



AN ECODESIGN METHOD FOR PRODUCT ARCHITECTURE DEFINITION BASED ON OPTIMAL LIFE-CYCLE STRATEGIES

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1. Introduction

The idea of a design activity directed at reducing the environmental impact of processes and products has become widespread in the last ten years and has crystallised in new activities conducted with the specific objectives of integrating environmental requirements into traditional design procedures. This has given rise to a new approach to the design activity known as *Design for Environment (DfE)* or *Green Design (GD)* [OTA 1992; Billatos and Basaly 1997; Graedel and Allenby 1998].

Design for Environment can be defined as a design methodology directed at the systematic reduction or elimination of environmental impacts involved in the processes and life-cycles of products. In the specific context of Product Design, DfE is interpreted as investigating the optimal product architecture (layout, geometry, materials, juncture systems of parts) so as to guarantee an efficient life-cycle, envisioning better use and recovery of the resources involved. This requires a wider vision of the product development problem which extends beyond the context of production and use, as is involved in the approach known as *Life-cycle Design (LCD)*. Here the design activity takes into consideration all the phases of the product's life-cycle (development, production, distribution, use, maintenance, disposal and recovery) in the context of the entire design process, from concept definition to detailed project development [Keoleian and Menerey 1993]. In particular, three aspects of this approach are emphasised: the wider vision of the entire life-cycle; the assumption that the most effective interventions are those implemented in the earliest design phases; the simultaneity of operations of analysis and integration on the various aspects of the design problem.

Beginning with this premise, Life-Cycle Design uses models, methodologies and design instruments to integrate product evolution, from concept to disposal, with a wide range of requirements [Ishii 1995]. The choice between design alternatives must be guided by functions which take account of the main factors of the product's success, identified as design objectives: product properties, optimisation of resources, characteristics of production processes, conditions of use, environmental protection and life-cycle costs [Alting 1993].

2. Research aims and objectives

From the viewpoint where a generic industrial product must pass through all the phases making up its life, and where design strongly influences the behaviour of the product in each phase, the designer requires new methodological aids and suitable instruments of analysis and evaluation that best harmonise the various aspects of a wide-ranging design activity.

The objective of the research was to develop a methodological support, complete with the fundamental mathematical modelling, to aid the study of product architectures and investigate their environmental

efficiency. The latter can be determined in various ways. The arrangement proposed seeks to optimise the intervention strategies which appear more effective for an environmentally efficient life-cycle: those aimed at maintaining performance during the phase of use, in that they can favour the extension of the product's working life; those oriented at the planning of recovery processes at the end of the working life, in that they are directed at reducing the impact of disposal and at the recovery of resources. The instrument must also support a duo of action typologies: analysis of conventional architectures for a correct definition of the intervention strategies most appropriate to pre-existing products; redesign of architectures for the improvement of environmental performance and for the development of new environmentally acceptable products.

3. Environmental quality of product life-cycle

As primary objective of a design intervention oriented at the environmental quality of a product, the fundamental principles of DfE suggest the optimisation of the distribution of resource flows involved in the entire life-cycle. This type of intervention can be interpreted as: reducing the volumes of the materials used; extending the product's working life; closing the cycles of the resource flows in play by recovery operations. In this study, therefore, environmental quality is sought through the optimisation of strategies to extend the working life (maintenance, repair, upgrading and adaptation of the product), and by recovery strategies at the end of life (direct reuse of components, and recycling materials in the primary production cycle or in external cycles), as summarised in Fig. 1.

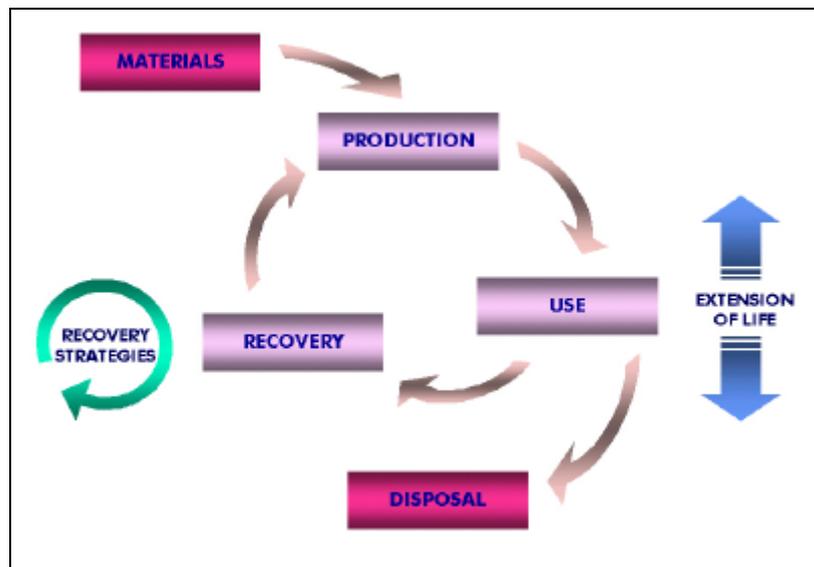


Figure 1. Product life-cycle and strategies for extension of life and recovery at end of life

3.1 Strategies for extension of working life

Referring to all the phases of the entire cycle, extending the working life of a product leads to a saving in energy and material resources 'upstream' and a reduction in refuse 'downstream'. In fact, this type of intervention allows the same necessities to be satisfied by fewer elements. Extension of a product's life can be achieved through several intervention typologies: maintenance, repair, upgrading and adaptation.

Maintenance – Maintenance activities include not only monitoring and diagnosis, aimed at the programmed substitution of parts subject to wear, but also operations of ordinary cleaning.

Repair – Essentially, the removal and substitution of parts suffering damage and impaired performance.

Upgrading and adaptation – Upgrading involved the substitution or the addition of components, while adaptation requires a reconfiguration of the main components of the product. Both are motivated by phenomena of obsolescence.

3.2 Strategies for recovery at the end of working life

With clear reference to Fig. 1, recovery operations at the disposal of a product allow the closure of the life-cycle, with the consequent environmental benefits: decrease in virgin materials entering the cycle, because in part substituted by resources recovered; recovery of energy and material resources used in production, and therefore improvement in the intensity of their use; reduction of flows of refuse.

Strategies for the recovery of resources at end of life can be divided into various typologies [Dowie 1994]. In general, the main recovery levels are the reuse of parts and the recycling of materials. Each of these is associated with a different potential of environmental benefit which depends on the different weights of the recovery flows in the life-cycle.

Reuse of parts – Components not suffering excessive deterioration during use can be recovered, if necessary after being re-generated by intermediate processes (re-manufacturing), as components for re-assembly, with a saving in the energy, costs, volumes of raw material and any emissions involved in the process of producing parts.

Recycling materials – Materials from parts which cannot be used for re-assembly or re-manufacturing can be recycled by recovery processes involved in the life-cycles of the materials themselves, or they can be treated and used in external production cycles to manufacture products with inferior characteristics.

Only those parts which cannot be recovered even at this last level are directed towards waste disposal processes.

4. Design method

Briefly, the method developed is divided into several successive moments, as summarised in Fig. 2. The first phase consists of analysing the product architecture with the aim of identifying the determining characteristics and unavoidable design constraints. Re-interpreted using a tool for strategy evaluation, the general architecture is mapped to evidence the distribution of the most appropriate strategies in relation to the characteristic properties of the various parts making up the product. This type of investigation can have two different goals: defining the most suitable strategies to apply to a predefined conventional architecture; the development of new architectures in accord with the most effective strategies for the extension of working life and recovery of resources.

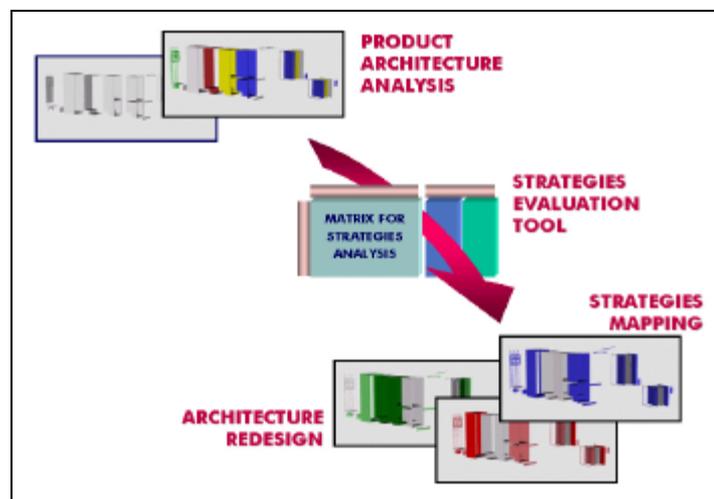


Figure 2. Summary of design method

4.1 Product architecture and design choices

In general, by product architecture we mean the arrangement and relationships of the physical blocks making up the functional elements of a product [Ulrich and Eppinger 2000]. Functional elements are those units which perform single operations and transformations, contributing to the overall product function. Defining product architecture consists, therefore, of first defining the modularity and

approximate geometric configuration (layout), and of identifying the interactions between the main units or modules. A successive level of analysis refers to the definition of components (dimensions, shape, material) and of junction systems. This definition of product architecture is interpreted in two successive levels of design choices: 1) modularity and layout; 2) properties of components. These choices in turn determine two corresponding typologies of component characteristics: separability and accessibility; performance (durability, reliability and other physical characteristics).

4.2 Preliminary analysis of product architecture

The preliminary analysis of product architecture consists of three phases: 1) definition of main functional units; 2) analysis of interaction between units (and definition of the consequent layout constraints); 3) analysis of characteristic performances required of each unit.

As mentioned above, the functional units are those which, together, produce the overall functioning of the system, divided into physical blocks which perform the single operations. Once defined, the results of the analysis of the interactions between these units is expressed by a symmetrical interaction matrix:

$$IU = [iu_{ij}]_{n \times n} \quad (1)$$

where iu_{ij} represents the interaction (value of 1 or 0) between the i -th and j -th units [Kusiak 1999].

Analysing the characteristic performance of the functional units, instead, consists of defining the performance constraints which, for each unit, can be expressed by one or more functions of the type:

$$Pf = Pf(Gf, Gv, Sh, MtPp) \quad (2)$$

where Pf represents the characteristic performance, Gf and Gv the fixed and variable geometric parameters, Sh the form characteristics and $MtPp$ the properties of the material [Giudice et al. 2001a].

4.3 Investigation typologies

As mentioned above, the method proposed supports two different investigation typologies: 1) analysis of conventional architecture, for a correct definition of the most suitable interventions for pre-existing products and an evaluation of environmental criticality; 2) architecture redesign for the improvement of environmental performance and the development of environmentally acceptable products.

4.3.1 Analysis of criticality and potentiality of the conventional architecture

At this level of intervention, the proposed method is directed at the most correct mapping of strategies for extending working life and recovery at end of life, according to the properties of the pre-existing construction units. This mapping is achieved using the matrix of strategy evaluation described below. The matrix translates some determining factors for the single strategies into component suitability to the strategy. The determining factors, as shown below, are classified as dependent on, or independent from, the design choices. In the case where a pre-existing structure is analysed, the design choices have already been made and therefore the entire set of these factors must be evaluated to define the optimal strategies. From the analysis of the conventional architecture it is possible to: 1) define the main components and its constituent materials; 2) identify the functional units; 3) evaluate the modularization of the functional units (correspondence between units and components); 4) analyse the interactions between the components (which must respect the necessary interactions between functional units).

This then provides a matrix of component interaction:

$$IC = [ic_{ij}]_{m \times m} \quad (3)$$

Using the matrix of strategy evaluation, it is possible to quantify the predisposition of each main component of the product in relation to each strategy of life extension and end of life recovery. Then, in order that the most suitable strategies are really practicable, the architecture must allow the necessary separability of the components [Giudice et al. 2001b]. To evaluate separability, which represents the main criticality of the architecture, matrix (3) must be transformed into a matrix of the irreversible junctions (each interaction is translated into junction)

$$IC^* = [ic^*_{ij}]_{m \times m} \quad (4)$$

where ic^*_{ij} is 1 if the junction between the i -th and j -th components is irreversible and 0 if it is reversible or inexistent. The separability of the components can then be expressed by the following vector:

$$SC = (sc_1 \quad \dots \quad sc_i \quad \dots \quad sc_m) \quad (5)$$

where sc_i is 1 (separable component) if $\sum_{j=1}^m ic^*_{ij} = 0$. Otherwise it is 0 (inseparable).

4.3.2 Redesign of product architecture

The first phase of architecture redesign is the analysis of the opportunity of redesign based on the functionality and performance constraints imposed on the main units, introduced in 4.2 and expressed by the interaction matrix (1) and by a function set of type (2).

In the case of architecture redesign, the instrument for the evaluation of optimal strategies is used ignoring the determining factors directly dependent on design choices (which must subsequently be optimised), and taking into account only those dependent on factors external to the design choices (required characteristics and functionality, conditions of use).

The results of this first analysis, dependent on solely external factors, indicate which design choices would respect the predisposition of each component to the life extension and end of life strategies. With these results it is also possible to evidence any affinities that may exist between components. Components similar in terms of suitability for both the strategies and the required functional performance can be appropriately grouped. These indications are then implemented in the first level of design choices (layout, modularity). Having defined the main components, it is necessary to modify the interaction matrix of the functional units (1) in the component matrix (3).

The next level of design choices (that of components: typology of materials, durability, reliability) is approached in terms of:

- required performance characteristics, expressed by (2);
- indications obtained from the preliminary evaluation of the optimal strategies.

The optimal choice is identified by varying the design parameters and evaluating the subsequent effects on the strategy distribution.

To complete redesign, the system of junctions must be defined so that it guarantees:

- functional interaction between components;
- separability, allowing the strategies identified as optimal for each component.

Also in this case, separability depends on the system of junctions through a matrix of type (4) and can be expressed using a vector of type (5).

4.4 Verification instruments

The result of redesigning must be analysed to evaluate the effectiveness in terms of reaching the goals set. The results of redesigning with respect to extending the product's working life can be evaluated using appropriate instruments for the analysis of the properties of product serviceability [Gershenson and Ishii 1993], which quantify its level of maintainability and reparability as a function of

architecture efficiency. With regard to evaluating performance in terms of environmental impact, it is possible to apply instruments for LCA (*Life-cycle Assessment*), which allow the evaluation of the environmental impact of the optimised product's life-cycle. This type of analysis, now widely employed, consists of evaluating the energy and environmental weights associated with industrial activities or processes in general. The evaluation covers the product's entire life-cycle, including the treatment of raw materials, manufacturing, use, reuse, recycling and waste disposal [SETAC 1991]. Operating these types of evaluation on the redesigned architecture and comparing the results with those obtained on the conventional architecture, it is possible to determine the benefits obtained and, therefore, the effectiveness and the success of the redesigning performed.

5. Strategy evaluation tool

5.1 Determining factors for strategies

The evaluation instrument allowing life extension and recovery strategies to be related to the product architecture consists of a series of matrices which seek to quantify the predisposition of each main component in terms of each practicable strategy. This quantification is obtained by evaluating the potentiality of the components in relation to the determining factors for each strategy. These factors must be considered as component properties which render it predisposed to the application of one or more of the strategies under examination.

The determining factors, as noted above, are distinguished by their dependence on, or independence from, the design choices. The former (durability, reliability, resistance) are directly dependent on choices made at the component level (materials, geometry). They are generally quantifiable by evaluating physical-mechanical properties (resistance, etc.) and by applying instruments for the analysis of component reliability and life prediction. The others depend on factors external to design choices (required characteristics and functionality, conditions of use). Generally, their quantification can only be based on qualitative evaluations. The determining factors are summarised below in relation to each strategy under examination (Tab. 1 – Strategies for extension of working life; Tab. 2 – Strategies for recovery at end of life). Those depending on design choices are evidenced in italics.

Table 1. Extension of life strategies and determining factors

MAINTAINANCE	CLEANING NEED
	PHYSICAL DETERIORATION (EXTERNAL FACTOR)
	<i>DURATION</i>
REPAIR	DAMAGES (EXTERNAL FACTORS)
	<i>RELIABILITY</i>
	<i>DURATION</i>
UPGRADING/ RECONFIGURATION	OBSOLESCENCE
	USE MODE CHANGES
	USE ENVIRONMENT CHANGES

Table 2. End of life strategies and determining factors

PARTS REUSE	PHYSICAL DETERIORATION (EXTERNAL FACTOR)
	TECHNOLOGICAL OBSOLESCENCE
	<i>DURATION</i>
MATERIALS RECYCLING	PHYSICAL DETERIORATION (EXTERNAL FACTOR)
	TECHNOLOGICAL OBSOLESCENCE
	<i>DURATION</i>
	<i>RECYCLABILITY</i>

5.2 Implementation of matrices for analysis of strategies

To create a strategy analysis matrix, the main components must first be entered, according to the indications obtained from the preliminary analysis of product architecture. One line of evaluation terms corresponds to each component, one term for each determining factor of the strategy for which the potentiality of the components is to be assessed. In this way a matrix can be developed for each strategy, completed by final column consisting of the global evaluation terms corresponding to each

component. These final terms are understood as the sum of the terms in the corresponding matrix line, appropriately weighted according to the importance of each determining factor.

The mathematical model can be summarised as follows. Indicate by C_i the i -th of the m components making up the architecture and by DF_j^X the j -th of the n^X determining factors for the practicable strategy X . The matrix M^X for the evaluation of strategy X can be expressed as:

$$M^X = \left[m_{ij}^X \right]_{\substack{j=1,2,\dots,n^X \\ i=1,2,\dots,m}} \quad (6)$$

where the term m_{ij}^X quantifies the j -th determining factor for the strategy X , relative to the i -th component. Then indicate by w_j^X the weight of the j -th determining factor for strategy X . The aptness A_i^X of the i -th component C_i to strategy X represents the Index of Strategy X for the i -th component:

$$A_i^X = \sum_{j=1}^{n^X} w_j^X \cdot m_{ij}^X \quad (7)$$

A correct use of the model proposed requires not only an appropriate quantification of the strategy determining factors, but also their normalisation to render them homogeneous in relation to the application of (7), and an evaluation of the weighting of each factor in relation to the strategy.

6. Case study: Architecture analysis and redesign of a refrigerator

Their widespread use in all households makes ‘white’ domestic appliances (refrigerator, washing machine, dish washer) particularly sensitive to the problems of disposal and recovery. In the case of the refrigerator, this problem is compounded by the large variety of product typologies produced to meet varying consumer demands, which can make it vulnerable to a reduction in its useful life. This is compounded by a problem of recovery resulting from the conventional product architecture which, at present, irreversibly unites a wide variety of different and incompatible materials. This problem has led to legislative pressure seeking to restrain the environmental impact of this specific manufacturing sector, intervening at different phases of the life-cycle. In particular, the EU has introduced a certification of product eco-compatibility, called the European Union Ecolabel, a seal of ecological quality applied to various mass-consumer product typologies, including the refrigerator [2000/40/EC].

6.1 Preliminary analysis of product architecture

Following the methodology discussed, the first phase consists of a preliminary analysis of the product architecture to define: main functional units; interactions between units (and consequent layout constraints); characteristic performances required of each unit.

In the case of the refrigerator, the 6 main functional units summarised in Tab. 3 were identified and associated with their main performance characteristics. The matrix of the interactions between the main units (symmetrical matrix) is reported in Tab. 4.

Table 3. Functional units and main performances requested

FUNCTIONAL UNITS		MAIN PERFORMANCES REQUESTED
U ₁	External coating	Shock resistance – Structural sturdiness – Thermal insulation
U ₂	Rear panel	Thermal insulation
U ₃	Thermal insulator	High thermal insulation – Structural sturdiness
U ₄	Internal coating	Hygienic and washable – Structural sturdiness – Thermal insulation
U ₅	Plant	Thermodynamic performance
U ₆	Plant-cell interface	Thermal insulation

Table 4. Functional interaction between main units

	U ₁	U ₂	U ₃	U ₄	U ₅	U ₆
U ₁	-	1	1		1	
U ₂		-	1			
U ₃			-	1		
U ₄				-		1
U ₅					-	1
U ₆						-

6.2 Analysis of criticality and potentiality of conventional architecture

From the analysis of the conventional architecture it is possible to define the main components and their materials, and to identify the functional units, as shown in Fig. 3. It can be seen that in this case, unit 6, which transfers the cooling action generated by the cooling plant 5 to the internal cell 4, coincides with part of the plant itself (evaporation plate), thus units U_5 and U_6 are grouped together in a single component C_5 (cooling plant).

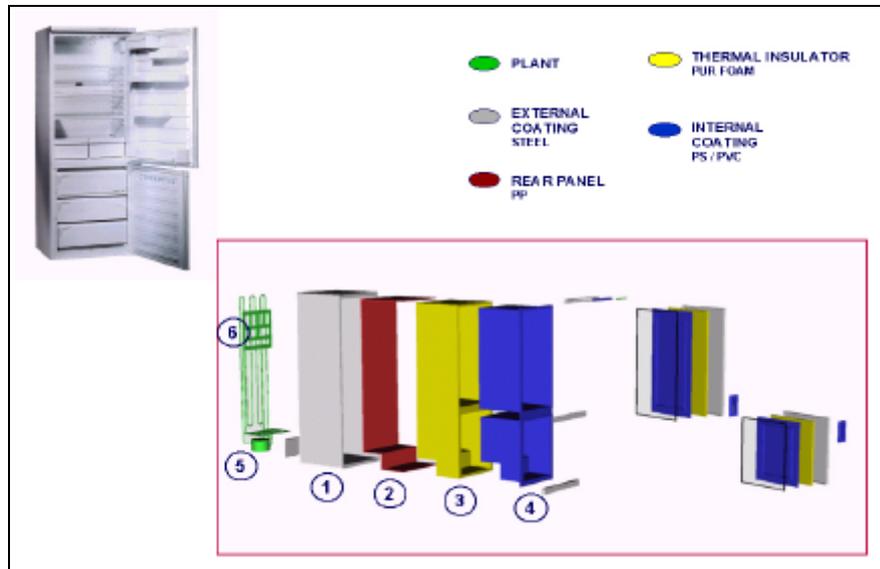


Figure 3. Conventional architecture

From the conventional architecture analysis it is also possible to determine the main criticality, the impossibility of separating the parts at the end of the working life because of the foam insulation element which joins all the cabinet components and part of the cooling system. This criticality is expressed by the matrix reported in Tab. 5, where the irreversible junctions (4) are reported in the upper part, and the consequent vector of component separability (5) is given on the lower line.

Table 5. Irreversible junctions and components separability

	U_1	U_2	U_3	U_4	U_{5+6}
	C_1	C_2	C_3	C_4	C_5
U_1	-		1		
U_2		-	1		
U_3			-	1	1
U_4				-	
U_{5+6}					-
	0	0	0	0	0

Figure 4 shows the strategy evaluation matrices regarding each strategy under examination (maintenance, repair, reuse, recycling). Of the determining factors for each strategy, those dependent on design choices (material typology, reliability, durability), which in this type of analysis are taken as pre-established parameters, are highlighted. Once quantified, the parameters were broken down into value ranges of 4 different levels (0-zero; 1-low; 2-medium; 3-high). The figures also show the corresponding strategy indices calculated according to the normalisation and weighting method introduced above (5.2).

If cleaning operations are excluded, the component most requiring servicing (maintenance and repair) is the cooling plant. This is not completely separable from the rest of the structure, as confirmed by the information reported in Tab. 5 (the evaporators are embedded in the polyurethane foam). There is, therefore, a good level of serviceability only for some parts of the cooling plant.

With regard to strategies for end of life, these involve the polyurethane insulation (for reuse), and the metal and polymer casings. However, once again the zero separability of these components does not permit optimal strategies to be applied.

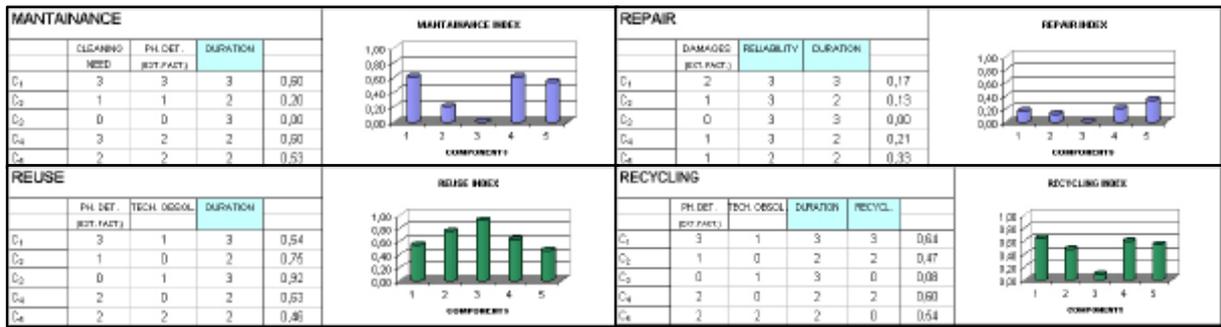


Figure 4. Matrices for strategies evaluation and strategies indices

In conclusion, the environmental potentials evidenced cannot be realised, highlighting the criticality of the conventionally manufactured product, due to the poor separability of the components. Figure 5 shows the results of the LCA, performed with SimaPro software (Pré Consultants). The main processes making up the entire life-cycle are summarised on the left, while the environmental impacts of the manufacturing, use (hypothesising a life of 8 years) and disposal phases are quantified on the right. The first two phases lead to the greatest impact. The disposal phase consists exclusively of dumping.

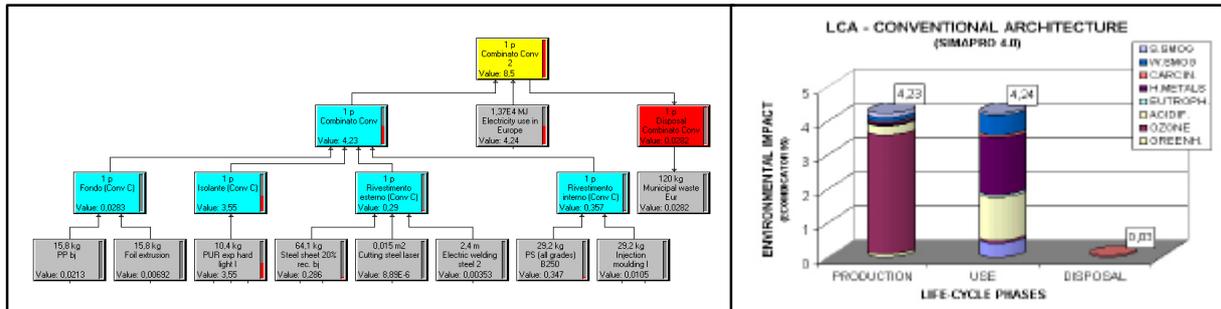


Figure 5. LCA for the conventional architecture

6.3 Redesign of product architecture

From the analysis of potentiality and criticality it is possible to identify the problems and limitations presented by the conventional architecture, which in the case under examination are principally: 1) dispersion of the thermodynamic plant in the entire unit; 2) heterogeneity of the materials; 3) impossibility of separating the parts at end of use.

The first phase of redesign involves the use of tools to evaluate the optimal strategies, ignoring determining factors directly dependent on design choices (which must be optimised subsequently) and taking into consideration only those dependent on factors external to design choices (characteristics and functionality required, conditions of use). The results of this first phase are reported in Fig. 6. As shown by the first two matrices, if cleaning operations and damage due to external accidents are excluded, the need for maintenance and repair is concentrated in the cooling plant (unit 5). This suggests making design choices that respect this disposition so that servicing is concentrated on the single most sensitive unit, making all its components separable from the product and easily accessible. The other two matrices identify the units offering the best opportunities for reuse (units 2, 3, 6) and those most suitable for recycling (units 1, 4). Unit 5 offers broadly equivalent opportunities (the complexity of the cooling system requires, however, a deeper level of analysis). Also in this case, the results obtained provide indications for the most appropriate design choices. Further, they evidence the close affinity between unit 2 (rear panel) and unit 6 (element transferring the cooling action from the cooling plant into the cell), also confirmed by an identical sensitivity to servicing and identical requirements in characteristic performance (Tab. 3).

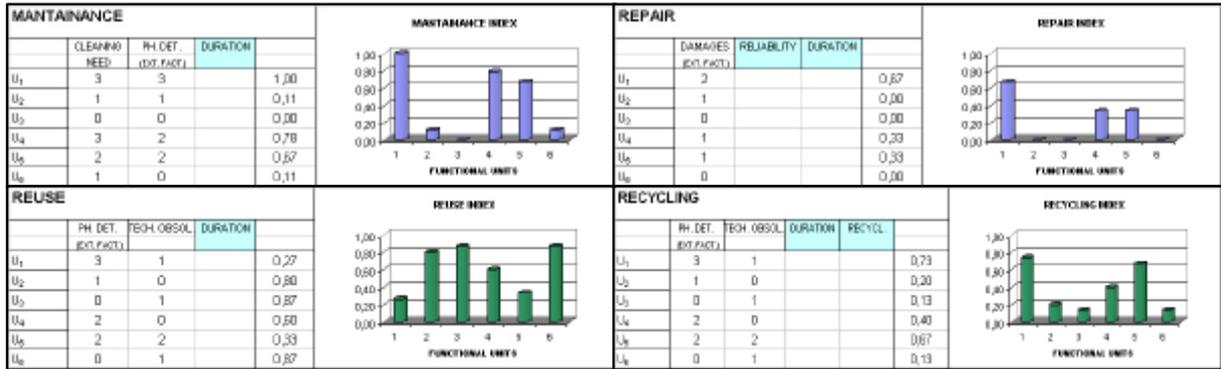


Figure 6. Matrices for strategies evaluation and strategies indexes (Redesign)

To interpret these indications in a first level of design choices (layout):

- unit 5 (cooling plant) is subdivided into two main components, the cooling plant C_5 and an external case C_6 which houses the entire system and separates it from the rest of the manufactured product;
- units 2 and 6 are combined in a single component C_2 .

The next level of design choices (components definition), is approached with respect to:

- the required performance characteristics, reported in Tab. 3;
- the indications obtained from preliminary evaluation of the optimal strategies (Fig. 6).

The optimal choice is identified by varying the design parameters and evaluating the consequent effect on the distribution of strategies, quantified by the values assumed by the strategy indices. In the case under examination, the optimal choices are realised in the architecture shown in Fig. 7, which summarises the layout of the functional units, general geometry, the materials chosen for each component and the distribution of optimal strategies.

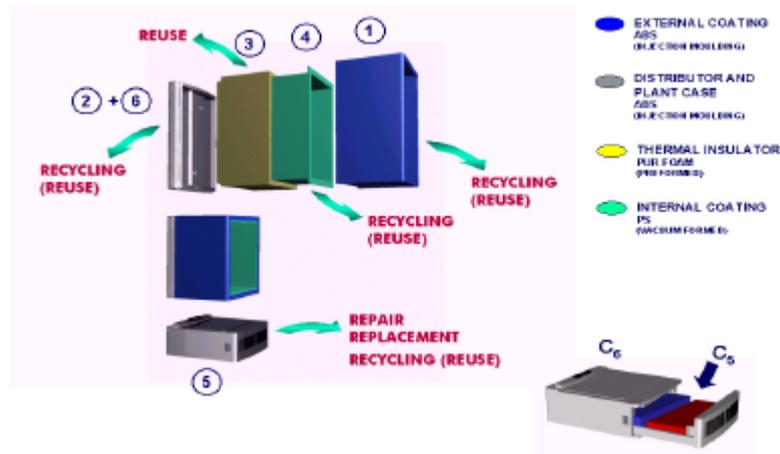


Figure 7. Redesigned architecture

To complete the redesign, it is necessary to define a jointing system that:

- guarantees the redefined functional interactions;
- guarantees the separability, allowing the execution of the strategies identified as optimal.

The jointing system proposed, respecting the functional interactions, involves a single juncture between the external lining and the rear component which closes the cell and transmits the refrigerating action of the cooling plant into the cell itself. The overall jointing system could present a single irreversibility in the connection between the cooling plant (C_5) and its casing (C_6), however these together make up the cooling unit. Table 6 summarises the matrix of irreversible junctions (4), the component separability vector (5), and the separability vector of the functional units. It can be seen that the single irreversibility does not effect the complete separability of the main units.

Table 6. Irreversible junctions, components separability, functional units separability

	U ₁ C ₁	U ₂₊₆ C ₂	U ₃ C ₃	U ₄ C ₄	U ₅ C ₅	U ₅ C ₆
C ₁	-					
C ₂		-				
C ₃			-			
C ₄				-		
C ₅					-	1
C ₆						-
	1	1	1	1	0	0
	1	1	1	1	1	1

Conducting an LCA on the redesigned architecture and comparing the results with that performed on the conventional architecture, it is possible to evaluate the environmental benefits conferred and, therefore, the effectiveness of the redesign method used.

In Figure 8, the environmental impact regarding the main phases of the life-cycle are reported on the left. With respect to the conventional architecture (Fig. 5), the new architecture is characterised by a marked increase in impact both during production (+11%) and during use (+19%), due to a greater increase in electricity consumption because the new architecture requires a more powerful cooling plant). In compensation, the complete separability of the system allows a disposal phase so efficient that these negative effects are balanced, resulting in an environmental impact over the entire life-cycle which is better than that of the conventional architecture (-25%). This is evidenced on the right in Fig. 8, which directly compares the whole life-cycles of the conventional and redesigned architectures. This confirms the effectiveness and good outcome of the redesigning.

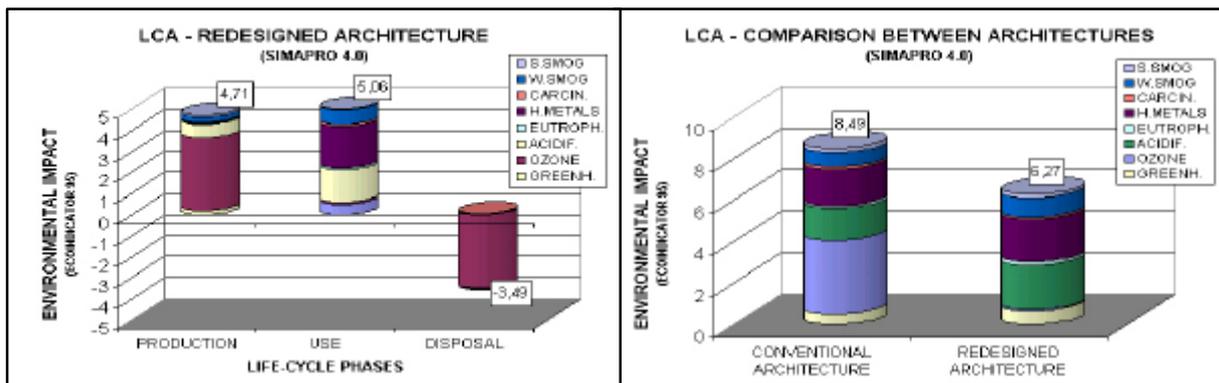


Figure 8. LCA for the redesigned architecture (left), and comparison between conventional and redesigned architectures (right)

7. Conclusions

The paper describes the development of a methodological tool, complete with the fundamental mathematical modelling, for the study of product architectures with the aim of determining their environmental efficiency. Environmental efficiency was pursued through two intervention typologies: those directed at maintaining performance during use (strategies for the extension of working life) and those oriented towards the recovery of resources (strategies of recovery at the end of life).

The method is based on several successive phases: preliminary analysis of product architecture (definition of the unavoidable requisites of the architecture); evaluation of optimal strategies for each main component; definition and implementation of the separability that allows the optimal strategies to be applied. Further, the method supports the design operation at two different levels: definition of layout and modularity; choice of the main characteristics of components (geometry, materials, durability).

The case study examined highlighted the versatility of the method used as an instrument for: 1) analysis of environmental criticality and potentiality of conventional architectures, for a correct

definition of the most suitable intervention strategies on pre-existing products; 2) architecture redesign, taking account of unavoidable requisites, and integrating them with new requirements for the environmental efficiency of the product's life-cycle.

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References

- Alting, L., "Life-Cycle Design of Products: A New Opportunity for Manufacturing Enterprises", In: Kusiak, A., "Concurrent Engineering: Automation, Tools and Techniques", John Wiley & Sons, New York NY, 1993.
- Billatos, S., Basaly, N., "Green Technology and Design for the Environment", Taylor & Francis, Bristol PA, 1997.
- Dowie, T., "Green Design", World Class Design to Manufacture, Vol. 1, No.4, 1994.
- Gershenson, J., Ishii, K., "Life-Cycle Serviceability Design", In: Kusiak, A., "Concurrent Engineering: Automation, Tools and Techniques", John Wiley & Sons, New York NY, 1993.
- Giudice, F., La Rosa, G., Risitano, A., "Optimal Material Selection in the Design for Environment Process", ENTREE 2001 Environmental Training in Engineering Education, Florence, Italy, 2001, pp 215-234.
- Giudice, F., La Rosa, G., Risitano, A., "Product Recovery-Cycles Design: Extension of Useful Life", IFIP International Conference on Feature Modelling in Advanced Design for the Life Cycle Systems, Valenciennes, France, 2001.
- Graedel, T., Allenby, B., "Design for Environment", Prentice Hall, Upper Saddle River NJ, 1998.
- Ishii, K., "Life-Cycle Engineering Design", Journal of Mechanical Design, Vol.117, 1995, pp 42-47.
- Keoleian, G., Menerey, D., "Life Cycle Design Guidance Manual", EPA/600/R-92/226, Risk Reduction Engineering Laboratory, United States Environment Protection Agency, 1993.
- Kusiak, A., "Engineering Design: Products, Processes, and Systems", Academic Press, San Diego CA, 1999.
- OTA, "Green Products by Design: Choices for a Cleaner Environment", OTA-E-541, Office of the Technology Assessment, Congress of the United States, 1992.
- SETAC, "A Technical Framework for Life-Cycle Assessment", Society of Environmental Toxicology and Chemistry, Washington D.C., 1991.
- Ulrich, K., Eppinger, S., "Product Design and Development", McGraw-Hill, New York NY, 2000.
- 2000/40/EC, "Commission Decision Establishing the Ecological Criteria for the Award of the Community Eco-label to Refrigerators", EC Official Journal, L 013, 19/01/2000.

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