 1), called *Disassemblability analysis*.

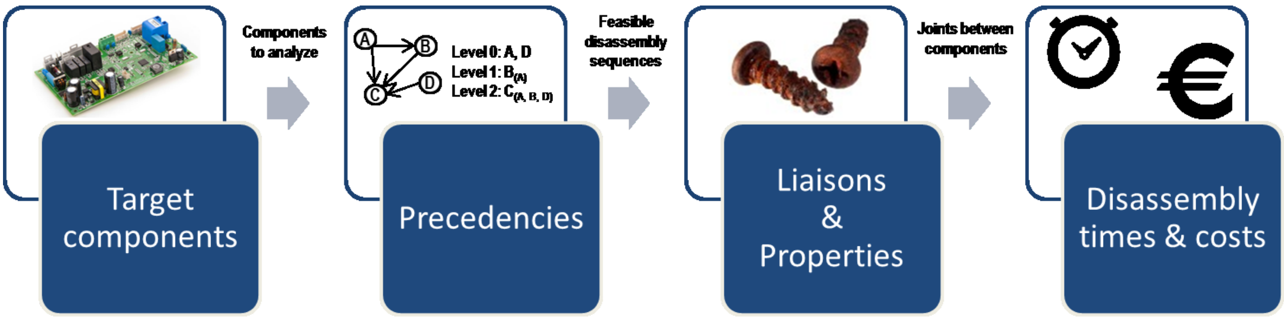

Figure 1: Methodology for "Disassemblability analysis"

The disassemblability estimation and the generation of disassembly sequences begins with the choice of the *Target Components*. Although they strictly depend on the product typology, they are generally selected based on normative, economic or maintenance reasons and belong to one of the following categories: (i) high residual value parts, (ii) hazardous components, (iii) parts containing incompatible materials, or (iv) components that require maintenance during the product lifetime.

The definition of *Precedencies*, between components or sub-assemblies that compose the product structure, is a required phase to derive feasible disassembly sequences. The general rule adopted for defining the precedencies is the following: "*a generic component "A" has to give the precedence to another component "B" if A must be disassembled after B*". Following this rule, the product components and sub-assemblies are subdivided into different disassembly levels. Level "0" contains all components that can be disassembled, initially, from the entire product. Level "1" contains components that can be disassembled only after removing one or more components of Level "0". In general, each component at Level "N" has to give precedence to one or more components belonging to Level "N-1". By using this information, it is possible to extrapolate feasible disassembly sequences to reach each target component, considering precedencies and obstructions. A broader description of this approach is given in a previous research work of the same authors (Mandolini, Favi, Germani, Marconi, 2018) and it is part of the state of the art in this field [47].

Once feasible disassembly sequences are calculated, it is necessary to "give a value" to each of them. The definition of *Liaisons & Properties* is an essential step toward the estimation of disassembly times. This phase is based on a classification and characterization of liaisons. A *liaison* is defined as "*the connection (mechanical, electrical, etc.) between two components which can be removed by a specific disassembly operation*". Liaisons have been subdivided into two different hierarchical levels: classes and types. For each liaison type, a standard disassembly time has been defined (Table 2).

Table 2. Standard disassembly times for the liaison types stored in the Liaison_DB [47]

Liaison class	Liaison type	Standard disassembly time Ts [s]
Threaded	Screw	4
	Threaded rod	4
	Nut	4
Shaft-hole	Pin	3
	Linchpin	3
Rapid joint	Snap-fit	2
	Guide	3
	Dovetail	3
	Dap joint	2
Piping	Rubber hose	2
	Spring Clip	4
Electric	Coaxial cable	4
	Electric plug	2
	Screw terminal	2
	Ribbon cable	2
Prevent extraction	Circlip	4
	Split pin	4
Not removable	Nail or Rivet	6
(destructive operation)	Welding	10
	Adhesive	6
Motion transmission	Tang or Key	3
	Spline profile	3
Washer	Washer	2
Bearing	Bearing	5
Magnetic	Magnetic	2
Visual obstruction	Visual obstruction or contact	1

The standard disassembly time is relative to a reference liaison (e.g. nut with a specific diameter, head type, etc.), disassembled with a specific tool (e.g. screw gun, spanner, etc.) in a standard condition (e.g. not worn/rusted). The last assumption is particularly important because the purpose of selective disassembly, both in the cases of maintenance and EoL, is the possibility to recover products or components without destructive actions. For instance, in the case of a nut liaison type, the reference is set to a new nut (not used or damaged) with a hexagonal head, threaded on a bolt for a length of 10 mm or less, a diameter between 4 mm and 12 mm and disassembled with a screw gun. In this case, the standard disassembly time (4 seconds) equals the assembly time. In addition to the standard disassembly time, several properties and relative corrective factors have been defined to take into account the peculiarity and specificity of each liaison under analysis (e.g., wear, geometric dimensions, and disassembly tools). Starting from the standard disassembly times and liaison characteristics, corrective factors are used to estimate the effective disassembly times of liaisons. This represents an essential feature of the proposed approach with the aim of guaranteeing a high reliability and consistency in the time estimation. Table 3 provides an extract of the liaison classification and characterization, specific for a nut.

Table 3. Liaison classification for a nut

Liaison class	Liaison type	Ts [s]	Liaison properties	Liaison corrective factors (Cf)
Threaded	Nut	4	Number	Integer (always $\geq$ 1)
			Head type	Hexagonal = 1.0 Slotted/Castle = 1.0 Square = 1.1 Nylon insert self-lock = 1.2 Wing = 1.2 Coupling = 1.3 Acorn/Cap = 1.1
			Length on bolt thread	L $\leq$ 10 mm = 1.0 10 mm < L $\leq$ 20 mm = 1.1 L > 20 mm = 1.2
			Diameter	D $\leq$ 4 mm = 1.2 4 mm < D $\leq$ 12 mm = 1 D > 12 mm = 1.2
			Tool	Screw gun = 1 Manual = 2.0 Spanner = 1.3 Pliers = 1.9
			Wear	Completely worn / rusted = 2 Partially worn / rusted = 1.3 Not worn / rusted = 1.0

Standard disassembly times and corrective factors are defined according to an in-depth literature review, several empirical case studies and analyses of different products, made in collaboration with expert stakeholders involved in the EoL management (i.e. dismantling centers) [16][17][18]. This analysis has been performed for different product families (electric and electronic equipment, vehicle, industrial machinery, etc.) and all the retrieved information have been used for the creation of a knowledge repository, called *Liaison DB* repository.

Disassembly Times & Costs are calculated for each target component starting from: (i) feasible disassembly sequences (output of the second step),' and (ii) liaison specific disassembly time (output of the third step). The effective disassembly time for each operation (associated to a liaison removal) is estimated by multiplying the standard disassembly time by the different corrective factors relative to the selected liaison properties, as shown in Eq. 1.

$$op = Ts \cdot \prod_k CF_k \qquad \text{Eq. 1}$$

where op is the disassembly time of the considered disassembly operation, Ts is the standard disassembly time of the considered liaison and CF_k are the liaison corrective factors.

The disassembly time for each feasible sequence is calculated by summing the contributions of each involved disassembly operations (Eq. 2).

$$seq\_n_{Tx} = \sum(op\_1_{Tx}, op\_2_{Tx}, \dots, op\_m_{Tx}) \qquad \text{Eq. 2}$$

where seq_n_{Tx} is the disassembly time of *n-th* disassembly sequence for the target component Tx and op_m_{Tx} is the disassembly time relative to the *m-th* disassembly operation. The cost can be successively derived by multiplying the time by the unitary labor and equipment costs.

The calculated values allow identifying the product criticalities and de-manufacturing operations that require the longest time or the highest cost. The best disassembly sequence is retrieved using a mathematical optimization approach, which allows finding the optimum solution from a range of possible alternatives (i.e. the feasible sequences), as reported in the following Eq. 3.

$$BDS_{Tx} = \min(seq\_1_{Tx}, seq\_2_{Tx}, seq\_3_{Tx}, \dots, seq\_n_{Tx}) \qquad \text{Eq. 3}$$

where BDS_{Tx} is the Best Disassembly Sequence, Tx is the *x-th* target component, seq_n_{Tx} is the *n-th* feasible disassembly sequence and n is the overall number of feasible disassembly sequences calculated for the target component Tx.

3.2 Product/component recyclability ratio

To define the product EoL performances, the chosen metric is the *Recyclability Ratio* proposed by the Joint Research Centre of the European Commission [54]. This index has the aim of preventively estimating the quantities of materials that could be potentially recycled at the product EoL, as depicted in the following Eq.4 and Eq.5.

$$RR = \sum_{i,k} \frac{m_{recycle_{i,k}}}{m_{i,k}} \qquad \text{Eq. 4}$$

$$m_{recycle_{i,k}} = m_{i,k} \cdot D_{i,k} \cdot C_{i,k} \cdot M_{R\,i,k} \qquad \text{Eq. 5}$$

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 or the Bill of Materials (BoM) of the product under analysis;

- The Disassembly Index ($D_{i,k}$) is retrieved by using the disassembly times and disassembly sequences calculated through the methodology previously presented;
- The Material Degradation Index ($M_{R,i,k}$) is retrieved from the literature 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 defined within this work considering the material contaminations (e.g., varnishes, coatings, coupled materials) and incompatibilities.

In particular, for plastic materials, which are the most critical to separate and recycle due to their chemical differences (i.e., plastics are made from completely different polymers), a compatibility matrix developed by ECMA International [55] has been used as baseline. According to this approach, the Contamination Index has been adjusted using an additional factor (between 0 and 1). For example, an additional factor of 0.5, which represents a limited compatibility for thermoplastics has been identified between PP (principal plastic) and PA (excess plastic). For other materials (e.g. metals), the Contamination Index and the other factors have been defined accordingly to direct observation of dismantling centers activities [16].

4 LeanDfD tool

This section presents a detailed description of the software tool, including its architecture (section 4.1), the databases (section 4.2), the document data structure and required input/output (section 4.3), and the general workflow (section 4.4). The LeanDfD tool has been implemented as a desktop application based on the features highlighted in the following sections.

4.1 LeanDfD requirements and architecture

LeanDfD is a design tool oriented to engineers and designers, which implements the calculation methods presented in section 3. According to the Agile methodology for software development [56], the LeanDfD tool functionalities have been defined starting from the tool user stories (US). These latter have been identified by designers and prioritized according the MoSCoW method [57]. The list of user stories was a result of two dual-moderator focus groups (one for each manufacturing enterprise involved). Each group was composed by a software analyst (computer science background), a researcher (mechanical engineering background) and six designers (mechanical and electrical engineering background). User stories respect the following syntax: ***As*** *<persona>,* ***I want*** *<what?>* ***so that*** *<why?>*. Table 4 contains an extract of those user stories, with related priority and necessary modules to develop in the LeanDfD tool.

Table 4: Extract of the main prioritized LeanDfD user stories (M = Must, S = Should, C = Could, W = Would)

ID	Description	Priority	LeanDfD Module
1	*As* designer, *I want* to know the feasible disassembly sequences for each component (or sub-assembly) or for the entire product *so that* I can compare different design alternatives.	M	Product Disassemblability
2	*As* designer*, I want* to know the disassembly time for each component (or sub-assembly) or for the entire product *so that* I can evaluate the disassemblability of the product under analysis.	M	Product Disassemblability
3	*As* designer, *I want* to store the analyses within a PDM/PLM system, *so that* I can manage these ones in the future.	M	Export interface
4	*As* designer, *I want* to create a simple and clear report of the product disassemblability/recyclability analyses *so that* other engineers can understand the product performances.	M	Export interface
5	*As* designer, *I want* to assess the recyclability rate for the entire product and for each component (or sub-assembly) *so that* I can evaluate the recyclability performances at the end-of-life.	M	Product Recyclability
6	*As* designer, *I want* to know information about critical components and the adoption of hazardous materials *so that* I can choose the best alternative.	M	Product Recyclability
7	*As* designer, *I want* to perform a disassemblability/recyclability analysis starting by a product BoM exported from a PDM/PLM system, *so that* I can work without a 3D CAD model.	M	Import Interface
8	*As* designer, *I want* to know re-design suggestions, *so that* I can improve the product disassemblability and recyclability.	M	Re-design suggestions DB
9	*As* designer, *I want* that the disassemblability and recyclability calculation will be carried out using past experience of the company or dismantling centers*, so that* I do not need to input unitary disassembly times.	M	Liaisons DB

10	*As* designer, *I want* to know the disassembly cost for each component (or sub-assembly) or for the entire product *so that* I can evaluate the disassemblability of the product under analysis.	S	Product Disassemblability
11	*As* designer, *I want* to know the most important properties for each material used in the product *so that* I can evaluate the product end-of-life performances.	S	Material DB
12	*As* designer, *I want* to perform a disassemblability/recyclability analysis starting by a 3D CAD model exported from a CAD system, *so that* I can be faster and objective.	S	Import Interface
13	*As* designer, *I want* a tool able to automatically extract from a 3D CAD model liaisons and precedencies, *so that* I can perform a quick and robust analysis.	C	-
14	*As* designer*, I want* to visualize the 3D CAD model when defining precedence and liaisons, *so that* I can easily evaluate accessibility related problems.	C	3D Viewer

From the analysis of the user stories, the software architecture of LeanDfD has been defined (Figure 2). The tool architecture consists of five modules and three different databases conceived to assist designers in the following functionalities: (i) data import and editing (related user stories: #7, #12, #14), (ii) performance indicators assessment (#1, #2, #5, #6, #9, #10, #11), (iii) re-design activities definition (#8) and (iv) data export (#3, #4). Because user story #13 is not linked to any LeanDfD module, this will be a future functionality.

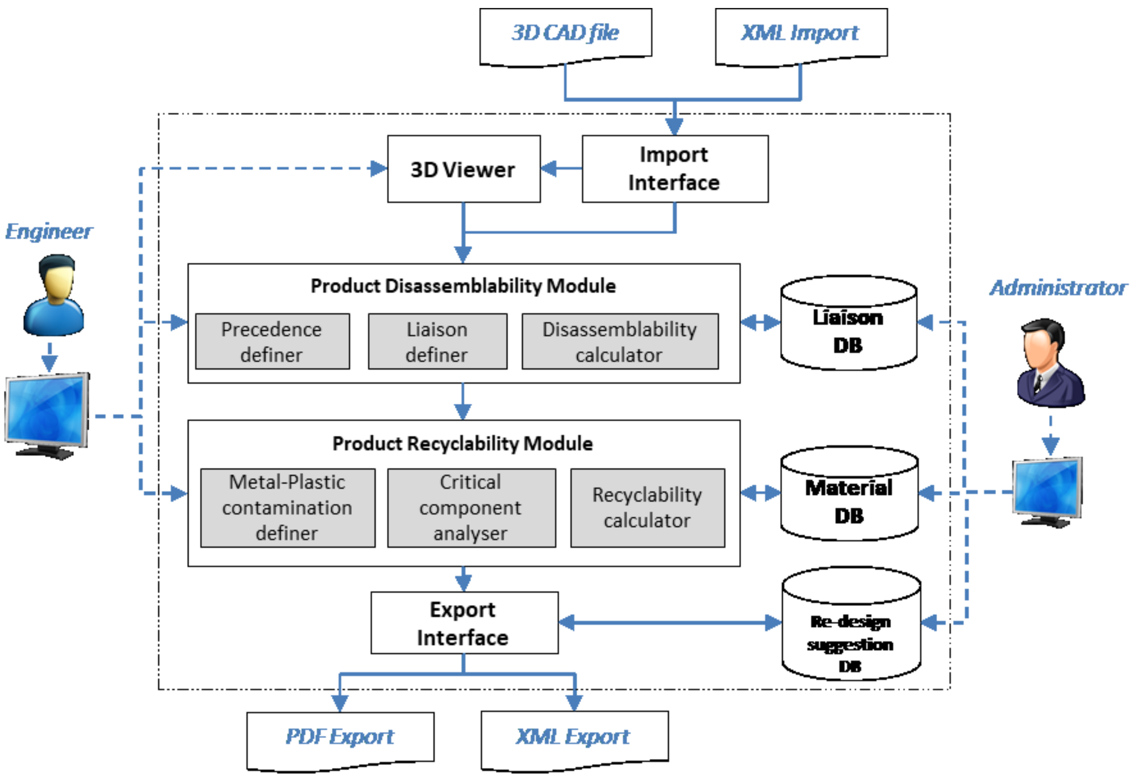

Figure 2: LeanDfD tool architecture: modules and databases

The first module, the *Import Interface*, permits the import of an external file from a 3D CAD (US #12) or Product Data Management System (US #7). The purpose of this module is to make available the product structure both in terms of BoM and/or 3D model. LeanDfD accepts as input a 3D geometry that can be read from a standard 3D CAD file (.step format) or through a direct connection to a mechanical CAD system.

Although the CAD model of a product is usually available during the embodiment design, LeanDfD also accepts as input a .xml file that describes the product BoM. This function is useful when engineers want to evaluate the product disassemblability/recyclability even before the geometric product modelling, perhaps during the conceptual design phase. The .xml file format referred to in this paper is based on Favi et al. [58], but similar formats can be generated by PDM systems.

The second module is the *3D Viewer* and it has been conceived to "virtually" navigate the 3D CAD model of the product (only in the case of importing a 3D geometry). The purpose of this module is to evaluate geometric disassembly aspects related to accessibility and priorities (US #14). The main functionalities of this module consist in highlight, view/hide parts and explode the components/sub-assemblies to facilitate the analysis. As example, after the removal of the first components (Level "0") the software highlights the possible components that can be removed in the subsequent level (Level "1") based on a collision analysis done within the 3D CAD model.

The third module, called *Product Disassemblability Module*, is the core of the tool since it allows to assess the product disassemblability (US #1, #2, #10). It has been conceived with the aim to be connected to the *Liaison DB* (US #9) and 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 procedure detailed in section 3.1. The precedence is a consequence of a visual obstruction if physical liaisons are not present (as described in the second module). 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., quantity, dimensions, weight, wear condition, tools, etc.). Once all the precedencies and liaisons have been defined, the *Disassemblability Calculator* (the third sub-module) assesses all the feasible disassembly sequences and determines the best one in terms of time or cost (following the equation 1, 2 and 3).

The fourth module, called *Product Recyclability Module*, has been conceived to evaluate the product recyclability ratio, supporting designers in improving the product EoL performance (US #5, #6). Connected to the *Material DB* (US #11), it inherits information from the previous module, namely the product BoM, materials of the components, liaisons and relative attributes, target components, disassembly sequences and times. The *Product Recyclability Module* consists of three sub-modules. The first sub-module, *Metal-plastic contamination definer*, permits the engineer to set additional information concerning the material contamination (e.g., glues and foams). 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. 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 fifth module LeanDfD, *Export Interface*, has been conceived to generate a report (.pdf or .xml file formats) containing the results of the product disassemblability and recyclability analyses (US #3, #4, #5). This report encloses also the re-design suggestions, retrieved from the *Re-Design suggestions DB* (US #8) according to specific rules that consider the results of the analyses carried out so far by the product disassemblability and recyclability modules.

4.2 LeanDfD databases

The LeanDfD assessment modules (*Product Disassemblability Module* and *Product Recyclability Module*) are linked with two different databases. The first one, *Liaison DB* (Figure 3), contains data required for the calculation of the product disassemblability (e.g., liaisons, disassembly times, and tools required). The second one, *Material DB* (Figure 4), contains data for the calculation of the product recyclability rates (material properties, material compatibility matrices, etc.). The structure of both repositories allows to classify the knowledge about liaisons (see section 3.1) and materials recyclability (see section 3.2), needed to support the calculation of the effective disassembly time and product/component recyclability ratio.

The *Export Interface* is connected to the *Re-design suggestions DB* (Figure 5), which contains the re-design suggestions proposed to designers for improving the product disassemblability and/or recyclability. For each re-design suggestion, the database defines its context of application (products or functional groups for which the action is valid), its priority/rating and when to use it (i.e. condition).

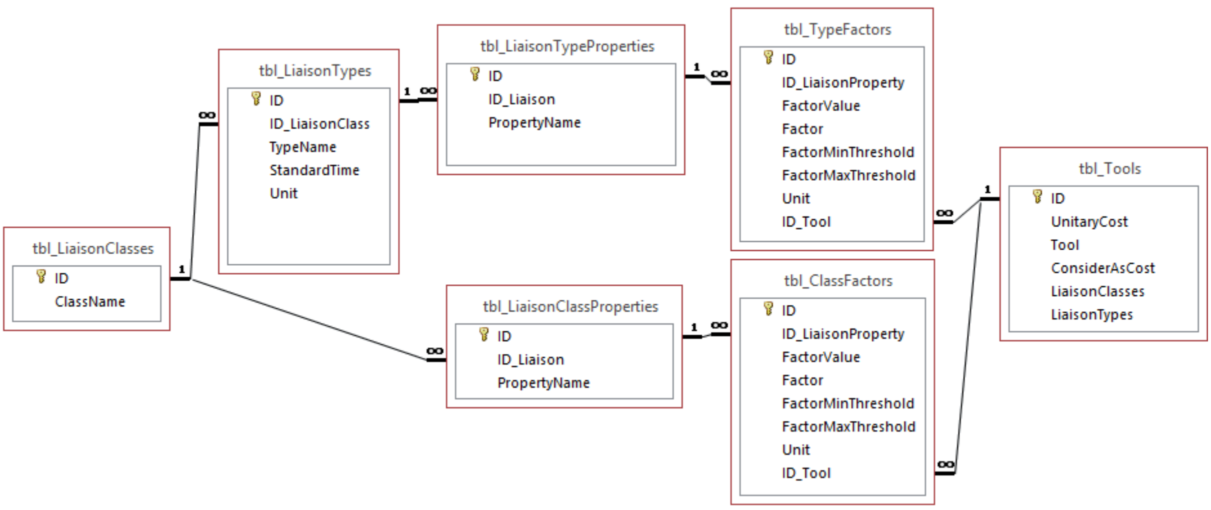

Figure 3: Liaison DB structure

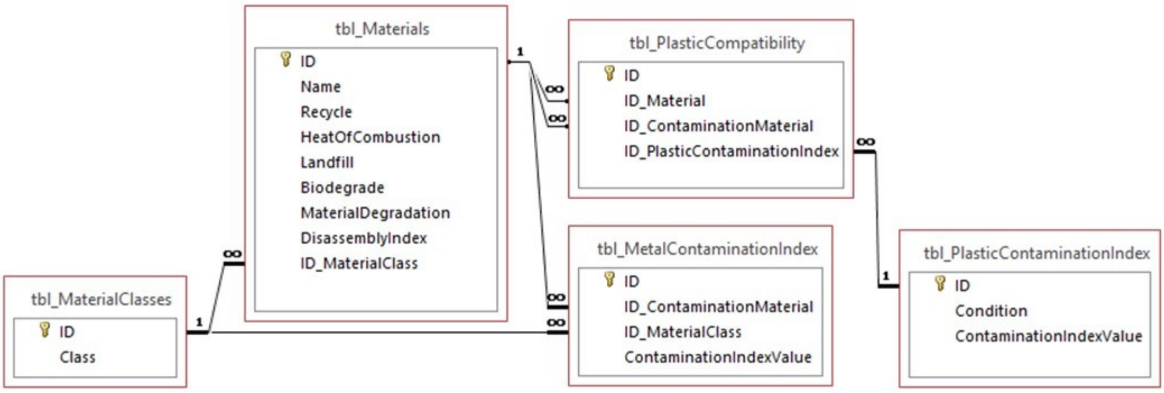

Figure 4: Material DB structure

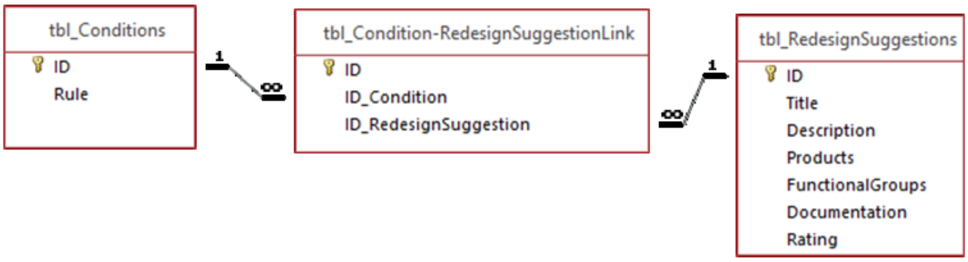

Figure 5: Re-design suggestions DB structure

The features of the three repositories are reported in Table 5.

Table 5. Tables and description of repositories

DB	Table	Description
Liaison DB	*Liaison Classes*	Liaison classes (e.g., Threaded, Shaft-Hole, Rapid joint). See Table 2.
	Liaison Types	Liaison types (e.g., screw, nut and threaded rod for the threaded Liaison Class) with relative disassembly time in standard conditions (new, not damaged, not rusted and not deformed). See Table 2.
	Liaison Type Properties	Properties related to a specific *Liaison Type* (e.g., screw length, diameter, and head type). See Table 3.
	Liaison Type Factors	Corrective factors for each *Liaison Type Property*. See Table 3.
	Liaison Class Properties	Properties related to a specific *Liaison Class* (e.g., wear). See Table 3.
	Liaison Class Factors	Corrective factors for each *Liaison Class Property*. See Table 3.
	Tools	List of tools used in disassembly operation and related to *Liaison Type* or *Liaison Class*.
Material DB	*Material Classes*	Material classes (e.g., Aluminum, Copper, Carbon Steel, Thermoplastic Polymers).

	Materials	Material attributes (e.g., possibility to recycle, heat of combustion, material degradation).
	Plastic Compatibility	Compatibility matrix between different plastics (compatible, partially compatible or incompatible polymers).
	Plastic Contamination Index	Plastic contamination index values (compatible = 1, partially compatible = 0.5, incompatible = 0).
	Metal Contamination Index	Metal contamination index values (variable in the range 0 - 1).
Re-design suggestions DB	*Conditions*	Product conditions in terms of disassemblability and recyclability, compared to threshold values.
	Re-design suggestions	Suggestions for improving the product disassemblability and/or recyclability.
	Conditions-Re-design Suggestions Link	Many-to-many relationship between conditions and re-design suggestions.

4.3 LeanDFD input/output and data structure

Several data are required as inputs and other data are provided as outputs. Table 6 summarizes inputs and outputs data, with relative type and source (3D CAD model or user input). The latter helps clarifying how retrieving the needed data in real design contexts.

Table 6: Input and Output data with types and sources

Field	**Input/output**	**Data type**	**Source**
Bill of Material and 3D Model	Input	Product Structure	3D CAD model
Material for each component	Input	String	3D CAD model
Mass for each component	Input	Numeric	3D CAD model
Contamination of materials (coatings, glues, adhesives, etc.)	Input	List (of Materials)	3D CAD model
Target components	Input	List (of Components)	User input
Disassembly levels	Input	List (of Integers)	User input
Precedence between components or sub-assemblies	Input	List (of Components)	User input
Liaisons between components or sub-assemblies	Input	List (of Liaisons)	User input
Properties of each liaison	Input	List (of Liaison Properties)	User input
Disassembly time for each target component/sub-assembly	Output	Numeric	-
Disassembly cost for each target component/sub-assembly	Output	Numeric	-
Re-design suggestions/rules	Output	List (of rules and examples)	-
Feasible disassembly sequences for each target component/sub-assembly	Output	List (of Disassembly Sequences)	-
Recyclability rate for each component	Output	Numeric	-
Recyclability rate for the entire product	Output	Numeric	-
Material EoL properties	Output	List (of Materials)	-

Critical component EoL documentation	Output	List (of Documents)	-

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 6). 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*.

After the completion of the disassembly analysis, each *Document* also contains information about the overall *Product Recyclability Index* and the list of *Feasible Disassembly Sequences*. The latter consists of a list of Disassembly *Operations*, comprising a list of *Removed Components*, the needed *Tools* and a *Time* and a *Cost*.

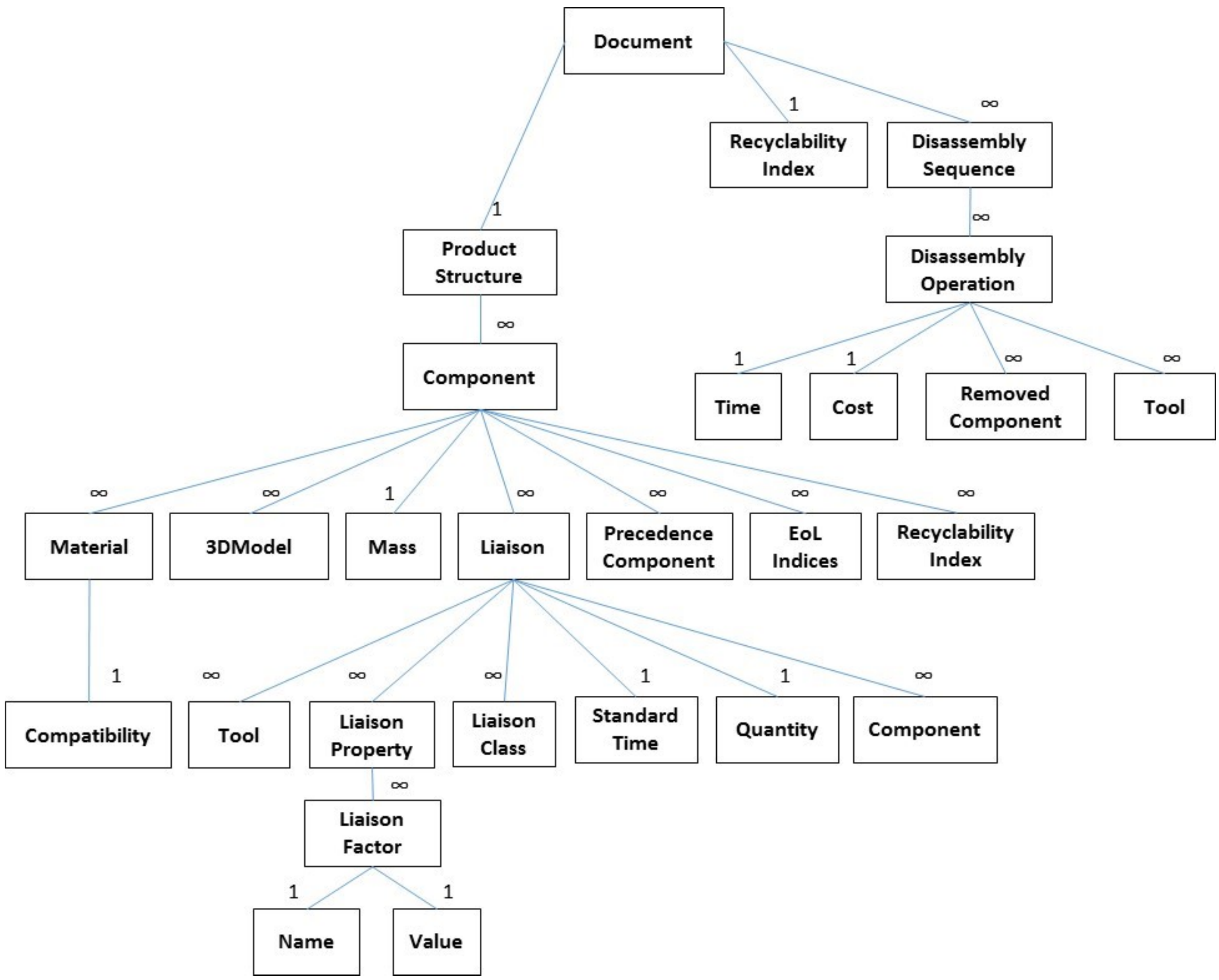

Figure 6: LeanDfD file data structure

4.4 Workflow description of the proposed tool

Figure 7 presents the design framework and the general workflow adopted to support designers in improving products disassemblability and recyclability.

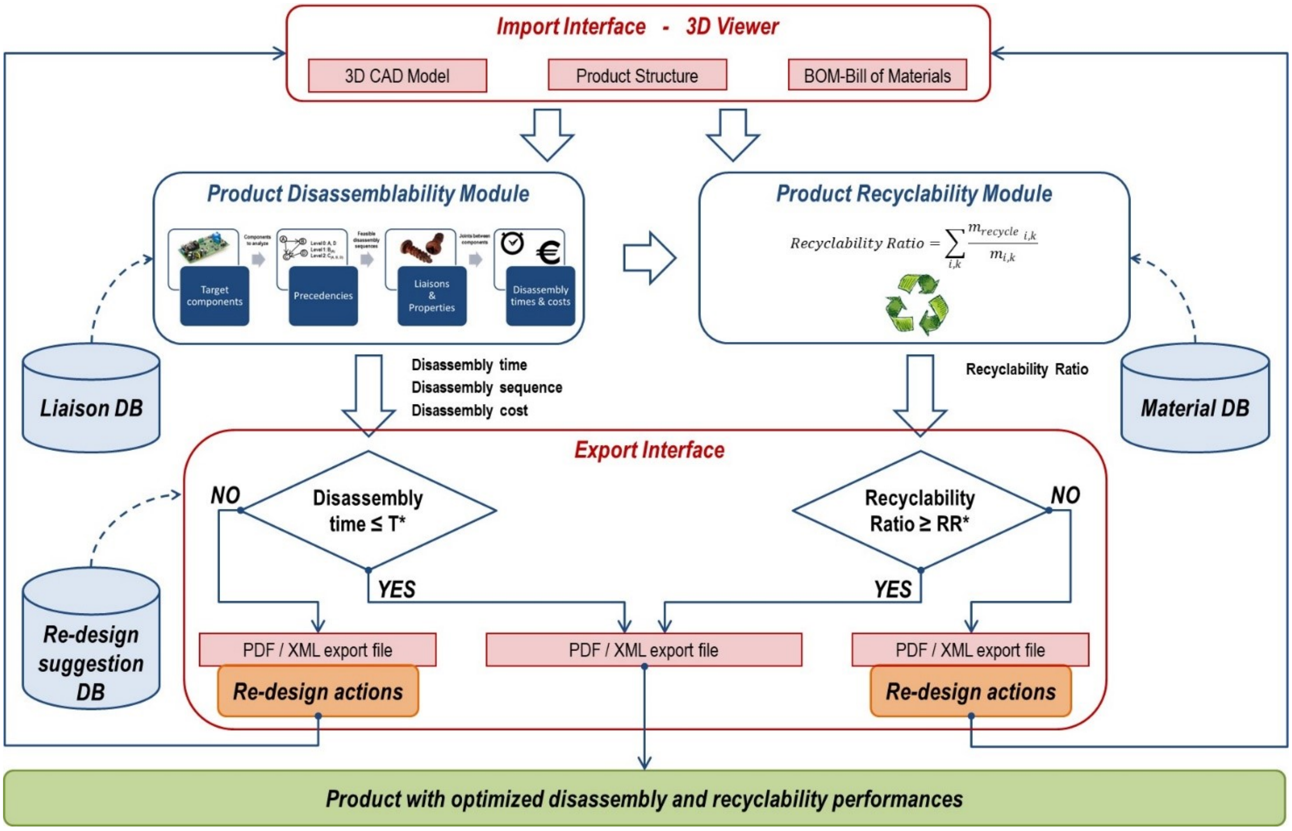

Figure 7: General framework of the design method

The starting input data are the product virtual models (e.g., BoM, 3D CAD model), which can be imported through the *Import Interface* and "navigated" using the *3D Viewer* integrated within the LeanDfD tool. Taken together, these virtual representations contain all the needed information to realize the assessments (e.g., product structure, connections between components, and materials). By using the *Product Disassemblability Module* (with its sub-modules detailed in the previous sections), it is possible to calculate the feasible disassembly sequences and consequently to derive the best one. The link with the *Liaison DB* allows assessing the effective disassembly time as well as the disassembly cost (multiplying disassembly time with the labour cost). By using the *Product Recyclability Module*, it is possible to calculate the recyclability ratio (*RR*) starting from the disassembly time retrieved by the *Product Disassemblability Module* and data stored in the *Material DB*.

After the assessment phase, results are exported and displayed through the *Export Interface*. If the disassemblability/recyclability performances do not reach an established target (T^* for disassembly time and/or RR^* for recyclability ratio), a re-design phase starts. The definition of thresholds (T^* and RR^*) depends on numerous aspects, such as:

- the characteristics of the product/component under analysis (e.g., value of component);
- the company strategy (e.g., interest in closed-loop scenarios, environmental objectives);
- cost-benefit analyses of the different EoL scenarios; and
- normative compliance.

For example, if a company is interested in implementing a remanufacturing business model for one of its products, the target value T^* could be fixed equal to the maximum disassembly time that guarantees an economic benefit for this EoL scenario.

Once the target values are univocally established, the general strategy should consist in improving product features to minimize the disassembly time and/or to maximize the potential recyclability ratio. In general, different situations can arise, and each one is driven by different reasons. Table 7 illustrates the possible conditions deriving from the disassemblability and recyclability analyses, together with specific re-design suggestions proposed by the tool (general suggestions independent by the specific product), accordingly with criticalities observed during the analyses (*Re-design suggestions DB*). The link between disassemblability and recyclability analyses and specific re-design suggestions, has been implemented within the tool, by using detailed mathematical models (Table 7). The parameters involved in the definition of the mathematical models are:

- Nr = number of items to remove to reach the target component;
- $\frac{\Delta t}{\Delta x}$ = derivative of cumulative disassembly time (t) with respect to a single disassembly operation (x);
- t^* = company target time for a single disassembly operation (this value is pre-set equal to 10 but it can be changed based on company objective);
- Ad = presence of adhesive liaison type (Boolean – true or false);
- Co = presence of Coating or varnish treatment (Boolean – true or false);
- Pt = type of different plastics used in the product.

Suggestions proposed by LeanDfD are then used by design engineers for defining the re-design actions/solutions to be used for the specific product. During this step, the design team, stimulated by the suggestions LeanDfD proposed and acting according to the internal processes, identifies and implements those design actions for improving the product disassemblability and/or recyclability. Research activities and design studies are required for establishing the right re-design action. An iterative process of re-design and checking of the new product version is generally needed to finally reach the desired condition and obtain a product with optimized disassembly and EoL performances.

Table 7. Re-design suggestions based on disassemblability and recyclability analyses

Condition	Description	Mathematical models	Results interpretation	Re-design suggestions
T > T*	The product under analysis does not reach the expected disassemblability performance	Nr ≥ 10	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	General re-design suggestions are provided based on the implemented mathematical method: - Modify the product architecture (e.g. to position target components in the external layers of the product) - Improve the accessibility to target components (e.g. to use fast systems for the disassembly of cover panels and chasses) - Reduce the overall number of components (e.g. to merge component whenever is feasible) - Change the access to target components (e.g. re-think the way to access to target components)

$\frac{\Delta t}{\Delta x} \geq t^*$	The disassembly time for a particular operation is too long. The issue is related to the typologies of liaisons used to assemble the components	An analysis of corrective factors for the specific assembly operation is required. Additional mathematical models are necessary to identify detailed re-design suggestions starting from the analysis of the most impactful corrective factor: - *If* number of items/joints have the higher value among corrective factors *Then* reduce number of items/joints (e.g. re-arrange joints position) *Or* change liaison type (e.g. use snap-fit whenever is possible, avoid threaded elements) - *If* tool have the higher value among corrective factors *Then* change the liaison features (e.g. standardize screw typologies to reduce changes in disassembly tools) or use automatic tool (e.g. electric, pneumatic, etc.) *Or* reduce the changes in disassembly tools. - *If* wear have the higher value among corrective factors *Then* segregate the area from humidity (e.g. using a plastic box) *or* change material for the liaison (e.g. use stainless steel, aluminum, etc.) - *If* geometrical features (length, dimension, etc.) have the higher value among corrective factors *Then* change liaison geometry (e.g. increase sizes of screws and bolts to be easily handled by operators or reduce the length of threaded elements whenever is possible).
Item *j-th* is present in more than 70% of retrieved disassembly sequences considering all the selected target components	The *n-th* operation necessary to remove the *j-th* item is in the critical path. The issue is related to a specific disassembly task (position and assembly method)	An analysis of disassembly operations sequences is required. Additional mathematical model is necessary to identify specific re-design suggestions starting from the position of the j-th item in the sequences: - *If j-th* item is in the first 2 items of target disassembly sequences *Then* adopt fast joints to remove the *j-th* item (e.g. use snap-fits, mechanical clips or dovetails whenever is possible, avoid threaded elements) - *If j-th* item is in the first 5 items of the disassembly sequences *Then* modify the product architecture (e.g. move the *j-th* component in the core of the product)

		A sequence of *n-items* to remove is present in more than 70% of retrieved disassembly sequences considering all the selected target components	The same disassembly sequence is necessary whatever is the target component The issue is related to a specific set of components (how they are assembled and positioned to each other)	- To merge components together whenever is feasible - To avoid the use of threaded elements to assemble the items of the sequence (e.g. use snap-fits, mechanical clips or dovetails whenever is possible) - To avoid the use of tools for the liaison elements (e.g. remove items with hands)
$RR < RR^*$	The product under analysis does not reach the expected recyclability performance	Ad Co	The contamination of certain components or materials is high	- Avoid the use of glues and adhesives to couple heterogeneous materials - Avoid the use of material contaminations such as varnishes or particular coatings (e.g. chromium plating)
		$Pt \geq 2$	The materials used are not easy to separate and recycle at the EoL	- Adopt materials with a higher potential recyclability ratio (e.g. metals) - Avoid the use of incompatible or partially compatible plastics (e.g. ABS and PE)
$T \leq T^*$	The product is compliant with the company's disassemblability targets	No mathematical models have been implemented	NA	NA
$RR \geq RR^*$	The product is compliant with the company's recyclability targets	No mathematical models have been implemented	NA	NA

5 Case study

A case study has been performed to test the usefulness of the DfD tool in supporting designers during the identification of criticalities and the improvement of a washing machine. The tool has been provided to a group of designers and engineers with skills on different functional modules (e.g. electric components, structural modules, etc.) of the product itself. The objective of the re-design project was the improvement of the washing machine performances in terms of disassemblability. A collaboration among design team members has been required using the LeanDfD tool to reach a new washing machine configuration.

5.1 Application: washing machine

A washing machine has been selected to test the proposed methodology and tool, since this product represents a comprehensive and complete case study. The analyzed washing machine 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 and 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 made from plastic (ABS - acrylonitrile butadiene styrene), and the drum is fabricated from stainless steel (AISI 430). The analyzed target components are listed in Table 8, and the main motivations that justify this choice are reported there.

Table 8: Target components with the identified reasons for disassembly

Target component	Reasons for disassembly			
	Legislation	Maintenance	Remanufacturing	Material recovery
Drum				X
Water Pump	X	X	X	
Electric Motor	X	X	X	
Capacitor	X	X		
Electronic Board	X			X

5.2 Disassemblability analysis and re-design actions

The first activity was the analysis of the current situation of the proposed washing machine model, needed to highlight criticalities. Due to the integration with the CAD systems, the user could import and visualize the product 3D model directly within the tool. The CAD viewer guided the designers during the input of the needed information about the precedencies and the liaisons between components. The actual conditions of the washing machine and related liaisons (e.g., dust and rust) have been considered by opportunely setting the liaison properties (data gathered from the service department of the enterprise).

Once completed the definition of the product disassembly model, data about the disassembly times and corrective factors, stored within the Liaison DB, have been used to determine the best disassembly sequence and the disassembly time for the selected target components (see the list in the previous section). First, LeanDfD calculated the disassembly tree for each chosen target component (see the example relative to the capacitor and the water pump in Figure 8). It allowed analyzing the disassembly levels, the feasible disassembly sequences, and the disassembly depth for each component (i.e., number of operations to perform) and the clear visualization of the connections to remove for each disassembly sequence.

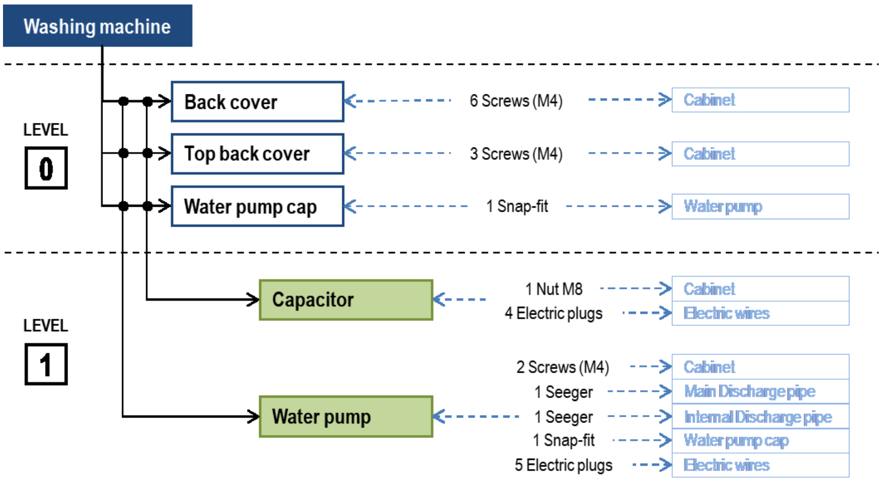

Figure 8: Disassembly tree for the Capacitor and the Water Pump calculated by LeanDfD

Second, a cumulative disassembly time graph was automatically calculated, considering the feasible disassembly sequence 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 and complex product structures. Figure 9 reports the cumulative disassembly time graph calculated for the electric motor.

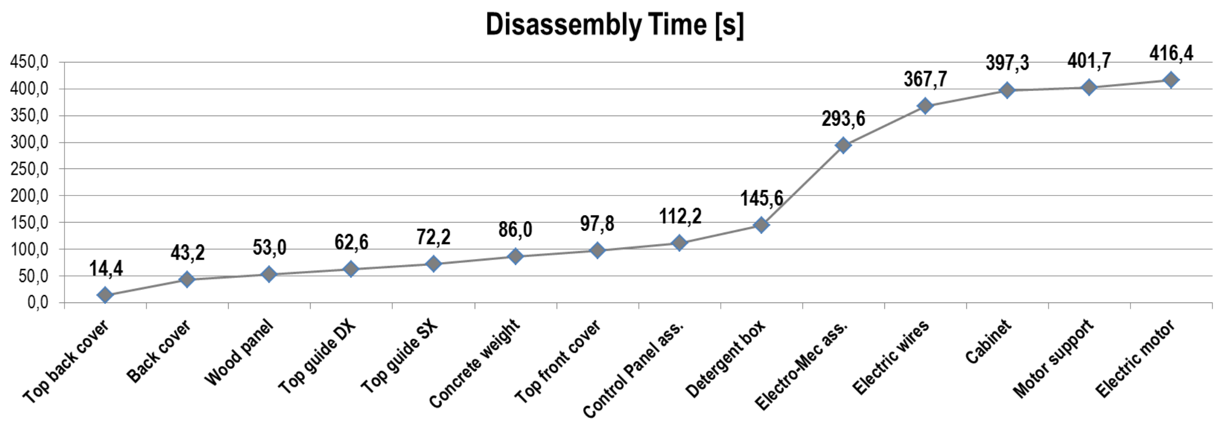

Figure 9: Cumulative disassembly time for the electric motor calculated by the DfD tool

In this case, the overall disassembly time (416.4 seconds) is not acceptable for maintenance reasons. Several criticalities have been identified by using the LeanDfD tool:

- Nr (*electric motor*) ≥ 10;
- $\frac{\Delta t}{\Delta x} = \frac{t(Detergent\ box) - t(Control\ Panel\ ass.)}{1} \geq 15$
- $\frac{\Delta t}{\Delta x} = \frac{t(Electro{-}Mec\ ass.) - t(Detergent\ box)}{1} \geq 15$
- $\frac{\Delta t}{\Delta x} = \frac{t(Electric\ wires) - t(Electro{-}Mec\ ass.)}{1} \geq 15$
- $\frac{\Delta t}{\Delta x} = \frac{t(Cabinet) - t(Electric\ wires)}{1} \geq 15$

  where t* = 15 has been defined as target value by the company
- *Top back cover* item is present in more than 70% of retrieved disassembly sequences considering all the selected target components
- *Back cover* item is present in more than 70% of retrieved disassembly sequences considering all the selected target components
- *Wood panel* item is present in more than 70% of retrieved disassembly sequences considering all the selected target components
- A sequence of items to remove (*Top back cover, Back cover, Wood panel, Top guide DX, Top guide SX*) is present in more than 70% of retrieved disassembly sequences considering all the selected target components

Appendix A reports a detailed set of design review actions implemented for the *Electric motor* item of the current model of washing machine, based on the re-design suggestions provided by the LeanDfD tool.

As example, in Figure 10 is shown a screenshot of the software tool interface related to the identification of *Wood panel* (yellow highlighted) after the application of mathematical models for the identification of criticalities. *Wood panel* is a critical item because it is present in more than 70% of retrieved disassembly sequences for selected target components.

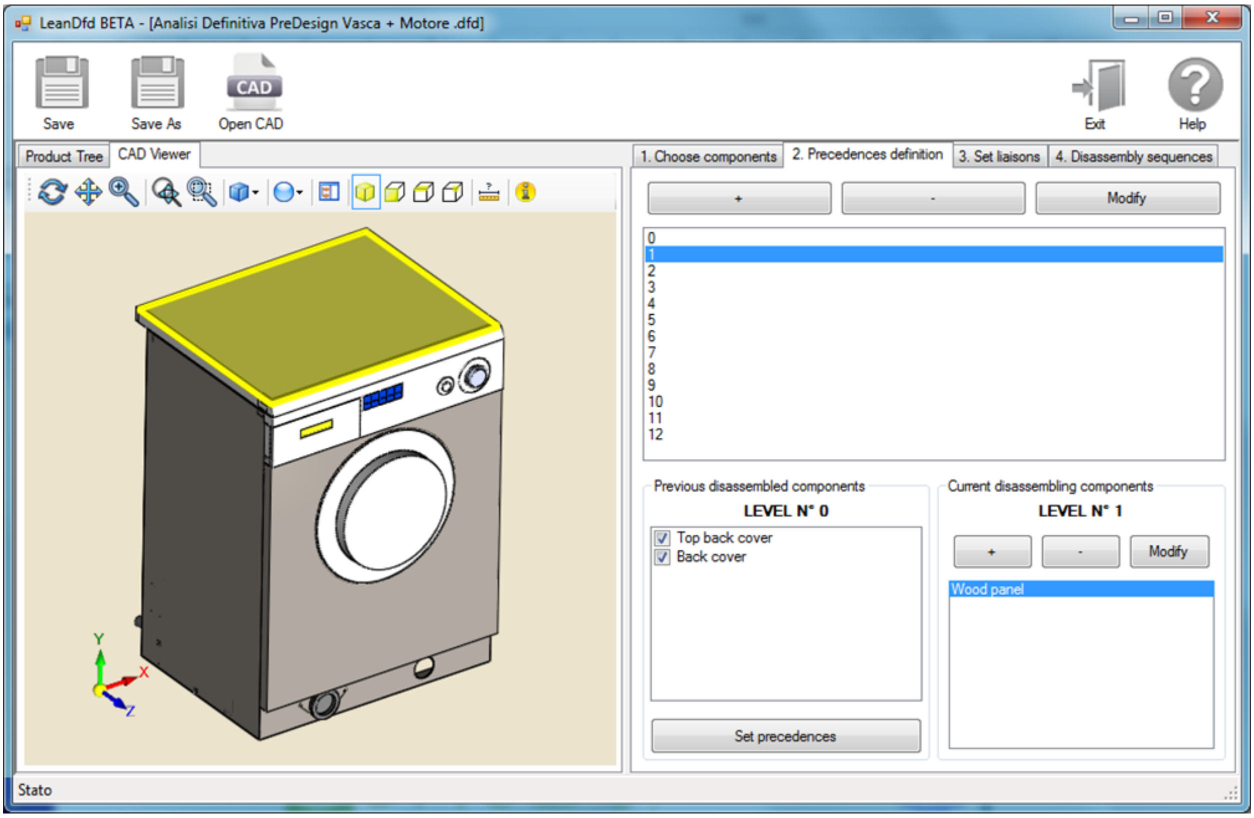

Figure 10: *Wood panel* item identification (yellow) by LeanDfD user interface (3D model viewer).

This type of analysis has been performed for each target component with the aim of identifying the main features to be improved during the re-design phase. A summary of results is displayed in Table 9 (rows relative to the Original Design).

Re-design actions have been implemented modifying the geometry of the different parts, as proposed for the electric motor, and they have been implemented using a CAD system (hereunder some examples).

- The top panel, originally made by four plastic parts and a plywood panel, has been re-designed as a single ABS component (Figure 11). Since this component has an aesthetic rather than a structural function, the adoption of five snap-fits (two cantilever and three cylindrical) in substitution of the original 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 in the general assembly.

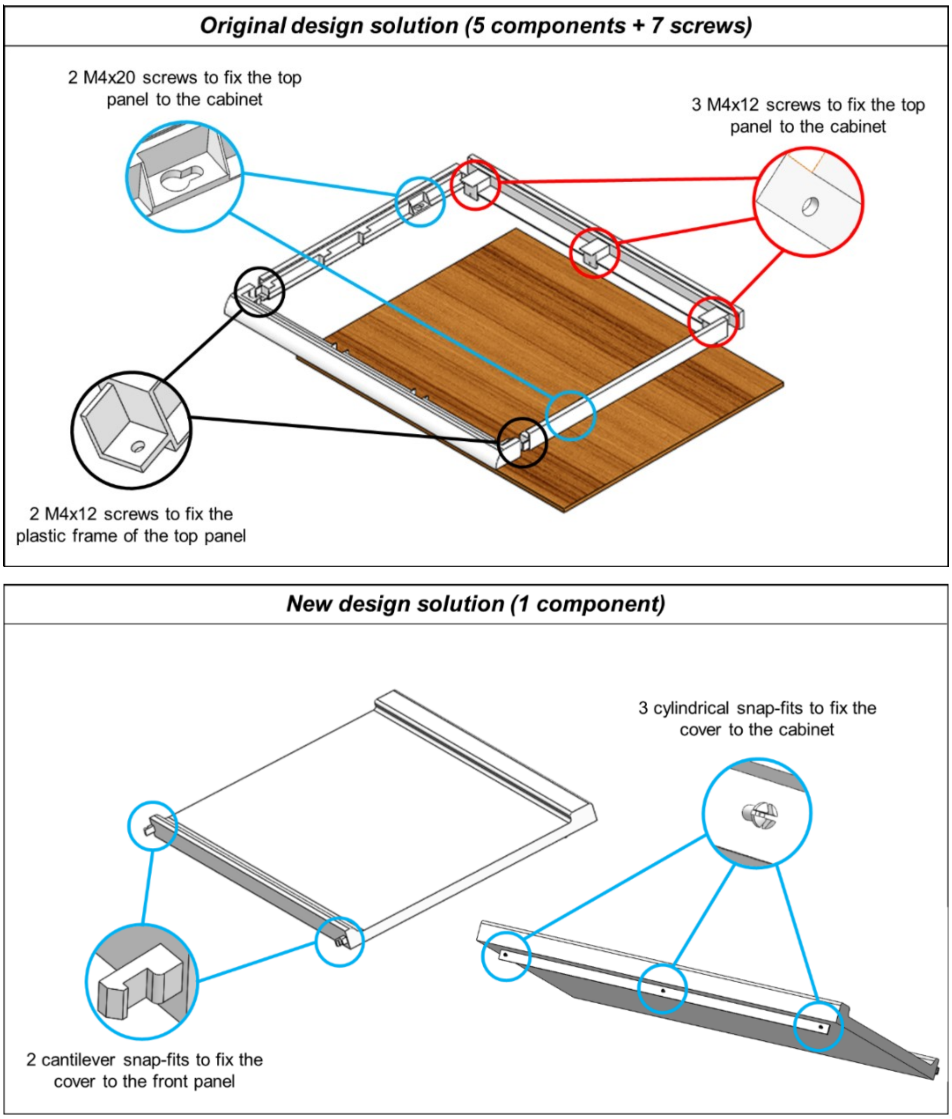

Figure 11: Top panel re-design

- 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.
- The electric motor assembly has been improved to mitigate the problems related to the accessibility. In the original design, the motor is fixed through two long shank bolts, which can be unscrewed only by using two hands. This solution leads 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. 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
    - ✓ shifting the position of the electric motor.
- The problem related to the electric plugs and cables of electric motor, water pump and main electronic board has been mitigated through the adoption of alternative electric connections (grouped electric connector covered with plastic protection).

- The assembling of electronic board support, originally fixed to the main framework using six screws has been modified using only two screws, while two snap-fits have been added to obtain the necessary structural performance (as evaluated by a successive dedicated analysis).

5.3 Results and discussion

The re-design process, supported by the proposed DfD tool, achieved tangible benefits for all of the considered target components. The obtained results are presented in Table 9, which compares the performances of the original design with the new washing machine solution in terms of components and liaisons to remove before reaching the target.

Table 9: Comparison between Original Design (OD) and New Solution (NS) in terms of disassembly depth

Target component	Version	Components to remove [No.]	Liaisons to remove [No.]	Disassembly time [s]
Drum	OD	17	84	468.1
	NS	9	58	210.5
Water Pump	OD	2	16	66.8
	NS	2	9	40.4
Electric Motor	OD	13	75	416.4
	NS	1	6	29.8
Capacitor	OD	1	11	44.0
	NS	1	6	17.4
Electronic Board	OD	10	45	225.6
	NS	5	28	133.9

Examining the results presented in Table 9, the main improvement is related to the electric motor: a reduction in the disassembly time of 92.8% has been obtained. Another tangible improvement is related to the drum disassembly time, reduced by approximately 55% by the implementation of the re-design actions.

In conclusion, this case study highlights how the LeanDfD tool is able to support the implementation of Design for Disassembly actions to improve the disassemblability, maintainability and EoL performances of products. First of all, the tool is able to identify criticalities through the calculation of the disassembly sequences and the estimation of the disassembly times for each target component. Then, it helps in rapidly evaluating the impact of the design choices, in terms of the disassemblability and recyclability performances. However, it must be said that LeanDfD can be only used for re-design projects, where a reference product model is available. In case of a new product design, first of all an initial product configuration must be developed, while successively the proposed tool can be used to optimize the design solution, toward the reduction of the disassembly time and/or the maximization of the material quantity with a closed-loop lifecycle.

6 Conclusions

The paper presents a method and a design tool for quantitatively assessing the product disassemblability and recyclability. The first evaluation is based on the liaisons and assembly connections existing among the components, related properties, and disassembly precedencies. The time of each disassembly operation is estimated by considering the real conditions of the liaisons, at the end of life, for each removed component (e.g., presence of rust due to the working environment). The tool determines the best disassembly sequence for the selected target components solving the optimization problem that minimizes the disassembly time. The time-based approach allows to define robust and reliable best disassembly sequences for the defined target components, since the time estimation is based on the knowledge about mechanical liaisons retrieved through the direct observation of de-manufacturing activities at the dismantling centers. This knowledge, classified and stored within the Liaison DB, integrated in the LeanDfD tool, includes the condition of the product at the time of disassembly, the liaison features, the tools and equipment, etc. A maximum error of 8% has been noticed between the estimated disassembly time using this approach and the time assessed with an experimental analysis (considering different paths).

With the aim of fostering the use of such a method during the design stage, a software tool called LeanDfD has been developed. The paper presents its use scenario, software architecture (focusing on its databases), the data structure of a disassemblability/recyclability analysis and the input/output data. A group of designers used the tool during a re-design project, with the aim of improving the disassemblability/recyclability of a washing machine. The software system allowed the designers to find the disassemblability criticalities for the reference product, providing tangible support for its improvement.

The field of application (i.e. mechatronic products) is currently the main limitation of the LeanDfD tool. In particular, the proposed repositories have been developed classifying mechanical and electrical liaisons typically used in such products. To enlarge the "system boundaries" for the tool usage, a dedicated investigation to other industrial sectors (naval, furniture, etc.) is required.

Moreover, to enhance the tool usability and reduce the impacts (in terms of needed time and effort) on the traditional design process, the integration with CAD systems should be strengthened, by implementing 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 [44], manual inputs can be drastically reduced. Furthermore, through the topological analysis of the product 3D geometry, based on the definition of the disassembly features, some liaisons can be automatically retrieved with the aim to identify the right liaison class.

Future work will be focused firstly, on improving feedbacks provided to designers by the tool. In particular, the present work should be integrated with eco-knowledge management systems [59] to reinforce the aid to designers during the definition of alternative product solutions. Another outlook will be the possibility to integrate the outcomes of the LeanDfD tool (e.g. disassembly time) to circular economy metrics to assess the economical profitability of the sustainable EoL scenarios (e.g. reuse, remanufacturing).

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References

[1] I.C. De los Rios, F.J.S. Charnley. Skills and capabilities for a sustainable and circular economy: The changing role of design. Journal of Cleaner Production. 160 (2017). 109-122. https://doi.org/10.1016/j.jclepro.2016.10.130.

[2] M. Peruzzini, M. Germani, C. Favi. Shift from PLM to SLM: A method to support business requirements elicitation for service innovation. In: IFIP Advances in Information and Communication Technology (2012). 111-123. https://doi.org/10.1007/978-3-642-35758-9_10.

[3] M. Szwejczewski, K. Goffin Z. Anagnostopoulos. Product service systems, after-sales service and new product development. International Journal of Production Research 53 (2015). 5334-5353. https://doi.org/10.1080/00207543.2015.1033499.

[4] P. Goodall, E. Rosamond, J. Harding. A review of the state of the art in tools and techniques used to evaluate remanufacturing feasibility. Journal of Cleaner Production. 81 (2014). 1-15. https://doi.org/10.1016/j.jclepro.2014.06.014.

[5] M.D. Bovea, V. Pérez-Belis, V. Ibáñez-Forés, P. Quemades-Beltrán. Disassembly properties and material characterisation of household small waste electric and electronic equipment. Waste Management. 53 (2016). 225-236. https://doi.org/10.1016/j.wasman.2016.04.011.

[6] P. Vanegas, J.R. Peeters, D. Cattrysse, P. Tecchio, F. Ardente, F. Mathieux, W. Dewulf, J.R. Duflou. Ease of disassembly of products to support circular economy strategies. Resources, Conservation & Recycling. 135 (2018). 323-334. https://doi.org/10.1016/j.resconrec.2017.06.022.

[7] P. Dewhurst. Product design for manufacture: design for disassembly. Industrial Engineering. 25 (1993). 26–28.

[8] D.H. Lee, J.G. Kang, P. Xirouchakis. Disassembly planning and scheduling: Review and further research. Journal of Engineering manufacture. 215 (2001). 695-709. https://doi.org/10.1243/0954405011518629.

[9] M. Santochi, G. Dini, F. Failli. Computer Aided Disassembly Planning: State of the Art and Perspectives. CIRP Annals - Manufacturing Technology. 51 (2002). 507-529. https://doi.org/10.1016/S0007-8506(07)61698-9.

[10] R. Bogue. Design for disassembly: a critical twenty-first century discipline. Assembly Automation. 27 (2007). 285-289. https://doi.org/10.1108/01445150710827069.

[11] A. Gungor, S.M. Gupta. Disassembly sequence planning for products with defective parts in product recovery. Computers & Industrial Engineering. 35 (1998). 161-164. https://doi.org/10.1016/S0360-8352(98)00047-3.

[12] B. Adenso-Díaz, S. García-Carbajal, S. Lozano. An efficient GRASP algorithm for disassembly sequence planning. OR Spectrum. 29 (2007). 535-549. https://doi.org/10.1007/s00291-005-0028-x.

[13] H.E. Tseng, C.C. Chang, S.C. Lee, Y.M. Huang. A Block-based genetic algorithm for disassembly sequence planning. Expert Systems with Applications, 96 (2018). 492-505, https://doi.org/10.1016/j.eswa.2017.11.004.

[14] C.B. Kalayci, S.M. Gupta. Artificial bee colony algorithm for solving sequence-dependent disassembly line balancing problem. Expert Systems with Applications. 40 (2013). 7231-7241. https://doi.org/10.1016/j.eswa.2013.06.067.

[15] Z. Zeqiang, W. Kaipu, Z. Lixia, W. Yi. A Pareto improved artificial fish swarm algorithm for solving a multi-objective fuzzy disassembly line balancing problem. Expert Systems with Applications. 86 (2017). 165-176. https://doi.org/10.1016/j.eswa.2017.05.053.

[16] C. Favi, M. Germani, M. Mandolini, M. Marconi. Includes Knowledge of Dismantling Centers in the Early Design Phase: A Knowledge-based Design for Disassembly Approach. Procedia CIRP. 48 (2016). 401-406. https://doi.org/10.1016/j.procir.2016.03.242.

[17] C. Favi, M. Germani, M. Mandolini, M. Marconi. Disassembly Knowledge Classification and Potential Application: A Preliminary Analysis on a Washing Machine. In Volume 4: 21th Design for Manufacturing and the Life Cycle Conference; Charlotte, USA (2016). https://doi.org/10.1115/DETC2016-59514.

[18] M. Marconi, M. Germani, M. Mandolini, C. Favi. Applying Data Mining Technique to Disassembly Sequence Planning: A Method to Assess Effective Disassembly Time of Industrial Products. International Journal of Production Research. In-Press (2018). https://doi.org/10.1080/00207543.2018.1472404 .

[19] K. Ishii, C.F. Eubanks, M. Marks. Evaluation methodology for post-manufacturing issues in life-cycle design. Concurrent Engineering: Research and Applications. 1 (1993), 61-68. https://doi.org/10.1177/1063293X9300100107.

[20] E. Zussman, A. Kriwet, G. Seliger. Disassembly-Oriented Assessment Methodology to Support Design for Recycling. CIRP Annals - Manufacturing Technology. 43 (1994), 9-14, https://doi.org/10.1016/S0007-8506(07)62152-0.

[21] M.Z. Hauschild, J. Jeswiet, L. Alting. Design for Environment - Do We Get the Focus Right? CIRP Annals Manufacturing Technology. 53 (2004). 1-4. https://doi.org/10.1016/S0007-8506(07)60631-3.

[22] P. Zwolinski, M.A. Lopez-Ontiveros, D. Brissaud. Integrated design of remanufacturable products based on product profiles. Journal of Cleaner Production, 14 (2006). 1333-1345. https://doi.org/10.1016/j.jclepro.2005.11.028.

[23] G. Gaustad, E. Olivetti, R. Kirchain. Design for Recycling: Evaluation and Efficient Alloy Modification. Journal of Industrial Ecology. 14 (2010). 286-308. https://doi.org/10.1111/j.1530-9290.2010.00229.x.

[24] C.M. Rose, K. Ishii. Product end-of-life strategy categorization design tool. Journal of Electronics Manufacturing. 9 (1999). 41-51. https://doi.org/10.1142/S0960313199000271.

[25] C. Favi, M. Germani, A. Luzi, M. Mandolini, M. Marconi. A design for EoL approach and metrics to favour closed-loop scenarios for products. International Journal of Sustainable Engineering. 10 (2017). 136-146. https://doi.org/10.1080/19397038.2016.1270369.

[26] P. Zwolinski, D. Brissaud. Remanufacturing strategies to support product design and redesign. Journal of Engineering Design. 19 (2008). 321-335. https://doi.org/10.1080/09544820701435799.

[27] S: Smith, L.Y. Hsu, G.C. Smith. Partial disassembly sequence planning based on cost-benefit analysis. Journal of Cleaner Production. 139 (2016). 729-739. https://doi.org/10.1016/j.jclepro.2016.08.095.

[28] A. De Ron, K. Penev. Disassembly and recycling of electronic consumer products: an overview. Technovation. 15 (1995). 363-374. https://doi.org/10.1016/0166-4972(95)96597-M.

[29] H. Srinivasan, N. Shyamsundar, R. Gadh. A framework for virtual disassembly analysis. Intelligent Manufacturing. 8 (1997). 277-295. https://doi.org/10.1023/A:1018537611535.

[30] N.S. Ong, Y. Wong. Automatic Subassembly Detection from a Product Model for Disassembly Sequence Generation. International Journal of Advanced Manufacturing Technology. 15 (1999). 425-431. https://doi.org/10.1007/s001700050086.

[31] H. Srinivasan, R. Gadh. Efficient geometric disassembly of multiple components from an assembly using wave propagation. Journal of Mechanical Design. 122 (2000). 179-184. https://doi.org/10.1115/1.533567.

[32] A. Gungor, S.M. Gupta. Disassembly sequence plan generation using a branch-and-bound algorithm. International Journal of Production Research. 39 (2001). 481-509. https://doi.org/10.1080/00207540010002838.

[33] C. Mascle, B.A. Balasoiu. Algorithmic selection of a disassembly sequence of a component by a wave propagation method. Robotics and Computer-Integrated Manufacturing. 19 (2003). 439-448. https://doi.org/10.1016/S0736-5845(03)00032-2.

[34] X. Zhang, S.Y. Zhang. Product cooperative disassembly sequence planning based on branch-and-bound algorithm. Journal of Advanced Manufacturing Technology. 19 (2010). 91-103. https://doi.org/10.1007/s00170-010-2682-7.

[35] L.M. Galantucci, G. Percoco, R. Spina. Assembly and Disassembly Planning by using Fuzzy Logic & Genetic Algorithms. International Journal of Advanced Robotic Systems. 1 (2004). 67-74. https://doi.org/10.5772/5622.

[36] E. Kongar, S.M. Gupta. Disassembly sequencing using genetic algorithm. International Journal of Advanced Manufacturing Technology. 30 (2006). 497-506. https://doi.org/10.1007/s00170-005-0041-x.

[37] F. Giudice, G. Fargione. Disassembly planning of mechanical systems for service and recovery: a genetic algorithms based approach. Journal of Intelligent Manufacturing. 18 (20017). 313-329. https://doi.org/10.1007/s10845-007-0025-9.

[38] W. Hui, X. Dong, D. Guanghong. A genetic algorithm for product disassembly sequence planning. Neurocomputing. 71 (2008). 2720- 2726. https://doi.org/10.1016/j.neucom.2007.11.042.

[39] S. Smith, G. Smith, W.H. Chen. Disassembly sequence structure graphs: An optimal approach for multiple-target selective disassembly sequence planning. Advanced Engineering Informatics. 26 (2012). 306-316. https://doi.org/10.1016/j.aei.2011.11.003.

[40] K. Xia, L. Gao, W. Li, K.M. Chao. Disassembly sequence planning using a Simplified Teaching–Learning-Based Optimization algorithm. Advanced Engineering Informatics. 28 (2014). 518-527. https://doi.org/10.1016/j.aei.2014.07.006.

[41] M. Kheder, M. Trigui, N. Aifaoui. Disassembly sequence planning based on a genetic algorithm. Journal of Mechanical Engineering Science. 229 (2015). 2281-2290. https://doi.org/10.1177/0954406214557340.

[42] K. Meng, P. Lou, X. Peng, V. Prybutok. An improved co-evolutionary algorithm for green manufacturing by integration of recovery option selection and disassembly planning for end-of-life products. International Journal of Production Research. 54 (2016). 5567-5593. https://doi.org/10.1080/00207543.2016.1176263.

[43] S. Kara, P. Pornprasitpol, H. Kaebernick. A selective disassembly methodology for end-of-life products. Assembly Automation. 25 (2005). 124-134. https://doi.org/10.1108/01445150510590488.

[44] F. Cappelli, M. Delogu, M. Pierini, F. Schiavone. Design for disassembly: a methodology for identifying the optimal disassembly sequence. Journal of Engineering Design. 18 (2007). 563-575. https://doi.org/10.1080/ 09544820601013019.

[45] K.W. Kang, H.H. Doh, J.H. Park, D.H. Lee. Disassembly leveling and lot sizing for multiple product types: a basic model and its extension. International Journal of Advanced Manufacturing Technology. 82 (2012). 1463-1473. https://doi.org/10.1007/s00170-012-4570-9.

[46] N. Papakostas, G. Pintzos, C. Triantafyllou. Computer-aided design assessment of products for end of life separation and material handling. CIRP Annals - Manufacturing Technology. 64 (2015). 185-188. https://doi.org/10.1016/j.cirp.2015.04.023.

[47] M. Mandolini, C. Favi, M. Germani, M. Marconi. Time-based disassembly method: how to assess the best disassembly sequence and time of target components in complex products. International Journal of Advanced Manufacturing Technology. 95 (2018). 409-430. https://doi.org/10.1007/s00170-017-1201-5.

[48] L.H. Shih, Y.S. Chang, Y.T. Lin. Intelligent evaluation approach for electronic product recycling via case-based reasoning. Advanced Engineering Informatics. 20 (2006). 137-145. https://doi.org/10.1016/j.aei.2005.11.003.

[49] S. Chen, J. Yi, H. Jiang, X. Zhu. Ontology and CBR based automated decision-making method for the disassembly of mechanical products. Advanced Engineering Informatics. 30 (2016). 564-584. https://doi.org/10.1016/j.aei.2016.06.005.

[50] C. Herrmann, A. Frad, T. Luger. Integrating the end-of-life evaluation and planning in the product management process. Progress in Industrial Ecology. 5 (2008). 44-64. https://doi.org/10.1504/PIE.2008.01854.

[51] T.F. Go, D.A. Wahab, M.N.Ab., Rahman, R. Ramli. A Design Framework for End-of-Life Vehicles Recovery: Optimization of Disassembly Sequence Using Genetic Algorithms. American Journal of Environmental Sciences. 6 (2010). 350-356. https://doi.org/10.3844/ajessp.2010.350.356.

[52] L. Issaoui, N. Aifaoui, A. Benamara. Solution space reduction of disassembly sequences generated automatically via computer aids. Journal of Mechanical Engineering Science. 229 (2014). 2977-2986. https://doi.org/10.1177/0954406214565803.

[53] S. Harivardhini, K. Murali Krishna, A. Chakrabarti A. An Integrated Framework for supporting decision making during early design stages on end-of-life disassembly. Journal of Cleaner Production 168 (2017). https://doi.org/10.1016/j.jclepro.2017.08.102.

[54] F. Ardente, M.-A. Wolf, F. Mathieux, D. Pennington, In-depth analysis of the measurement and verification approaches, identification of the possible gaps and recommendations, European Commission. Joint Research Centre. Institute for Environment and Sustainability. Deliverable 2 of the project "Integration of resource efficiency and waste management criteria in the implementing measures under the Ecodesign Directive", 2011.

[55] ECMA International, Standard ECMA-341: Environmental Design Considerations for ICT & CE Products, 3rd Edition, 2008.

[56] R.C. Martin, Agile Software Development: Principles, Patterns, and Practices, Pearson Education, 2002.

[57] K. Bittner, I. Spence, Use Case Modeling, Addison-Wesley Professional, 2002.

[58] C. Favi, M. Germani, M. Mandolini, M. Marconi. Implementation of a Software Platform to Support an Eco-Design Methodology within a Manufacturing Firm. International Journal of Sustainable Engineering. 11 (2018). 79-96. https://doi.org/10.1080/19397038.2018.1439121.

[59] M. Germani, M. Mandolini, M. Marconi, A. Morbidoni, M. Rossi. A Case-Based Reasoning Approach to Support the Application of the Eco-Design Guidelines. In A. Y. C. Nee, B. Song, & S.-K. Ong (Eds.), Re-engineering Manufacturing for Sustainability-Proceedings of the 20th CIRP International Conference on Life Cycle Engineering, Singapore. (2013). 8186. https://doi.org/10.1007/978-981-4451-48-2_14.

Appendix A

Some examples of design review actions implemented for the Electric Motor target component.

Criticality (identified by using LeanDfD models)	Re-design suggestions	Implemented design review actions	Results
Nr (*electric motor*) ≥ 10	To modify the product architecture (e.g. to position target components in the external layers of the product)	NA	The two actions allow reaching the *electric motor* immediately after the removal of the *rear panel*, drastically reducing the disassembly time.
	To improve the accessibility to target components (e.g. to use fast systems for the disassembly of cover panels and chasses)	Assembly connections of *rear panel* with the *cabinet* have been changed avoiding the use of threaded elements to decrease disassembly time.	
	To reduce the overall number of components (e.g. to merge component whenever is feasible)	NA	
	To change the access to target components (e.g. re-think the way to access to target components)	*Electric motor* has been positioned in the central area of the washing machine, just behind the *rear panel*. Dimensions of *rear panel* (height and width) have been increased to facilitate the accessibility of the *electric motor*.	
$\frac{\text{t(Detergent box) - t(Control Panel ass.)}}{1} \geq 15$	If number of items/joints have the higher value among corrective factors Then reduce number of items/joints (e.g. re-arrange joints position) or change liaison type (e.g. use snap-fit whenever is possible, avoid threaded elements)	Different liaison types have been used in the original configuration to assemble *Detergent box* with the *Control Panel ass.* (3 screws, 1 snap-fit and 1 pin). All these liaisons can be substituted with only 2 cantilever snap-fits properly dimensioned and positioned.	The two actions allow reducing the disassembly time of the *Detergent box* even if the removal of this component is not anymore in the
	If tool have the higher value among corrective factors Then change the liaison features (e.g. standardize screw typologies to reduce changes in disassembly	NA	

	tools) or use automatic tool (e.g. electric, pneumatic, etc.), or reduce the changes in disassembly tools.		critical disassembly path for *electric motor* (after the implementation of other re-design actions)
	If wear have the higher value among corrective factors Then segregate the area from humidity (e.g. using a plastic box) or change material for the liaison (e.g. use stainless steel, aluminium, etc.)	NA	
	If geometrical features (length, dimension, etc.) have the higher value among corrective factors Then change liaison geometry (e.g. increase sizes of screws and bolts to be easily handled by operators or reduce the length of threaded elements whenever is possible).	NA	
$\frac{\text{t(Electro-Mec. ass.) - t(Detergent box)}}{1} \geq 15$	If number of items/joints have the higher value among corrective factors Then reduce number of items/joints (e.g. re-arrange joints position) or change liaison type (e.g. use snap-fit whenever is possible, avoid threaded elements)	Total number of M6x12 hexagonal head screws has been reduced in the *Electro-Mec. assembly* from 6 to 2.	The two actions allow reducing the disassembly time of the *Electro-Mec. assembly* even if the removal of this component is not anymore in the critical disassembly path for *electric motor* (after the implementation of other re-design actions)
	If tool have the higher value among corrective factors Then change the liaison features (e.g. standardize screw typologies to reduce changes in disassembly tools) or use automatic tool (e.g. electric, pneumatic, etc.), or reduce the changes in disassembly tools.	Different screw typologies (M4x12, M4x16, M6x8, hexagonal head, cylindrical head, etc.) have been standardized to the M6x12 hexagonal head (unscrewed used electro-pneumatic screwdriver).	
	If wear have the higher value among corrective factors Then segregate the area from humidity (e.g. using a plastic box) or change material for the liaison (e.g. use stainless steel, aluminum, etc.)	NA	
	If geometrical features (length, dimension, etc.) have the higher value among corrective factors Then change liaison geometry (e.g. increase sizes of screws and bolts to be easily handled by operators or reduce the length of threaded elements whenever is possible).	NA	
$\frac{\text{t(Electric wires) - t(Electro-Mec. ass.)}}{1} \geq 15$	If number of items/joints have the higher value among corrective factors Then reduce number of items/joints (e.g. re-arrange joints position) or change liaison type	More than 30 electrical connections of *Electrical wires* to *Electro-Mechanical assembly* have been grouped in a single plug and play system.	The two actions allow drastically reducing the

	(e.g. use snap-fit whenever is possible, avoid threaded elements)		disassembly time of the *Electric wires* even if the removal of this component is not anymore in the critical disassembly path for *electric motor* (after the implementation of other re-design actions)
	If tool have the higher value among corrective factors Then change the liaison features (e.g. standardize screw typologies to reduce changes in disassembly tools) or use automatic tool (e.g. electric, pneumatic, etc.), or reduce the changes in disassembly tools.	NA	
	If wear have the higher value among corrective factors Then segregate the area from humidity (e.g. using a plastic box) or change material for the liaison (e.g. use stainless steel, aluminium, etc.)	Plug and play system of electrical connector has been isolated from the dust and humidity using a plastic cover.	
	If geometrical features (length, dimension, etc.) have the higher value among corrective factors Then change liaison geometry (e.g. increase sizes of screws and bolts to be easily handled by operators or reduce the length of threaded elements whenever is possible).	NA	
$\frac{t(\text{Cabinet}) - t(\text{Electric wires})}{1} \geq 15$	If number of items/joints have the higher value among corrective factors Then reduce number of items/joints (e.g. re-arrange joints position) or change liaison type (e.g. use snap-fit whenever is possible, avoid threaded elements)	Several metallic zip ties have been used to group the *Electric wires*. Only 13 of these zip ties have been fixed to the *Cabinet* using snap-fits. The overall number of zip ties assembled with the *Cabinet* has been reduced to 9.	The two actions allow reducing the disassembly time of the *Cabinet* even if the removal of this component is not anymore in the critical disassembly path for *electric motor* (after the implementation of other re-design actions)
	If tool have the higher value among corrective factors Then change the liaison features (e.g. standardize screw typologies to reduce changes in disassembly tools) or use automatic tool (e.g. electric, pneumatic, etc.), or reduce the changes in disassembly tools.	NA	
	If wear have the higher value among corrective factors Then segregate the area from humidity (e.g. using a plastic box) or change material for the liaison (e.g. use stainless steel, aluminium, etc.)	The metallic zip ties used to fix the *Electrical wires* to the *Cabinet* have been subjected to rust and wear. Material has been changed (from carbon steel to PA 6.6).	
	If geometrical features (length, dimension, etc.) have the higher value among corrective factors Then change	NA	

	liaison geometry (e.g. increase sizes of screws and bolts to be easily handled by operators or reduce the length of threaded elements whenever is possible).		
A sequence of items to remove (*Top back cover, Back cover, Wood panel, Top guide DX, Top guide SX*) is present in more than 70% of retrieved disassembly sequences considering all the selected target components	To merge components together whenever is feasible	*Top back cover, Back cover, Wood panel, Top guide DX, Top guide SX* have been modified to have a single component made from a single plastic material (called *Top cover*).	The three actions allow drastically reducing items to remove for most of the disassembly sequences identified and consequently the disassembly time.
	To avoid the use of threaded elements to assemble the items of the sequence (e.g. use snap-fits, mechanical clips or dovetails whenever is possible)	Screws have been substituted by snap-fits. The unique *Top cover* re-designed component is fixed with *cabinet* using 3 cylindrical snap-fits and *Front panel* using 2 cantilever snap-fits	
	To avoid the use of tools for the liaison elements (e.g. remove items with hands)	Screws have been substituted by snap-fits and they do not require the use of special tools	
Top back cover item is present in more than 70% of retrieved disassembly sequences considering all the selected target components	If j-th item is in the first 2 items of target disassembly sequences Then adopt fast joints to remove the j-th item (e.g. use snap-fits, mechanical clips or dovetails whenever is possible, avoid threaded elements)	A deep re-design action has been implemented considering the possibility to merge different components (*Top back cover, Back cover, Wood panel, Top guide DX, Top guide SX*) and to substitute screws with snap-fits (see previous identified criticality for the *Electric motor*).	See previous result
	If j-th item is in the first 5 items of the disassembly sequences, then modify the product architecture (e.g. move the j-th component in the core of the product)	NA	
Back cover item is present in more than 70% of retrieved disassembly sequences considering all the selected target components	If j-th item is in the first 2 items of target disassembly sequences Then adopt fast joints to remove the j-th item (e.g. use snap-fits, mechanical clips or dovetails whenever is possible, avoid threaded elements)	A deep re-design action has been implemented considering the possibility to merge different components (*Top back cover, Back cover, Wood panel, Top guide DX, Top guide SX*) and to substitute screws with snap-fits (see previous identified criticality for the *Electric motor*).	See previous result
	If j-th item is in the first 5 items of the disassembly sequences, then modify the product architecture (e.g. move the j-th component in the core of the product)	NA	

Wood panel item is present in more than 70% of retrieved disassembly sequences considering all the selected target components	If j-th item is in the first 2 items of target disassembly sequences Then adopt fast joints to remove the j-th item (e.g. use snap-fits, mechanical clips or dovetails whenever is possible, avoid threaded elements)	NA	See previous result
	If j-th item is in the first 5 items of the disassembly sequences, then modify the product architecture (e.g. move the j-th component in the core of the product)	A deep re-design action has been implemented considering the possibility to merge different components (*Top back cover, Back cover, Wood panel, Top guide DX, Top guide SX*) and to substitute screws with snap-fits (see previous identified criticality for the *Electric motor*).	