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ANALYSIS AND OPTIMISATION OF DISASSEMBLY DEPTH DISTRIBUTION: AN APPLICATION IN ELECTRONIC DEVICE REDESIGN TO REDUCE ENVIRONMENTAL IMPACT AT END-OF-LIFE

F. Giudice and M. Kassem

Keywords: design for disassembly, disassembly depth, life cycle assessment, environmental impact, end-of-life

1. Introduction

In the last decade, the Waste stream from Electrical and Electronic Equipment (WEEE) has greatly increased as a result of these devices becoming increasingly characterised by both high obsolescence and rapid consumption rates. In the European Community, the increase in WEEE is estimated at 3-5% per year, three times higher than the average growth rate of the entire waste sector [EC-JRC 2006]. The environmental criticality of this phenomenon is easily understood given that more than 90% of WEEE is destined for landfills and incinerators without adequate treatment. To tackle this problem, various initiatives have been undertaken directing EEE manufacturers toward an integrated approach aimed at the development and management of products in an environmentally friendly way, by introducing an extended life cycle vision, with particular focus on the end-of-life phase. Within this perspective, the European Directive 2002/96/EC was issued, putting recovery intervention at the core of the measures to be followed by fixing minimum weight thresholds for compulsory recycling/recovery [EC2002/96 2003]. Consequently, the industrial and scientific communities have started investigating the possibility if making this intervention economically viable. Among the various areas and aspects analysed, the disassembly of end-of-life products has been the focus of the greatest number of research projects, as expressly advocated by the directive. More specifically, the development of procedures and tools aimed at designing products easy to disassemble (Design for Disassembly) has been recognised as a key issue for some time [Boothroyd and Alting 1992], and specific attention has also been paid to the design of electronic products [de Ron and Penev 1995].
The present paper proposes the application of a structured method for the analysis and reconfiguration of the disassembly depth distribution of components making up an electronic device, expressing the difficulty of their disassembly on the basis of spatial and junction constraints conditioning their removal, with the aim of obtaining a generalised improvement in ease of disassembly, in relation to the necessity of reducing their environmental impact. The method makes use of analytical instruments for the quantification of disassembly depth, and of an appropriate metric to assess the effectiveness of the distribution. As evidenced by the results from the case study, the methodology and associated tools provide information regarding the criticality of a system and make it possible to direct an intervention modifying the principal design parameters (characteristics of layout, shapes of components, and types of junction systems) in a way that improves the efficiency of disassembly. This is achieved through a reasoned redistribution of the disassembly depth of components, according to a simple but significant criterion: linking disassembly depth of components with their environmental impact allows the design

of a system with higher ease of recovery at end-of-life for components whose production implies higher impact on the environment, therefore potentially recouping the environmental impact of product manufacture and so reducing the impact of the product's entire life cycle.

2. The structured method

The method developed [Giudice et al. 2006] is, first of all, able to elaborate data relative to the spatial configuration of the constructional system, to the geometric characteristics of its constituent parts, and to the associated junction systems, and, on the basis of this information, allows the characterisation of components in terms of their difficulty of disassembly.

Subsequently, it follows a simple analysis procedure: having selected the characteristics of the design solution to be analysed, it is possible to calculate the disassembly depth and the objective-property of each component; these give the distribution of the values assumed by an appropriate function quantifying the effectiveness of the design solution in relation to the need for disassembly.

This procedure can be used to:

- Estimate the distribution of the disassembly difficulty of components constituting a system and determine their criticality
- Redesign the system, improving its ease of disassembly through a reasoned redistribution of disassembly depth, guided by the characteristics of the single components that influence the opportuneness of disassembly

2.1 Evaluation of disassembly depth

The distribution of the disassembly depth of components is evaluated on the basis of the constructional properties of the system (layout, geometries of parts, types of junctions). These properties are translated into a corresponding mathematical model through matrices describing spatial and junction constraints, and characterise each component making up the system, on the basis of its disassembly difficulty, according to possible directions of disassembly. From the results of the characterisation, which indicates the set {Cd} of the n_D components to be removed and the set {Jd} of the f_D junctions to be eliminated, in order to disassemble each component in turn, it is then possible to calculate a numerical index dd quantifying its disassembly depth:

$$dd = dd_{SC} + \beta \cdot dd_{JC} = \frac{1 + n_D}{n} + \beta \cdot \frac{\sum_{k=1}^{h} \alpha_k \cdot f_{D_k}}{f} \qquad (1)$$

where $(1+n_D)$ is the number of all the components to be removed (including the component whose disassembly depth is being evaluated), n is the total number of components, f_{Dk} is the number of fasteners of the k-th type to be removed, f is the total number of fasteners in the system, α_k is the difficulty of disassembling a k-th type fastener, h is the number of fastener types, and β is a coefficient ($\beta > 1$) which takes into account the greater weight of the second term dd_{JC} with respect to the first dd_{SC}. Allowing for values of the coefficients α_k in the interval [0,1], $\alpha_k = 1$ indicates the maximum difficulty of disassembly. The index dd can then assume values belonging to the interval [0,1+β], the maximum value 1+β expressing the maximum disassembly depth.

So defined, the index dd can be compared to the maximum value present in the system under analysis, obtaining for each component C_i the normalised value $DD_i = dd_i/dd_{MAX}$.

The index dd expressed by equation (1) provides a theoretical evaluation of the disassembly depth, since it is based on an analysis of the components considered individually, as if each of them was, in turn, the single target of disassembly. The accuracy of this evaluation depends on the precision of the step where the sets of type {Cd} and {Jd} are determined. In principle, these sets can be obtained by resolving the problem of planning the selective disassembly of the each component at a time. This problem, which lies in the realm of Disassembly Process Planning, requires the definition of the optimal disassembly sequence of each component that is, in itself, a difficult problem to resolve, as is clear from studies reviewing the vast literature on this topic [Lambert 2003]. Alternatively, the same authors of the general method suggest using a rule-based approach, more suitable for the specific aims of the method itself [Giudice et al. 2006].

2.2 Evaluation of components objective-property

The principal goal of the method is to aid product redesign aimed at improving its ease of disassembly through a reasoned redistribution of the disassembly depth. To be truly reasoned, this redistribution must be guided by some characteristics of the single components which quantify the necessity or opportuneness of their disassembly. Starting with the main characteristics of each component (geometries, shapes, materials) it must be possible to evaluate those that may be the objective-properties of components, i.e. those properties which quantify the opportuneness of their disassembly. Indicating this generic property by op_i, it must be defined in such a way that the greater its value, the more appropriate it is to disassemble the corresponding component C_i. So defined, it can be compared to the maximum value present in the whole system to give the normalised form $OP_i = op_i/op_{MAX}$.
To define a significant object-property for the case under examination, the following criterion was assumed: to reduce the overall environmental impact of product life cycle, components with a high environmental impact in production must be recovered at end-of-life (so that this impact could be recovered too), requiring lower disassembly depths to facilitate their removal. Therefore, as objective-property here we suggest the use of indicators expressing the environmental impacts associated with the main phases of the component's manufacturing process. These can be evaluated using Life Cycle Assessment (LCA) techniques and the supporting tools for environmental impact quantification [Guinée 2002]. Here the Eco-indicator 99 method [Goedkoop and Spriensma, 2000] and SimaPro 5.0 software® (Pré Consultants BV, Amersfoort, The Netherlands) will be used. Eco-indicator 99 is a well-known quantitative evaluation method for LCA, that allows to elaborate the results from a preliminary data inventory phase, in order to obtain concise indicators of environmental impact (called "eco-indicators"). By using this method, the op_i of each component will be expressed by:

$$op_i = ei_{Mat} \cdot W + ei_{Prss} \cdot \mu \ \left(+ ei_{Mchg} \cdot \eta \right) \tag{2}$$

where ei_{Mat} is the eco-indicator per unit weight of material making up the component (W expresses the total material weight), ei_{Pcss} is the eco-indicator of the primary forming process per unit of μ, which can represent the characteristic parameter of the process or the quantity of material processed. The third term can be added to take account of secondary machining processes: ei_{Mchg} is the eco-indicator of the process per unit of characteristic process parameter η.
Eco-indicator 99 method is based on impact assessment calculations, consisting in procedures of data characterisation, normalisation, and weighting. It is affected by typical limitations of LCA techniques: subjectivity of preliminary assumptions; uncertainty over the quality and reliability of data; further assumptions and lacunae in procedures and models for data elaboration. Although these limitations cannot be ignored, and the results of calculation must be used carefully, eco-indicators can be considered as efficient instruments for the estimate of environmental effects, and are suitable for the purposes of the objective-properties evaluation.

2.3 Evaluation of disassembly depth effectiveness

After evaluating the disassembly depth and objective-properties of each component C_i, it is necessary to make use of a metric able to quantify the efficiency of the design solution in relation to the requirements of disassembly. With this aim, an index of disassembly depth effectiveness Θ_i, which is expressed as a function of DD_i and OP_i for each i-th component, is introduced:

$$\Theta_i = \left| \, OP_i - \left(1 - DD_i\right) \right| \tag{3}$$

Minimising the indices Θ_i, which can assume values in the interval [0,1], corresponds to seeking a configuration characterised by lower disassembly depths for components with a greater need for recovery and, vice versa, by greater disassembly depths for components with lower need for recovery.

3. A case study on a video-entryphone

The method was applied on a video-entryphone module (Figure 1). A three-dimensional block diagram was used to schematise the product, showing the layout of the real product, the overall dimensions of each component and reciprocal relations of spatial obstruction, and the junction constraints. The system was divided into two subsystems: the main body (subsystem 1), and the receiver (subsystem 2). The components and junctions considered are listed in Tables 1 and 2.

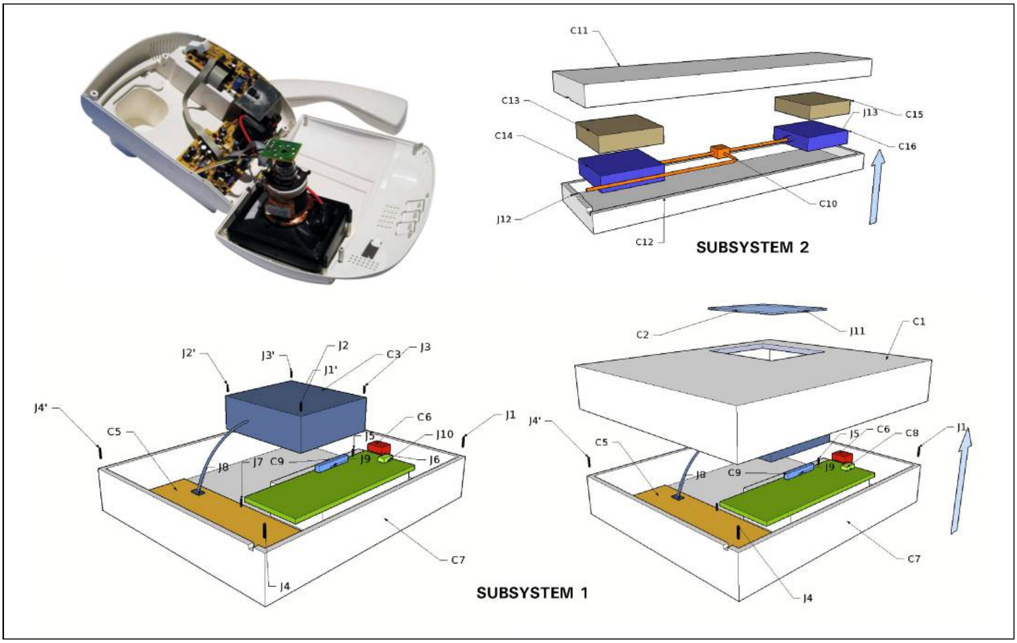

Figure 1. The product chosen for the case study and its two main subsystems

Table 1. Components and junctions of subsystem 1 with objective-property (op) and disassembly difficulty (α_k) estimated values

Comp	Description	op_i [mPt]
C1	Cover	30.7
C2	Transparent panel	5.9
C3	CRT group	590.2
C4	Insertable card	2.9
C5	Synthesis board	273.2
C6	Switch cover	0.3
C7	Base	48.6
C8	Receiver group	372.6
C9	Interface connection plate	84.7

Junction	Description	α_k
J1, J1', J4, J4'	Fixing screws C1-C7	0.92 (1)
J2, J2', J3, J3'	Fixing screws C3-C1	0.96 (2)
J5	Fixing screws C4-C7	0.92 (3)
J7	Fixing screws C5-C7	0.92 (3)
J6	Groove connection C6-C7	0.95 (4)
J8	Insertion connection C3-C5	0.00 (5)
J9	Insertion connection C9-C4	0.00 (5)
J10	Insertion connection C8-C4	0.00 (5)
J11	Groove connection C2-C1	1.00 (6)

Table 2. Components and junctions of subsystem 2 with objective-property (op) and disassembly difficulty (α_k) estimated values

Comp	Description	op_i [mPt]
C10	Receiver connection wire	352.7
C11	Receiver cover	7.2
C12	Receiver base	9.7
C13, C15	Foams	0.1
C14	Microphone	1.1
C16	Loudspeaker	1.7
Junction	**Description**	α_k
J12	Groove connection C11-C12	0.86 (7)
J13	Groove connection C11-C12	1.00 (8)

3.1 Analysis of disassembly depth distribution and effectiveness

Having identified the preferential disassembly directions, the three-dimensional diagrams of the two subsystems, schematised in Figure 1, make it possible to easily characterise spatial and junction constraints for the disassembly of each component C_i, and so define sets $\{Cd\}_i$ and $\{Jd\}_i$.
Table 3 shows the results of n_D and f_D calculation for each component. As defined in equation (1), the term dd_{JC} differentiates between junction typologies according to their difficulty of disassembly. Therefore f_D for each component was differentiated in f_{Dk}, according to the number of each k-th junction type that fastens the component. Furthermore, to complete the calculation of the disassembly depth index by means of equation (1), it is necessary to make an appropriate choice of the values to be attributed to the coefficients α_k, expressing the disassembly difficulty of each k-th fastener type. To quantify this difficulty, in this application the UFI metric (Unfastening Effort Index) was used to estimate the disassembly difficulty of fasteners [Sodhi et al. 2004], as a function of fastener type attributes effecting its ease of removal (form, dimensional range, operating expedients). Each UFI value was compared to the maximum value present in the whole system to give the normalised value in the interval [0,1]. The resulting values of α_k are reported in Tables 1 and 2 (fasteners k-type are specified between brackets).
With regard to the evaluation of the objective-properties, as considered in Section 2.2, the op_i for each component was estimated (reported in Tables 1 and 2) as the environmental impact of manufacturing processes, calculated by means of eco-indicators and SimaPro software, according to equation (2), and expressed in millipoints (mPt), as suggested by Eco-indicator 99 impact assessment method.
Finally, disassembly depth effectiveness was assessed by means of metric (3), a function of normalised values DD_i and OP_i.

Table 3. Results of components depth characterisation: Number of components (n_D), number of k-type junctions (f_{Dk}), total number of junctions (f_D) to be removed

Comp	n_D	f_{Dk}	f_D	Comp	n_D		f_D
C1	1	4 (f_{D1})	4	C9	1	4 (f_{D1}), 1 (f_{D5})	5
C2	0	1 (f_{D6})	1	C10	1	1 (f_{D7}), 1 (f_{D8})	2
C3	2	4 (f_{D1}), 4 (f_{D2}), 1 (f_{D5})	9	C11	0	1 (f_{D7}), 1 (f_{D8})	2
C4	4	4 (f_{D1}), 1 (f_{D3}), 1 (f_{D4}), 2 (f_{D5})	8	C12	6	1 (f_{D7}), 1 (f_{D8})	2
C5	3	4 (f_{D1}), 2 (f_{D3}), 1 (f_{D5})	7	C13	1	1 (f_{D7}), 1 (f_{D8})	2
C6	1	4 (f_{D1}), 1 (f_{D4})	5	C14	4	1 (f_{D7}), 1 (f_{D8})	2
C7	8	4 (f_{D1}), 4 (f_{D2}), 2 (f_{D3}), 1 (f_{D4}), 3 (f_{D5})	14	C15	1	1 (f_{D7}), 1 (f_{D8})	2
C8	1	4 (f_{D1}), 1 (f_{D5})	5	C16	4	1 (f_{D7}), 1 (f_{D8})	2

The final results of the method applied to the original product are reported in Figures 2 and 3, for subsystems 1 and 2, respectively.

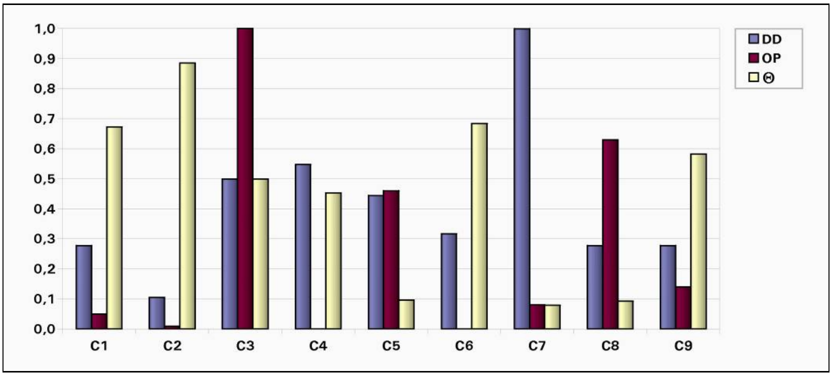

Figure 2. Distribution of disassembly depth (DD), objective-property (OP), and disassembly depth effectiveness (Θ) for subsystem 1

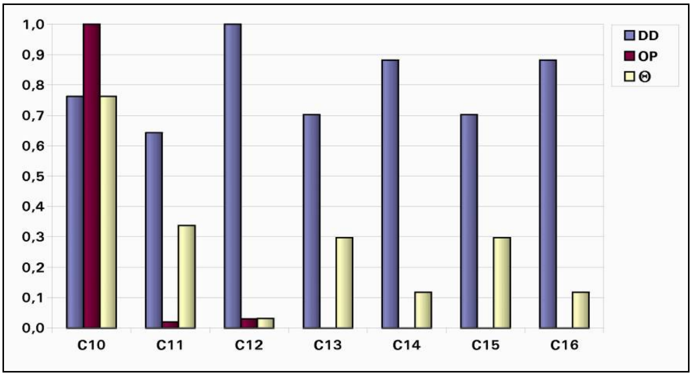

Figure 3. Distribution of disassembly depth (DD), objective-property (OP), and disassembly depth effectiveness (Θ) for subsystem 2

From Figure 2, it is clear that for subsystem 1, C3, C5 and C8 are the components requiring optimisation during redesign interventions, which can operate on the components directly (by modifying shape and junction), and indirectly (by modifying their position in the layout). These are components with high values for OP (normalised value of op), i.e. the components suitable for removal and recovery at product end-of-life. Components C5 and C8 are not strictly critical since their disassembly depths are adequate to requirements, and in fact their disassembly effectiveness is good (low values of Θ). However, it could be worthwhile to further reduce the disassembly depths of these components, even though this will lead to some worsening of the depth effectiveness of other components characterised by low values of both disassembly depth and objective-property (these do not require disassembly). Component C3 is the most critical as its high objective-property value is coupled with great disassembly depth. Therefore, in subsystem 1, C3 is the component requiring the most attention during redesign.

For subsystem 2, the most critical component is C10 as it has simultaneously a high value for disassembly depth DD and the highest value for objective-property OP. Furthermore, it is important to note that the actual disassembly depth of component C10 is higher than that indicated in Figure 3 because its removal requires the preliminary disassembly of component C8 of subsystem 1. This also implies a further need to optimise component C8 within its subsystem.

3.2 Improving redesign intervention and results

Following the suggestions derived from the analysis above, the redesign interventions described in Figures 4, 5, 6 were developed. They involved both the change of junction types and the shape/layout position of some components.

- For components C3, C4 and C5 fixing it was adopted a new junction type which can be classified as ‘key snap-fit’ (Figure 4, Figure 5b, and Figure 5c), instead of screws. This new junction type allows the reduction of the disassembly depth of the targeted components since it requires lower disassembly effort to be unfastened.
- The plate for the heat dissipation of the component C4 was replaced with a new smaller plate with fins. The new plate has the same heat dissipation capacity as the original one and it is disposed in the vertical plan in such a way that the removal of the component C5 is not obstructed by C4 (Figure 5c).
- The connections of wire C10 was changed on both sides by using the RJ type junction, which requires much lower disassembly effort than the former one. This intervention has resulted in some changes to be made on components C4, C11, C12, C7, in order to house the new type of junctions (Figures 6b, 6c, 6d).

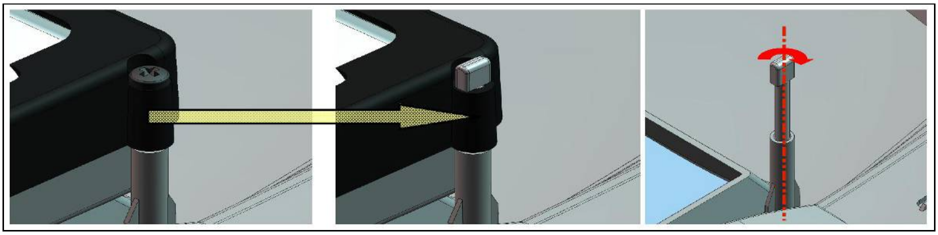

Figure 4. Modification of junctions (J2, J3, J2’, J3’) fixing C3

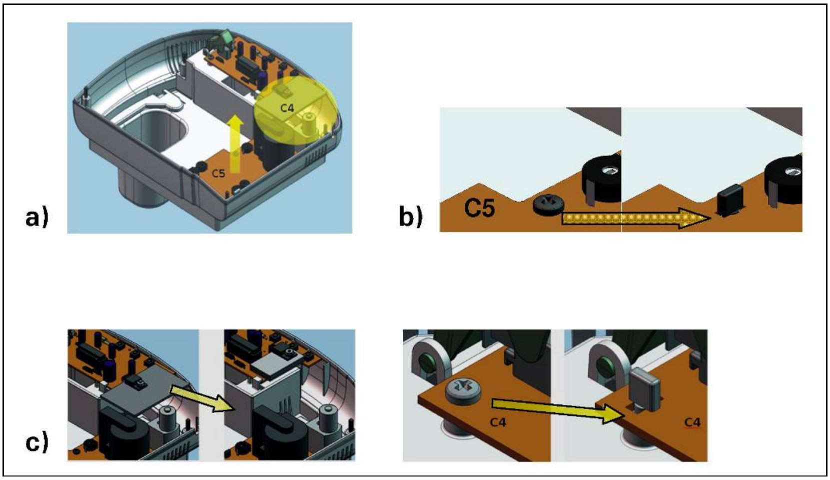

Figure 5. Modification of fixing C4 and C5 to base C7: a) Original layout; b) Modification of junction (J7) fixing C5; c) Modification of C4 shape and junction (J5)

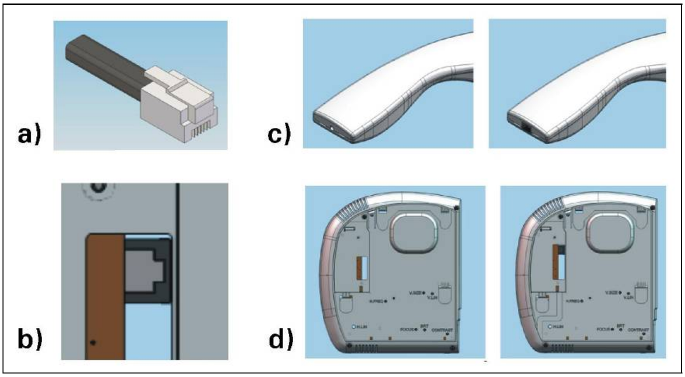

Figure 6. Modification of subsystem 1 and 2 connection: a) 'RJ' type junction; b) Modification of C4 lower side; c) Modification of C11 and C12 to house C10; d) Resulting modification of C7

Subsequently, the analysis tools were applied on the redesigned product, and the results compared to those of the previous analysis on the original design. The comparison was performed both at the local level (single components) and global level (whole system), before and after the redesign interventions. The results of the local comparison are shown in Table 4. It can be seen that the disassembly depth was reduced for all the components targeted by the preliminary analysis phase. It is also important to note that improvements in the disassembly depth of components C3 and C5 resulted in a worsening in that of component C4. This is acceptable as component C4 is characterised by low environmental impact, so that its disassembly depth can be increased to favour other components having greater need of recovery at end-of-life. Disassembly effectiveness

Table 4. Results of comparison between the two solution

Component	Disassembly depth (dd)	Normalised disassembly depth (DD)	Normalised objective-property (OP)	Disassembly effectiveness (Θ)
C3 original	0.99	0.52	1.00	0.52
C3 redesigned	0.72	0.48	1.00	0.48
C5 original	0.92	0.49	0.46	0.05
C5 redesigned	0.66	0.44	0.47	0.10
C8 original	0.54	0.29	0.63	0.08
C8 redesigned	0.18	0.12	0.63	0.25
C4 original	1.03	0.55	0.00	0.45
C4 redesigned	1.04	0.70	0.00	0.30
C10 original	1.49	0.68	1.00	0.68
C10 redesigned	0.40	0.24	1.00	0.24

The comparison between the two design solutions in terms of disassembly effectiveness (Θ function) is reported in Figure 7. With regard to the target components C3, C5, C8 and C10, it is clear that effectiveness of C3 and C10 was improved. The effectiveness of components C5 and C8, instead, seems to worsen: values of Θ function increased when passing from the original to the redesigned solution. This is a cue to clarify the meaning and use of Θ. This function quantifies the "distance" between OP and (1-DD), so in some cases (specifically when the value of OP is medium-low) the reduction of DD can produce an increase in Θ (this is precisely the case of components C5 and C8). Therefore, function Θ has not been introduced as a measure for the direct comparison of disassembly depth effectiveness of the same component in two or more different design solutions, but rather as a metric of systemic effectiveness of disassembly depth distribution within the same solution. In fact,

what it is significant is that the values of Θ for C5 and C8, after a redesign that has reduced their disassembly depth, remain among the lowest within the overall redesigned solution.
The same precaution has to be used in interpreting the redesign results for subsystem 2. On one hand, the components which showed an increase in Θ are all components with low environmental impact, i.e. not needing to be disassembled for recovery; on the other hand, the most critical component in the original system, C10, has become the component with the lowest disassembly depth and its Θ value has decreased by 65%. This condition indicates an effective redesign intervention.
Finally, it is important to note that, in general, direct comparison is not always appropriate between two different design solutions, as the maximum value by which the disassembly depths dd_i (and also op_i) are normalised can vary from one solution to the other. The most suitable comparison can be made in terms of "frequency distribution" of Θ function between the solutions to be compared, as shown in Figure 8. The results demonstrate the improvement of both subsystems 1 and 2, since in the redesigned version they have a higher number of components with Θ value in the lower intervals [0.0 , 0.2], [0.2 , 0.4] and [0.4 , 0.6], which means an overall effective disassembly depth redistribution in relation to the real need for the disassembly of components.

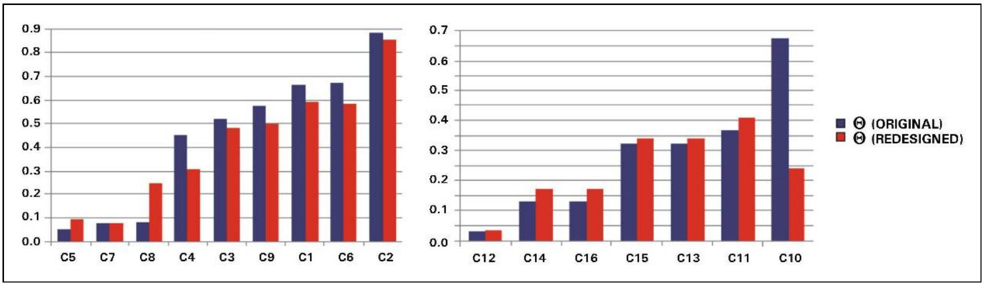

Figure 7. Direct comparison of disassembly depth effectiveness (Θ) values

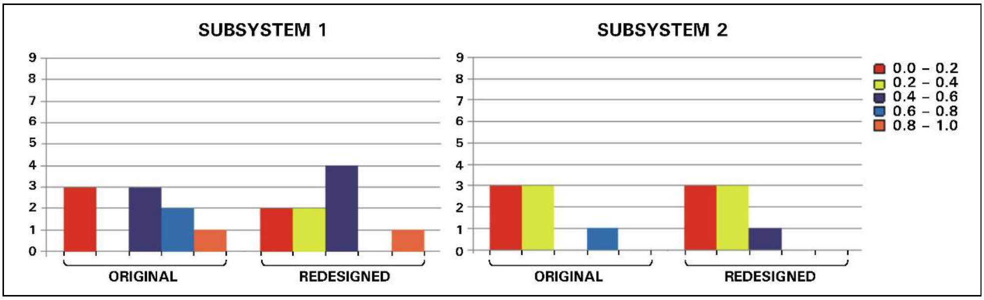

Figure 8. Comparison of frequency distribution of disassembly depth effectiveness (Θ) values

4. Conclusions

The method introduced in this paper provides an instrument for characterising the disassembly depths of product components in relation to their need for removal and recovery at end-of-life. The method offers designers the possibility of defining as objective-property, to be assessed for each component, the most appropriate function that could quantify the necessity of component disassembly. In the present study, the environmental impact of component production was used as objective-property in order to analyse and optimise the disassembly depth distribution in relation to the opportuneness of disassembling components at end-of-life to recover them, thereby recouping the environmental impact associated to their production and reducing the overall impact of their life cycle.

The described application on a video-entryphone showed the disassembly inefficiency of some key components, resulting from an imbalance between their 'disassembly difficulty' and 'disassembly necessity'. These components were considered 'critical components' and were targeted in redesign interventions, which considered their shape, junctions and position within the system layout.
The comparison between original and redesigned solutions demonstrated improvements on the local level, in terms of disassembly depth reduction for single critical components, and on the global level (with regard to the whole system), in terms of disassembly depth redistribution which maximises the number of components with greater disassembly depth effectiveness.
The fundamental concept indicated by the entire application of the method (analysis, redesign and comparison) is the importance of the trinomial 'layout - geometries of parts - types of junctions' for each component. It was shown that, with materials being equal (redesign did not change materials), to change the shape and/or the position of some components (those more environmentally critical), and the related fasteners, can improve their end-of-life efficiency by making them easier to disassemble.
By means of the proposed method, therefore, it is possible not only to analyse the distribution of disassembly depth in a system, but also aid its redesign with the aim of facilitating disassembly. If integrated into the design process, in fact, the method can allow the optimisation of a vast range of design choices (layout, shapes, junctions) to improve the ease of disassembly at different levels of the design process (particularly embodiment and detail design), in agreement with the basic principles of Design for Disassembly, so that it is possible to recover 'high-environmental-weight' components, or isolate hazardous ones, and meet regulation constraints at moderate and sustainable costs..

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Mohamad Kassem, PhD candidate
Università Politecnica delle Marche, Department of Mechanics
Via Brecce Bianche, 60131 Ancona, Italy
Tel.: +39 071 2204798
Fax.: +39 071 2204801
Email: kassem@virgilio.it