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An approach to analytically evaluate the product disassemblability during the design process

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Abstract

In order to favor the implementation of closed-loop scenarios at the product End of Life (EoL), it is essential to consider the disassembly phase during the design process. In this context, the paper presents a design for disassembly approach to quantitatively estimate the product disassemblability. The methodology is based on a knowledge database about liaisons, which have been classified and characterized with different properties, in order to take into account the liaison specificity and real conditions in the moment of the disassembly. Starting from the product structure and liaisons between components, the methodology allows to analytically calculate the disassembly time and cost of components/sub-assemblies. The case study (combination oven) demonstrates the usefulness of the proposed approach in identifying the product criticalities which is necessary to consider during the redesign phase in order to improve the product disassemblability performances.

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1. Introduction

The environmental problem is becoming extremely important in the modern society. In order to preserve the natural environment for future generations, it is essential to consider the variable "environment" during the development of new products, processes and services, as well as the other classical design drivers, such as costs, functional requirements or performances. To this aim, the design departments need to extend their view outside the company boundaries, considering not only the design and manufacturing phases but the whole life cycle, from material extraction to disposal.

In this context, the End of Life (EoL) is recognized as one of the most critical phases. This is essentially due to the fact that it is the most far away phase, in terms of time, from the moment of the product conception. But it is also well known that the EoL is the joining link to "close" the product life cycle. The accurate management of the EoL scenarios, in the early design stages, is emerging as a fundamental eco-design strategy for companies, in order to create closed-loop scenarios of materials (reuse of products or components, remanufacturing of components and recycling of materials).

Within the product EoL, the disassembly is a preliminary but fundamental phase. Only reducing a product into its individual components it will be possible, for example, to reuse or remanufacture components. The Design for Disassembly (DfD) concepts should be integrated within the design process, when designers have the necessary freedom to change different characteristics of the products, such as component materials or connection methods, with minimal impact on the manufacturing process or production costs.

The proposed paper provides a useful methodology which supports companies in the evaluation of the product disassemblability. It permits to analytically assess the disassembly phase, on the basis of the product architecture and liaisons between components, taking also into account the real condition of the product at the moment of the disassembly. And considering the disassembly processes and tools, as well as the labor cost, the disassembly cost of each component can be estimated. The integration of this methodology during the design process allows to

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quantitatively identify the most critical components/sub-assemblies from a disassembly point of view. This is an essential result to help designers to proceed in the right way during the improvement phase.

2. Literature Review

In the recent years international governments have issued directives, such as the disposal of electronic and electrical products and equipment, and the restrictions on the use of hazardous substances [1][2], which focus on the EoL phase, in order to force manufacturers to effectively participate to the waste treatment. The only possible way to facilitate the dismantling activities at the EoL, is the implementation of DfD or Design for EoL techniques.

Design for Disassembly is a well-known target design methodology which allows the easy separation of components in industrial products [3]. It involves the selection and use of appropriate materials, the design of components and product architecture and the selection and use of joints, connectors and fasteners which could be easily disassembled [4]. DfD makes the de-manufacturing plan of components simple and efficient, and must be considered, in particular, for components with a high quality/value [5].

In literature there are many works on issues about this important theme. Dewhurst [3] evaluates the depth of disassembly for particular components in a product to establish the effective cost convenience for disassembly operations. His index is one of the first examples of quantitative methodology to assess the feasibility of the disassembly process. Johansson [6] suggests the product properties that are essential for efficiency of the disassembly process: ease of identification, accessibility, ease of separation, and ease of handling of components and subassemblies. However, none of these works provide a method to estimate the disassembly time, which is one of the most important indicator of the ease of disassembly.

In the last decades, the most important works on disassembly methodologies have focused on extrapolating data from 3D CAD models. In particular, many researchers [7] have developed algorithms to find the transition matrix and the best disassembly sequence for components in an industrial product. Their topics are mainly oriented to the selective disassembly of components due to the high value. Kara et al. [8] propose an evaluation method to detect the possible paths for the disassembly of a specific component from the product. Kang et al. [9] propose an algorithm for the efficient derivation of a transition matrix based on a product's architectural information, which includes the product's physical connections and the relative geometric locations between individual parts. Several authors are focused on the disassembly scheduling. The identification of the optimal disassembly sequence is performed using linear programming and genetic algorithms [10][11]. Giudice and Fargione [12] propose an approach to disassembly process planning, based on genetic algorithms, that supports the search for the disassembly sequence best related to two aspects: service of the product and recovery at the end of its useful life. Srinivasan et al. [13] analyze the types of connections between components, the arrangement of components (product architecture), the directions of extraction and the first component to be disassembled in order to minimize time. A further step in this direction is the ability to recognize the type of mechanical liaisons between components, thus to generate an optimum disassembly sequence directly from the CAD product model. Different algorithms have been developed to solve Disassembly Sequence Planning, i.e. the determination of the sequence for disassembling component parts using combinatorial structure models [14]. Even if all these proposed methods are very interesting to solve the sequence planning problem, they do not provide quantitative outputs to measure the disassemblability of products.

Another method, called “virtual disassembly”, use Virtual Reality systems to create a realistic multimodal interaction (visual/audio/haptic) experience with the CAD product model and can support collaborative de-manufacturing between manufacturer/de-manufacturer, disposer and designer [15]. Aleotti and Caselli [16] describe a method to use Virtual Reality to find all physical admissible subassemblies for the automatic disassembly planning. Chen et al. [17] propose a virtual disassembly system which enables operators to disassemble products interactively in a virtual environment. Also these methods are mainly focused on the sequence planning and do not consider disassembly time and cost to assess the feasibility of the disassembly process at the EoL or during the maintenance phases.

Only few literature works consider the disassembly time estimation to measure the degree of disassemblability of products [18][19]. Anyway, none of these considers also the disassembly costs.

In this sense, this paper aims to go beyond the state of the art about design for disassembly methods, presenting a methodology to analytically estimate the disassembly time and cost for each product component/sub-assembly. In particular, this latter could also represent a tangible and very useful metric for designers, in order to assess the cost related to the maintenance and EoL phases, in a life cycle perspective. Using this methodology, designers can rapidly identify the most critical components from a disassembly point of view, to the aim of conceiving the correct product architecture or choosing the most appropriate joint methods.

3. Methodology

The final goal of the proposed methodology is to help designers in the application of a Design for Disassembly approach. It is essential to support designers in evaluating the disassemblability of components and sub-assemblies. The analytical estimation of the disassembly time and cost, for the feasible disassembly sequences, represents the first step toward the optimization of products considering the EoL aspects. The classification and characterization of the possible liaisons between components is the starting point for the successive quantitative evaluation.

3.1. Liaisons and properties

The methodology is based on the classification of the different liaisons which is possible to find within an industrial product. This represents the knowledge database, essential for the various steps of the methodology, which has been organized on the basis of an in-depth literature review, some empirical case studies, and analyzing different products, in particular home appliances (freezers, washing machines, etc.) and other complex products (i.e. machine tools).

Table 1 presents all the classified liaisons, subdivided in two different hierarchical levels: classes and types. The first level of classification (higher level) contains one or more liaison types. For each liaison type, a standard disassembly time has been defined. This is relative to a reference liaison, not worn and with standard condition (length, diameter, tool, etc.). For example, in the case of screws, the reference is a new screw (not used or damaged), with an hexagonal with notch head, a length of 20mm or less, a diameter between 4mm and 12mm and disassembled with a screw gun (see the factors with unitary values in Table 2 and Table 3). In this case the disassembly time equals the assembly time.

Table 1. Liaisons classification.

Classes	Types
Threaded	Screw
	Threaded rod
	Nut
Shaft-hole	Pin
	Linchpin
Rapid joint	Snap-fit
	Guide
	Dap joint
Electric	Coaxial cable
	Electric plug
	Screw terminal
	Ribbon cable
Prevent extraction	Circlip
	Split pin
Not removable	Nail or Rivet
	Welding
	Adhesive
Motion Transmission	Tang or Key
	Spline profile
Magnetic	Magnetic
Visual Obstruction	Visual Obstruction

Table 2. Threaded class properties and corrective factors.

Class	Properties	Condition	Corr. Factor [dimensionless]
Threaded	Wear	Not worn	1
		Partially worn	1,3
		Completely worn	2

Table 3. Screw type properties and relative corrective factors.

Type	Properties	Condition	Corr. Factor [dimensionless]
Screw	Head type	Hexagonal	1,2
		Hexagonal with notch	1
		Cylindrical	1,2
		Cylindrical with notch	1
		Cylindrical with hex notch	1,1
	Length	$L \leq 20$mm	1
		$20\text{mm} < L \leq 40$mm	1,1
		$L > 40$mm	1,2
	Diameter	$D \leq 4$mm	1,2
		$4\text{mm} < D \leq 12$mm	1
		$D > 12$mm	1,2
	Tool	Screw gun	1
		Spanner	1,2
		Screwdriver	1,4

In order to introduce the peculiarity of each liaison, several properties have been defined (i.e. geometrical dimensions, working environment, etc.). These properties are essential to take into account the real condition of each liaison at the moment of the disassembly, when the product has been used for several years and in different working conditions (i.e. wet environments). A corrective factor has been associated to each particular condition (i.e. the kind of tool used directly influences the disassembly time). These values are used to adjust the standard disassembly times, obtaining the effective disassembly times (i.e. using a screw gun, in specific cases, the disassembly time could be 40% faster than using a screwdriver).

The properties and the relative corrective factors have been chosen and estimated on the basis of a literature review and, in particular, thanks to the collaboration with dismantling companies. This experimental phase allows to measure the disassembly time of each liaison and comparing it with the standard assembly time, the corrective factors have been established and successively valued. Table 2 and Table 3 present an example for threaded class and screw type.

Among the type properties (Table 3), one is relative to the disassembly tools. A classification of the possible tools used during the disassembly operations has been done. And each liaison type has been correlated to one or more disassembly tools. Furthermore, each disassembly tool, as well as the labor, has been characterized with a hourly cost to use for the disassembly cost estimation.

3.2. Methodology steps

The proposed methodology to analytically estimate the disassembly time and cost is composed by several steps (Fig. 1). Starting from the product structure, this approach is able to help designers in the identification of the product criticalities from a disassembly and EoL point of view.

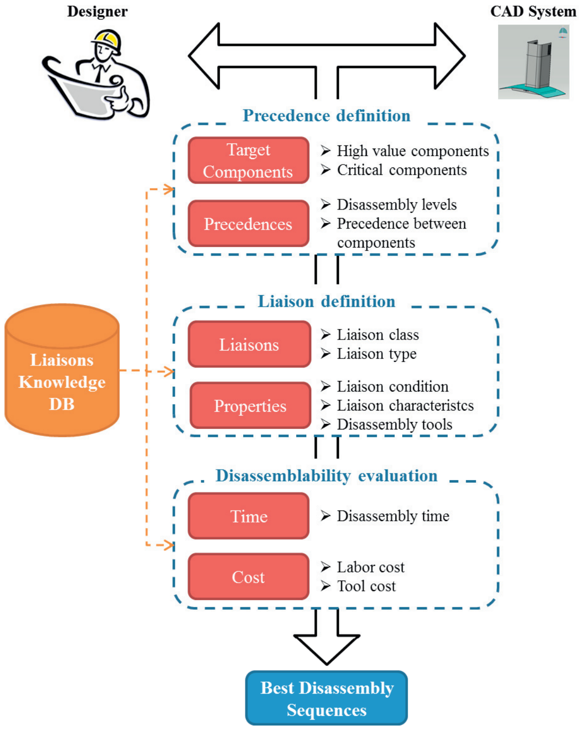

Fig. 1. Methodology steps.

The starting point of the approach is represented by the 3D CAD model, which contains the geometrical data and the hierarchical structure of a product. With the help of a CAD System, designers can configure new products and can easily retrieve all the necessary information to carry out a disassembly analysis.

The first phase of the analysis, called *Precedence definition*, is needed to specify the components which is necessary to analyze, the depth of the analysis and the relationship between components. First of all designers need to specify which components/sub-assemblies (called Target Components), have to be investigated from a disassembly point of view. In general, Target Components could be high value components which is necessary to easily disassemble at the EoL to obtain an high net revenue, or components which is necessary to treat in a proper way for legislative compliance (i.e. critical components of electrical equipment). Other important examples are those components which is necessary to substitute or maintain during the life cycle (i.e. lamps).

On the basis of the selected Target Components, it is necessary to specify the disassembly levels and the precedence between components/sub-assemblies. A component has a disassembly precedence in respect to another one, if it can be disassembled before the other (there is no obstruction). In this way components are subdivided in different disassembly levels. Level "0" contains all the components which is possible to remove without any precedence. Components belonging to Level "N" can be removed only after one or more components belonging to Level "N-1". For example, in Fig. 2 the components 1 and 4 of the simple assembly 1-2-3-4 can be removed immediately, while the component 2 can be removed only after the component 1. Not all the precedence have to be specified, but the modeling can stop at a certain depth, when all the Target Components have been reached. This information allows to build the Precedence Matrix (Fig. 2), in which a cell contains a "1" if the component in the column has the precedence in respect to the component in the row.

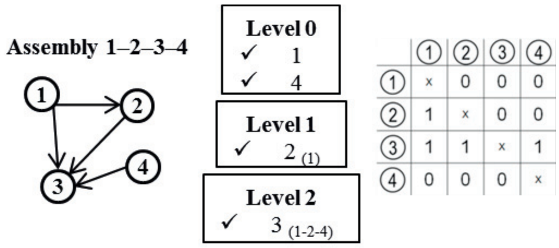

Fig. 2. Schematic representation of an assembly with the relative Disassembly Precedences and Precedence Matrix.

The disassembly precedences are essential to calculate the feasible disassembly sequences. All these latter ones have to begin with a component belonging to Level "0" and have to respect the specified disassembly precedence. For the example in Fig. 2, the sequence 1-2-4-3 is a feasible sequence to reach the component 3, while the sequence 1-2-3 is not a feasible sequence because the component 3 cannot be disassembled before the components 1, 2 and also 4.

Once the necessary precedence have been defined, the second phase, called *Liaison definition*, can start. For all the components/sub-assemblies considered in the previous phase, it is necessary to specify all the liaisons which link them to other components. Each defined liaison has to be characterized by a type, the relative properties and the tools to use during the disassembly. The liaison classification is important in this phase of the methodology because allows to associate, to each connection between product components, a specific liaison and a disassembly time and cost.

During the last phase, called *Disassemblability evaluation*, the degree of disassemblability of the chosen Target Component is evaluated. Considering the proposed knowledge database, the disassembly time for each specific liaison can be calculated with the following equation:

$$T_{ej} = T_s \cdot \prod_{i=1}^{I} CF_i \quad (1)$$

where T_{ej} is the effective disassembly time of the *j-th* liaison, T_s is the standard disassembly time and CF_i are the corrective factors of the considered liaison, at the chosen conditions.

Concerning the disassembly cost, instead, it can be calculated by the following equation:

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

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

The following Fig. 3 presents a simple example to show the calculation procedure to obtain the disassembly time and cost of a screw, on the basis of the standard time stored in the Liaisons knowledge database. From the results, it emerges the importance of the corrective factors, useful to consider the specificity of the analyzed liaison (a completely rusted screw).

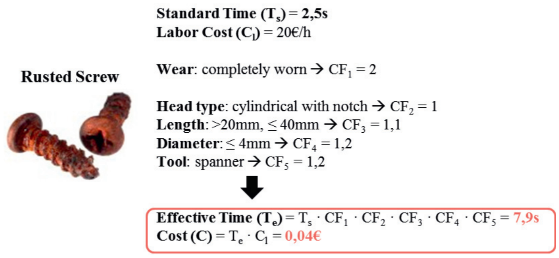

Fig. 3. Example of disassembly time and cost calculation for a screw.

Considering each feasible disassembly sequence and the effective disassembly time and cost of each liaison which has to be disassembled to reach the component under analysis, the total disassembly time and cost for a particular Target Component can be analytically estimated using the following equations:

$$T_t = \sum_{j=1}^{J} T_{ej} \qquad C_t = \sum_{j=1}^{J} C_j \tag{3}$$

where T_t and C_t are respectively the total disassembly time and cost of a particular component/sub-assembly, T_{ej} and C_j are respectively the effective disassembly time and the disassembly cost of the j-th liaison.

On the basis of the calculated values it is possible to find the best disassembly sequences. These permit to identify the product criticalities and the operations which require the longest time or the highest cost. These results should guide designers during the re-design phase in order to improve the product architecture or characteristics.

4. Case study

In order to test the proposed methodology, this section presents the experimental results obtained for the disassembly of a combination oven (grill + microwave), used for professional applications (restaurants, canteens, etc.). This complex product composed by several electric, electronic and mechanical components allowed to test the effectiveness and the robustness of the methodology, as well as to measure the error in the estimation of the disassembly time, in comparison to a real disassembly process. The analyzed product (Fig. 4) has a life time of about 5 years, during which the oven has been intensively used in a clean but wet environment. This permits to suppose possible wear for certain joining elements (in particular screws). In this study, three specific Target Components of the oven have been considered: the capacitor, the electronic board and the thermal resistor. The first two have been chosen because they are critical components according to EoL legislation [2]; they therefore need to be manual disassembled and then be managed following specific procedures. The latter, instead, is subject to wear and its substitution could be necessary during the product life time. For this reason, it is important to assess their disassemblability, trying to identify the criticalities and improve some product features.

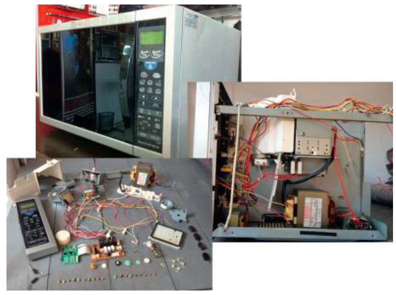

Fig. 4. The combination oven analyzed in the case study.

Table 4 presents the results of the disassembly analyses performed following step-by-step the proposed methodology. The experimental results confirm the reliability of the proposed method in the estimation of the disassembly time and cost. The maximum error between the estimated times, calculated considered the Liaison knowledge database, and the real times, measured during the real disassembly operations, is lower than 8%. This uncertainty value can be considered acceptable to identify the disassemblability of a product during the design process.

Table 4. Results of the disassembly analyses.

Component	Disassembly Sequence	Estimated Time [s]	Estimated Cost [€]	Error [%]
Electronic Board	1. Cover panel 2. Clicson thermostat 3. Rear panel 4. Right frame 5. Electronic board	165,8	0,92	7,6
Capacitor	1. Cover panel 2. Clicson thermostat 3. Rear panel 4. Capacitor	142,7	0,79	3,9
Thermal Resistor	1. Cover panel 2. Clicson thermostat 3. Rear panel 4. Electric motor 5. Electric motor support 6. Aluminum impeller 7. Thermal Resistor	229,5	1,28	5,9

Fig. 5 presents the disassembly time graph relative to the thermal resistor. The graph is built considering the disassembly sequence and the cumulative time to disassemble a particular component/sub-assembly. In this way the criticalities are visible just considering the slope of the curve.

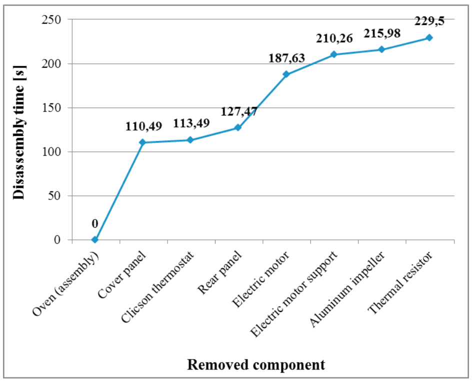

Fig. 5. Disassembly time graph for the thermal resistor.

From the results presented in Table 4 and in Fig. 5 it is clear that the most critical operation is the disassembly of the Cover panel, which is the Level 0 component, to remove in order to reach all the internal components. In particular it is linked with the frame by 14 screws which require a long time for the disassembly. Certainly, this aspect has to be considered for a future redesign of the oven, trying, for example, to reduce the number of screws used or separating the panel in three different parts (right, left and upper) in order to allow the disassembly of only the side of interest.

5. Conclusions

This paper presents an innovative methodology to assess the disassemblability of products during the design process. The proposed method allows to analytically calculate the disassembly time and, considering the necessary resources, also the cost. The calculation is based on a knowledge database which collects the most common liaisons which is possible to find in an industrial product. One of the most relevant innovation is the introduction of corrective factors, necessary to consider the specificity of each liaison and its “real” condition (e.g. wear) in the moment of the disassembly.

The application of the methodology during the design process allows companies to develop product with the disassembly phase in mind. This is essential both at the EoL, when critical components have to be easily dismantled, and during the maintenance phases to facilitate the substitution of broken components. In this sense, the output of this methodology could represent an additional documentation of a product, essential for service departments and dismantlers.

Future works will consist in the development of a tool to implement the proposed methodology steps. The integration with the CAD and PLM systems has to be considered to increase the tool usability and to further simplify the definition of the product disassembly model. In order to better consider the EoL phase, additional works will aim to include destructive disassembly operations (i.e. the use of waste mills), which are very common, in particular, during the dismantling of waste of electric and electronic equipment. Finally, the method should be improved in order to provide more suggestions, useful during the product redesign phase.

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