Design for X Tool to Introduce Sustainability in the Design Process

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Abstract. In the present market, Computer Aided Design and Computer Aided Manufacturing represent considerable tools to achieve better design and optimize the manufacturing phases. To customize and tailor these tools to the company's needs, knowledge-based engineering solutions have been developed.

The present paper proposes a method to support designers in the optimization of environmental sustainability aspects of their products, through a Knowledge Based Engineering approach. It allows the identification of design criticalities under the environmental issue, and on a life cycle perspective, supporting designers in their activity and favoring the knowledge use and re-use.

The approach proposed was applied to develop a prototype version of a tool. It was then applied in a case study of an Italian manufacturer of professional espresso coffee machines to analyze and improve the product recyclability and disassembly level.

Keywords: Knowledge-based engineering, Design for Environment, Design for X, Design rules, Sustainability index

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1 INTRODUCTION

In the present market, Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) represent considerable tools to achieve better design and optimize the manufacturing phases. At the present-day manufacturers are aiming to produce customized high-quality products, with little lead-time, and at reduced costs [8].

The conventional CAD/CAM tools are developed to meet the general needs of the market, but not the rapid or specific requirements of the market or customer.

Consequently, the companies are looking to customize or tailor these tools to improve their effectiveness. Among these strategies, one is the application of knowledge-based engineering (KBE) in commercial CAD/CAM systems. KBE is applied to automate repetitive design tasks favoring time savings, enabling designers to explore a larger part of the design space during the various design phases [19].

Numerous approaches and methodologies have been developed [13];[9]; they are generally universal, but sometimes they focus on specific, narrow substantive, or scope context [14]. Mainly oriented in the optimization of several general aspects, e.g., assembly, manufacturing, some of them are focused on specific aspects, or production processes, e.g., casting [4].

Despite these achievements, the more effective and efficient application of KBE in the industry still encounters various difficulties, both in the process of its application development and in conducting its further development. Difficult in the structuring of modelled engineering design knowledge represents one of the main barriers [14] together with difficulties in favoring knowledge reuse [19].

Furthermore, among the limits of actual CAD/CAM and KBE solutions, the complexity to address emerging knowledge issues, e.g., environmental sustainability. It's, today, not faced by available KBE approaches, but it represents a significant driver to include inside the design process.

The growing interest of the academic and industrial world in environmental sustainability is widely recognized and consumers consider a priority the prevention of pollution [12]. Academics and researchers developed a great number of methods, tools, and approaches to address environmental issues yet in the first phases of the design process [1].

On the side of environmental impact quantification, Life Cycle Assessment (LCA) represents a solid and consolidated methodology to assess the environmental impacts of products/services or processes. Primitively, LCA was chiefly utilized for analyzing product systems and comparing them with one another. In the last few years, the utility of LCA has expanded multifold, be it infrastructure planning or government policy [6]

Today, when the environmental sustainability issue is analyzed in correlation with CAD/CAM tools and/or KBE systems, data integration is the only question faced. The role of knowledge became predominant, and several works have been developed to extract and represent product-related information in a formalized format [11], e.g., OWL (Ontology Web Language), SWRL (Semantic Web Rule Language). Research interests in the integration of CAD and LCA tools are growing [20].

When integration is achieved, it regards the life cycle inventory phase, i.e., to facilitate the data collection and related modeling phase inside the LCA tool: data Exchange between CAD and LCA plays a vital role in integrating progress [5]. Fang et al. [1] presented an approach for the machine design and analysis within the CAD/Computer Aided Engineering (CAE) environment, as well as Landi et al., [9] aimed at integrating simulation results and environmental data. Russo and Rizzi [15] proposed a computer-aided methodology based on the integration of Structural Optimization and the LCA tool.

Tao et al., [17] proposed a life cycle modeling approach based on a feature mapping scheme between product, operation, and inventory to address the discrepancy in the principles of the utilized methodological approaches of LCA and CAD/CAE and enable data transformation between CAD/CAE and LCA models.

Two main limits, therefore, emerge: on the KBE side, the need to include new important design drivers, such as environmental sustainability, and to increase the knowledge sharing to support design activities. Regarding the integration between CAD and environmental methods and tools, the focus on the capitalization of knowledge can guide designers toward the identification of the best design choice also from the environmental perspective.

The present paper will face these two limits by proposing a method to support designers in the optimization of environmental sustainability aspects of their products, through a KBE approach. It allows the identification of design criticalities under the environmental issue, and from a life cycle perspective, supporting designers in their activity and favoring the knowledge use. [17].

In the following, the presentation of the proposed method and its objectives (Section 2), the description of the developed prototype version of the DfX tool (Section 3), and a discussion of the main results obtained (Section 4).

2 MAIN IDEA

The proposed method has the object to support the designer in the development of environmentally sustainable products, by the collection and the return of rules and feedback and by the calculation of product environmental indices. The core is represented by a knowledge DB, which advises the designer by identifying possible errors and/or criticalities, and a calculation module, which quantifies parameters for a simplified environmental assessment.

Design rules, oriented on environmental sustainability and in particular on product End of Life (EoL), are linked with the 3D CAD model. Material, physical, and manufacturing features represent the input from which design feedback and product indices are derived.

The link between design rules and sustainability is the 3D CAD model, developed during the engineering design process of parts or assemblies. The Design for Environment (DfE) rules are defined with a particular interest in product EoL and disassembly strategies; they suggest to the designer improvement strategies, underlining design criticalities and related possible solutions.

The goal is to make designers aware of the environmental sustainability of the choices made yet in the first design phase, supporting them and increasing their competencies in developing products with a life cycle perspective and optimized in environmental terms.

Figure 1 shows the method schema. It includes the inputs, which came automatically or manually by respectively the information contained in the 3D CAD model and product designer; the DB with content in terms of rules, environmental parameters, and algorithms; the calculation module, and then the outputs available for designers. The flow is circular, it returns to the product designer, the main user, and the beneficiary of tool outputs. He/she increases the knowledge and can actively contribute to the improvement of product environmental performance.

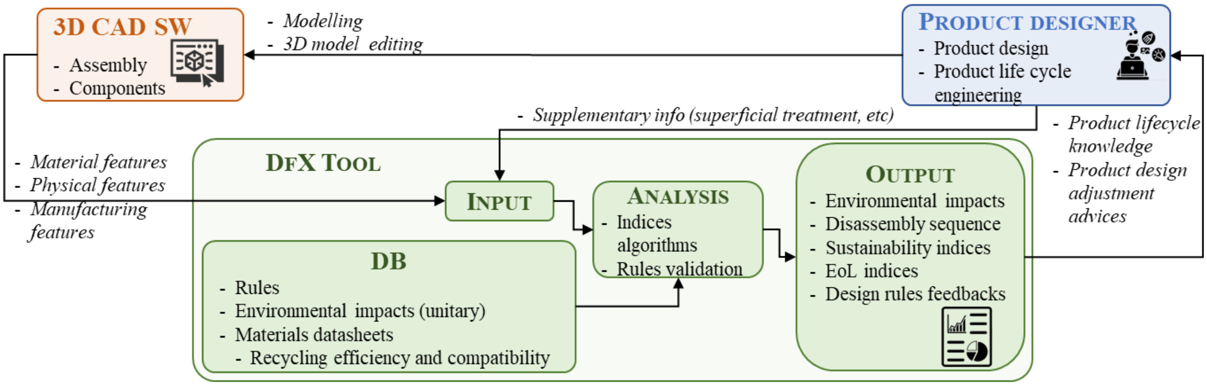


Figure 1: The proposed method.

Based on the proposed method, the related workflow is divided into four main steps.

- 3D CAD model: the starting point is the 3D CAD model of the part or assembly object of the analysis. The model contains information and product characteristics, and in the case of assembly, data about relations among parts.
- Recognition and extraction of characteristics: in this phase, the 3D CAD model is analyzed.
- The information obtained will be used for comparison with the DfE and Design for Disassembly (DfD) design rules.
- Analysis: This step allows to verify the design rules against the analysis of the features contained in the 3D model. To make this comparison possible it is necessary to have defined a framework, consisting of a database of rules (DB), mathematical equations, indexes, algorithms. Mathematical equations, indexes, and algorithms are used to verify the compliance of design guidelines retrieved from the literature or company knowledge with

information from 3D model data. At the end of the analysis, a report can be generated to summarize the validated/not-validated target design (DfX) rules, the identified criticalities, and quantification of environmental product performances (e.g., impact of the EoL phase, etc.).

- 3D CAD model update: in this phase, the designer, through the design suggestions coming from the tool and report, modifies the 3D model. Each design guideline recommends the type of design action to be implemented, how the design guideline improves the sustainability of the part, and an illustrative purpose image shows how the rule can be implemented. The feature recognition allows highlighting within the 3D model the specific features that do not comply with the rules to facilitate the introduction of the design modification. It is up to the designer to choose whether to implement the proposed design changes and if so, a new analysis is performed to check if the updated 3D model complies with the requirements. If there are still unapproved rules, the tool points out the need for further revision of the project. Therefore, an iterative flow is proposed.

The methodology introduced is based on the recognition of the characteristics of the models. A feature recognition procedure begins by defining the types of features to be identified. In general, it is possible to identify the following features:

- The manufacturing feature indicates a feature that consists of a series of related faces and properties. Some examples of product manufacturing features are holes, threaded holes, fittings, chamfers, milling features, turning features.
- The material feature also contains the information related to it
- The physical characteristics feature indicates the dimensions of the part or assembly (volume, area, shape, etc.).

By combining information from the features of the same part, it will be possible to know, for example, the transport limits, therefore the maneuverability of a part, or if a certain feature is feasible with the material considered or if it is accessible concerning the other features always belonging to the same part. Instead, by relating the features of two different parts within the same assembly, it is possible to determine the connection mode chosen between the two components. This will allow obtaining useful data to understand the assembly strategy and consequently provide a recommended disassembly strategy. The latter will be chosen concerning the sustainability principles related to the disposal of a product, such as the compatibility between recycled materials.

The output of the analysis, which consists in communicating the compliance with a rule can be divided into different levels of importance: a “Warning” outlines an error that generates potential problems or complications during the EoL or disassembly; while an “Information” is a suggestion that would be desirable to improve the EoL or disassembly process.

3 APPLICATION

Based on the proposed method, a prototype version of a DfX tool is developed. It was applied in a case study of an Italian manufacturer of professional espresso coffee machines.

The machine is a complex product, composed of 16 main assemblies and about 900 components. Materials employed must comply with functional and legislative constraints (i.e., contact with food, etc.). In the traditional design process, designers were used to selecting the material for each component but they are not able to obtain immediately the classification of the materials employed in the product. This is possible with the DfX tool (Figure 2).

Following the proposed method, the 3D CAD software is the source of all information regarding geometry (i.e., volume, area) and material of the components and assemblies. Those are then related by DfX DB to the necessary information. Together they constitute the input to the analysis. Figure 3 shows an example of feedback for the user. The outputs show the resulting $Recyclability_{index}$, calculated by scaling unitary impacts with geometrical information and warnings about the materials whose selection hampers the recycling process. In addition to that, criticalities about the most employed material are outlined.

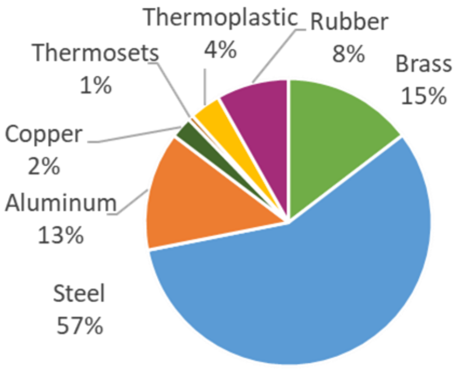
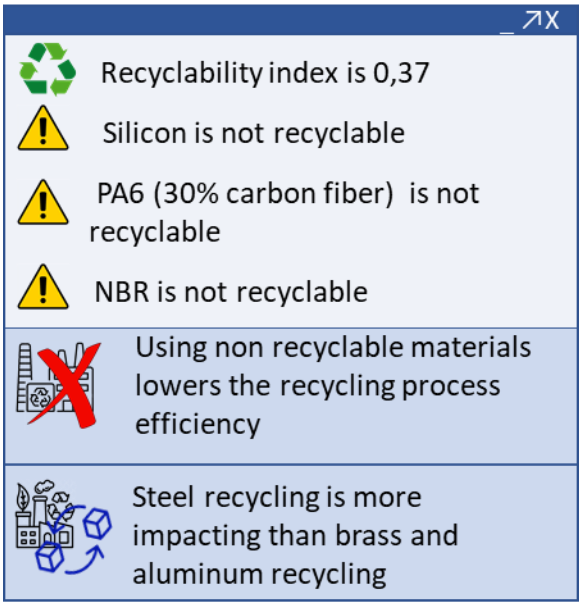


Figure 2: Material classification.

The coffee machine includes components made of non-recyclable materials; they are mostly plastic material, such as: PA6 (Polyamide 6, 30% carbon fiber), NBR (nitrile rubber), EPDM (Ethylene-Propylene Diene Monomer), etc. Although low in weight, these should be avoided or minimized. When their use is required by functional constraints and there are no alternatives to their use, their disassembly should be evaluated and made possible.



Recyclability index is 0,37

Silicon is not recyclable

PA6 (30% carbon fiber) is not recyclable

NBR is not recyclable

Using non recyclable materials lowers the recycling process efficiency

Steel recycling is more impacting than brass and aluminum recycling

Figure 3: Recyclability feedbacks for the user.

3.1 Recyclability

In the current application, the classification of the materials and the recyclability index were calculated. The materials' classification is extremely important to estimate the quality and quantity of the material scraps (i.e., to be valued by dismantlers), while the recyclability index compares (from an environmental point of view) recycling to different EoL strategies, as suggested by Huysman et al. [7]. Equation (3.1) shows the index formula; the algorithms of DfX tool implement the calculation, scale appropriately the unitary values shown in Table 1; from the table content, it is clear how different environmental impacts of recycling processes or raw material extraction may highly vary from one kind of material to another, although all are recyclable materials.

$$Recyclability_{index} = \frac{\sum_{j=1}^{P}\sum_{i=1}^{N} m_{recyc,i}\, RCR_{ij}\left(V_{n,ij}+D_{n,ij}-R_{n,ij}\right)}{\sum_{j=1}^{P}\sum_{i=1}^{N} m_{i,j}\, V_{n,ij}+M_n+U_n+\sum_{j=1}^{P}\sum_{i=1}^{N} m_{i,j}\, D_{n,ij}} \tag{3.1}$$

Where:

- Dn,ij (environmental impact for disposing of 1 kg of ith material of jth part) [unit/kg]
- Vn,ij (environmental impact for producing 1 kg of ith material of jth part) [unit/kg]
- Rn,ij (environmental impacts of production of 1 kg of ith recycled material of jth part) [unit/kg]
- RCRij (recycling index of ith material of jth part)
- Mn (environmental impact of production of jth part [unit])

Material Class	*Brass*	*Steel*	*Alluminum*	*Copper*	*Plastics*		
Materials					Thermosets	Thermoplastics	Rubber
Recyclability	Yes	Yes	Yes	Yes	No		No
Biodegradability	No	No	No	No	No		No
Dn,ij [kg CO_2eq /kg]	0,761	0,0043	0,761	0,761		0,699	
Vn,ij [kg CO_2eq /kg]	6,88	2,12	9,99	8,21	0,18	3,56	1,9
Rn,ij [kg CO_2eq /kg]	0,0738	3,2	0,34	0,0738		1,27	
RCRij	0,999	0,995	0,999	0,999		0,767	
Mnj [kg CO_2eq]	1,235	1,2	0,404	0,456		1,31	
Mn [kg CO_2eq]	89,676						

Table 1: Database information for the espresso coffee machine.

The unit is related to the environmental indicator chosen; in this case, it is Climate Change and the unit is kgCO2eq. The maximum value of the index is 1; it can be negative when recycling is not convenient. The overall recyclability index for the espresso coffee machine is equal to 0.3784.

According to the most recent standards (UNI CEI EN 45555:2020 [18]), the recyclability rate for Energy-related Products (ErP) shall be calculated in mass percent, as shown in Equation (3.2):

$$R_{cyc} = \frac{\sum_{k=1}^{n} m_k R_{cyc_k}}{m_{tot}}\, 100\% \tag{3.2}$$

Where mk is the mass of the k-th material, mtot is the total mass of the product and Rcyc is the recyclability factor of the k-th material.

According to the standard, the recyclability index is 0,907 (90,7%) for the coffee machine. This is relatively easy to assess, however it is extremely simple and only distinguishes between recyclable and non-recyclable materials. In ever-changing contexts, where Circular Economy (CE) is affirming and is imposing much more importance on the treatment of materials, the latter index is not able to go beyond the selection of recyclable/non-recyclable materials. This clearly explains why the two indexes provided substantial quantitatively different results.

From the first analysis results obtained with $Recyclability_{index}$ there is space for product improvement from the recyclability perspective. Several scenarios (S) have been defined and then analyzed.

First of all, the focus has been pointed to the non-recyclable materials; they account for less than 10% of total coffee machine mass; they are mostly employed in insulating components, sealing, hydraulic junctions, and pipes or hoses. Due to the function and dimensions of the abovementioned components, only pipes and hoses material were substituted (S1): the Ethylene-Propylene Diene Monomer (EPDM) and Polyvinylchloride (PVC) have been replaced with Copper (Cu); this material can fulfill the performances requirements for those parts. Certainly, the higher specific weight leads the part to be heavier, even with the same volume.

The overall coffee machine weight rose from 82 kg to 82,73 kg; Table 2 shows in detail the changes in materials compared to the initial version. $V_{n,ij}$, $D_{n,ij}$ and $R_{n,ij}$ refer to material characteristics and unitary, thus they remain the same for the subsequent scenarios. The new recyclability index is equal to 0,3795, while the R_{cyc} is 0,9137 (91,37%). Steel has the highest $R_{n,ij}$; re-design hypothesis focused on substituting steel with alternative recyclable materials, with lower recycling impact. Thus, the pedestal material (steel) was replaced with aluminum (S2). The different tensile strength also requires an increase in the volume of the component, so that the pedestal can support the product forces. The updated $Recyclability_{index}$ is 0,4255; the new R_{cyc} is 0,9102 (91,02%).

Further re-design hypothesis affected the upper and lower semi-bodies, initially made of brass. Both the use of aluminum (Al) and steel implicate a reduction of the $Recyclability_{index}$ and R_{cyc}: 0,4089 and 0,9072 (90, 72%) in the first case (S3), 0,3877 and 0,9083 (90,83%) in the second case (S4).

Table 2 summarizes the differences in material employed and the resulting indexes related to each scenario. In particular, the weight of the components affected by the changes is shown. S2 considers both changes of S1 and those related to the pedestal. Similarly, S3, where re-design hypotheses of S1, S2, and S3 are accounted. The last one, S4 considers redesign hypothesis related to S1, S2, and S4 (S3 and S4 re-design hypothesis refer both to the components of the semi-body; for this reason they are both compared to S2).

$\Delta_{As_{is}}$ depicts the change of the index relative to the As-is scenario; Δ_P refers to the changes of the index compared to the previously analyzed scenario.

Scenario	*Pipes*	*Pedestal*	*Semi-body*	$Recyclability_{index}$	$\Delta_{As_{is}}$	Δ_p	R_{cyc}	$\Delta_{As_{is}}$	Δ_p
As-is	EPDM/PVC	Steel	Brass	0,3784	-	-	0,907	-	-
S1	Cu	Steel	Brass	0,3795	0,30%	-	0,9137	0,71%	-
S2	Cu	Al	Brass	0,4255	12,44%	12,10%	0,9102	0,31%	-0,39%
S3	Cu	Al	Al	0,4089	8,08%	-3,88%	0,9072	-0,01%	-0,32%
S4	Cu	Al	Steel	0,3877	2,46%	-8,88%	0,9083	0,11%	-0,21%

Table 2: Recyclability indexes changes, according to the re-design hypothesis.

The prototype version of the tool allowed to quantify the $Recyclability_{index}$ and identify the main criticalities of the first design version, from the environmental perspective. The comparison of results, both for the current and re-designed versions, proved that highly simplified tools may not return a complete overview (of recyclable environmental sustainability); therefore, it is harder to identify any optimization strategy.

3.2 Disassembly

The tool analyzes the 3D CAD and extrapolates the information related to the parts involved in connections (i.e., screws). This information combined with that coming from the analysis of the precedencies allows obtaining the disassembly sequence. The evaluation of the sequence takes place through the complexity index, suggested by Soh et al. [16]. Throughout this result, the tool highlights DfD criticalities to improve the disassembly operation. In this context, complexity refers to the degree of difficulty encountered during the handling and removal of components due to specific physical attributes, such as size, thickness, and weight, which are extrapolated from 3D

CAD. The index simultaneously evaluates the complexity of manipulating the component and the complexity of disassembly. The quantitative assessments are enabled by the weighted average complexity index of the Icom part, as shown in the Equation (3.3):

$$I_{com} = \frac{C_h \sum_1^J C_{h,f} + C_r \sum_1^K C_{r,f}}{\sum_1^J C_{h,f} + \sum_1^K C_{r,f}} \tag{3.3}$$

Where

- $C_h = \frac{\sum_1^J C_{h,f}}{J}$ is the average index of manipulation complexity;
- $C_r = \frac{\sum_1^K C_{r,f}}{K}$ is the average index of disassembly complexity;
- $C_{h,f}$ is the difficulty factor defined in Table 3 for manipulation and is the number of non-zero manipulation attributes matched for each part.
- $C_{r,f}$ is the difficulty factor for disassembly and is the number of matched non-zero removal attributes for each part.

The weighted average complexity factor of the part will be used to evaluate each disassembly sequence to provide a quantitative complexity measurement for the removal of a particular component from the main subgroup. Table 3 summarizes the parameters for manual disassembly.

The difficulty factor for a mechanical disassembly process as shown in Table 3 is normalized by the U-effort indices obtained by Das et al [2].

The analysis is conducted on the dispensing group of a coffee machine. The target component is the electric resistance; it has been chosen because it is seldom addressed in maintenance operations.

Group	Attribute	Description	Cf
Handling (h)	Size	> 15 mm	0,75
		6 mm to 15 mm	0,81
		< 6 mm	1
	Thickness	> 2 mm	0,27
		0,25 mm to 2 mm	0,5
		< 0,25 mm	1
	Mass	<4,5 kg	0,5
		>4,5 kg	1
Removal (r)	Mechanical unfastening process	Screw/bolt standard head	0,56
		Screw/bolt Special head	0,88
		Nut and bolt	0,84
		Retaining ring	1
		Interference fit	0,72
		Key	0,6
	Tools required	0 tools	0
		1-3 tools	0,6
		>4 tools	1
	Specialized tools	None	0
		Involved	1

Table 3: Disassembly attributes.

A fast and easy disassembly would make maintenance activities shorter and more flexible. The analysis aims at obtaining the sequence of disassembly, evaluating the index of complexity for each component and therefore for the entire sequence. Figure 4 shows the disassembly flow that allows reaching the target component; one picture represents a step.

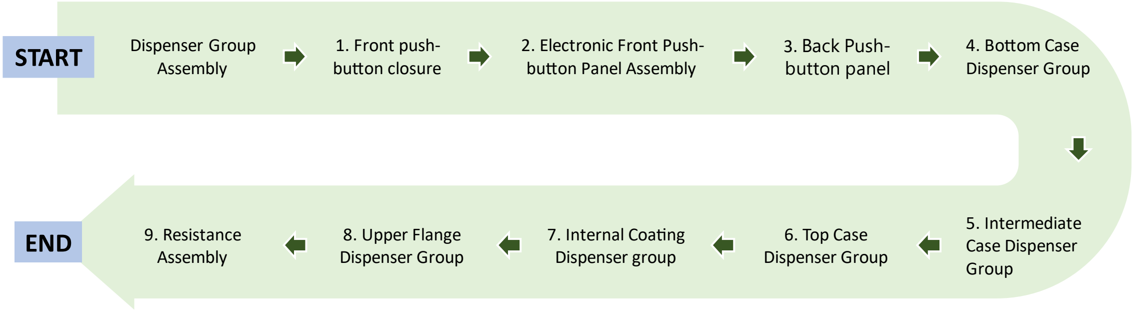


Figure 4: Electric resistance disassembly sequence.

In Table 4 all the information necessary for the calculation has been collected. The liaison type involved in the connection and its numerosity are contained in the third column. For each component, the mass and the overall dimensions are indicated, although ranges are given for more discretion The size of a part is defined as the non-diagonal dimension larger than the contour of the part projected onto a flat surface [16]; the three Cartesian coordinates are considered.

Disassembly Sequence	Part Name	Liaison Type	Width (x) [mm]	Size (z) [mm]	Thickness (y) [mm]	Mass [kg]
1	Front push-button closure	1 screw	120-130	90–100	0–10	0,120–0,130
2	Electronic Front Push-button Panel Assembly	4 screws	100-110	80–90	10–20	0,410–0,420
3	Back Push-button panel	4 screws	120-130	80–90	50–60	0,320–0,330
4	Bottom Case Dispenser Group	2 screws	170–180	150–160	100–110	0,590–0,600
5	Intermediate Case Dispenser Group	Free Part	150–160	90–100	10–20	0,100–0,110
6	Top Case Dispenser Group	2 screws	160–170	140–150	90-100	1,330–1,340
7	Internal Coating Dispenser group	Free Part	100–110	140–150	60–70	0,770–0780
8	Upper Flange Dispenser Group	6 screws	120–130	130–140	60–70	1,280–1,290
9	Resistance Assembly	2 Nuts	70–80	100–110	50–60	0,200–0,210

Table 4: Disassembly sequence components’ geometrical information.

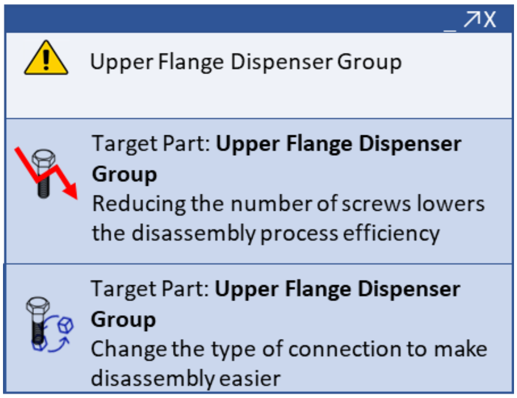
Table 5 contains the Percentage Impact Sequence for each component.

Disassembly Sequence	Part	Percentage Impact Sequence
1	Front Push-Button Closure	8%
2	Electronic Front Push-Button Panel Assembly	13%
3	Back Push-button panel	13%
4	Bottom Case Dispenser Group	9%
5	Intermediate Case Dispenser Group	9%
6	Top Case Dispenser Group	9%
7	Internal Coating Dispenser Group	9%
8	Upper Flange Dispenser Group	19%
9	Resistance Assembly	11%

Table 5: Complexity index parameters and results.

It is the percentage of the complexity index of the part, According to Equation (3.3), the index depends on the difficulty in handling and removing the part, and considers also the number of required tools. As far as removal concerns, the U-effort is calculated. It is given by multiplying the specific factor related to the type of connection (i.e., mechanical unfastening process done by screw bolt, nut and bolt, interference etc.) by how many times it is repeated in the same part.

The component with a higher complexity index is the Upper Flange Dispenser Group, which has a removal component index very high since it is connected through six screws to the Bottom Flange Dispenser Group. Its index has an impact that is far from the average value and its percentage of impact in the sequence is 19%, a very high impact for a sequence where only nine parts appear. The tool reacts with Information (Figure 5) that advises the user to reduce the number of screws or change the type of connection to make disassembly easier. A re-design hypothesis consists in fixing the Upper Flange Dispenser Group with four screws; this would reduce the complexity index of the part by 28% and the percentage impact sequence would drop from 19% to 14%. The designer is free to act on the component reliability thus increasing the time that elapses between two successive maintenances.



Upper Flange Dispenser Group

Target Part: **Upper Flange Dispenser Group**
Reducing the number of screws lowers the disassembly process efficiency

Target Part: **Upper Flange Dispenser Group**
Change the type of connection to make disassembly easier

Figure 5: Disassembly feedback for the user.

3.3 Validation Procedure

The application of the methodology to the case study showed great potentialities, supporting designers in the identification of product criticalities in terms of recyclability and disassembly. The next step will be the validation of the proposed method, realized by the direct users, and base on the evaluation of the following parameters:

- Resource availability: evaluate the resource in terms of staff competences needed to be able to use the tool and correctly interpret its results (e.g. training time, knowledge background, product expertise level);
- Acceptability: evaluate the obstacles encountered during the index calculation and consider the integration level with the other design tool;
- Implementation time; this point concerns both the time needed to complete the four steps of the methodology once it is fully implemented in the design process and also how long it takes before the methodology can be considered effectively integrated in the design process;
- Usefulness: the validation should consider the effectiveness and strength of the methodology both per se and compared to usefulness of other similar methodologies;
- Cost effectiveness: evaluate the advantages gained from the implementation of the methodology, compared to the resources employed to implement it.

4 DISCUSSION

The present work introduces a tool intended for target design, able to couple the potentialities of 3D CAD modeling software and strengthen the environmental awareness of designers. The DfX tool extracts geometrical, shape and feature information of a 3D model and correlates them with a DB.

This contains both details about materials and a set of rules to be verified to prove the quality of the design. In the current application, where a 3D model of a professional coffee machine is analyzed, the tool conducted the classification of the materials employed in the product and the calculation of the recyclability index. The index for the whole coffee machine is 0.38, for Climate Change indicator. This reveals that the coffee machine, although being complex, has great potentialities to be recycled. It is composed up to 90% in weight of recyclable materials, whose recycling process is less impacting than other EoL strategies (i.e. landfill). The recyclability index has been compared with a simpler, similar one; moreover, its initial value has been increased, by acting on the product materials.

First of all the non-recyclable components were investigated and alternative materials were chosen: pipes made of EPDM were replaced with copper pipes; both $Recyclability_{index}$ and R_{cyc} increase (S1); the latter increases more than the first, because copper has a higher specific weight than EPDM, thus more mass results to be recyclable in R_{cyc}. The same reason, that is the different specific weight of materials, determines a different trend for the two indices in S2: R_{cyc} decreases because Aluminum is lighter than steel, even with the increased volume; on the contrary, the lower environmental impact of the aluminum recycling process (compared to steel), is evident in the $Recyclability_{index}$. S3 and S4 do not lead to environmental benefits; consequently, it is recommended not to approve the suggested re-design hypothesis. However, it can be noticed the different reduction rates of the two recyclability indexes: $Recyclability_{index}$ in S3 decrease 50% less than S4; R_{cyc} instead, decreases 1/3 more in S3 than S4.

The use of simple indexes from one side enables to obtain of quantitative results, also with little information available; however, they may not consider important aspects of the factor that is evaluated (recyclability in the current case); consequently, the improvement direction suggested may not be clear.

The tool is intended to provide feedbacks and highlight criticalities related to sustainability matters; however, the technical validation of the analyzed alternatives lay outside the tool objectives. The tool supports the designers in evaluating the sustainability performances of the product, the designer, prior of after the use of the tool is called to validate the technical performances of the product, deriving from the re-design hypothesis (i.e., FEM analysis to prove resistance or thermal analysis to simulate thermal conductivity).

The tool algorithms have been used also evaluate the disassembly complexity of electric resistance, a component of the professional coffee machine that guarantees the high temperature of the water used in making coffee. There are two main considerations related to this choice: first of all the target component (electric resistance) was chosen for its frequency of maintenance operation. Secondly, not only the disassembly (complexity) has been evaluated, but also the complexity of manipulating the component. In doing this, geometrical information from CAD model is needed (such as dimensions, weight, etc.).

The main feedback deriving from the analysis of the disassembly sequence that aims to extract the electric resistance from the dispenser group suggests reducing the number of liaisons, when and where possible. For example, employing four screws instead of six in the Upper Flange Dispenser Group, would lower the percentage impact sequence would drop from 19% to 14%. The tool allows to identify the critical issues in the design phase and offers advice on how to address them; the final decision is left to the designer who, however, thanks to the tool, knows where to intervene.
Three are the main potentialities of the proposed tool:

- It can be used both before and after designing: whenever it is used during the part or assembly modeling the designer can receive feedback about the product design and future performances (manufacturing, EoL, environmental, etc.) each time the analysis is launched, and it will be updated every time; on the contrary, the designer can launch the analysis at the end of the design and verify whether it fulfills all the rules and to obtain a forecast of the product performances;
- It includes new important design drivers and support to awareness of designers: they may be extremely expert in the product and its functionalities but they can lack the knowledge about sustainability, EoL strategies, maintenance, etc. This tool allows them to obtain feedback and simplified forecasts, and thus introduce innovative targets in the design process;
- The database can be updated, both with conventional knowledge and with specific input; for example, any information deriving from product maintenance, use, or EoL phase may generate new design rules to verify or additional Key Performance Indicators (KPIs) to be evaluated (the F would require further algorithms development).

Future works will consist of the enlargement of the DB content to increase the knowledge available for designers to improve product environmental performances. In addition, the disassembly complexity index will be improved to be specialized for certain objectives, such as recyclability and disposal scenarios.

For the theme of recyclability, the index presented in this paper will be used; while for disposal, compatibility tables of the materials disposed of will be defined in agreement with the company's reference disposer. The company will be aware of the environmental and economic impact of its product at the end of its life, through information on mass flows out. Validation of the proposed method and tool will allow confirming their usefulness and efficacy in the analyzed industrial contest.

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