INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 01 GLASGOW, AUGUST 21-23, 2001

OPTIMISATION AND COST-BENEFIT ANALYSIS OF PRODUCT RECOVERY-CYCLES

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Keywords: Life-cycle design, design for recovery, life-cycle costing, mechanical product design

1 Introduction

When environmental considerations become a priority in the design process, the end of the product's life and its disposal must be included in the analysis. This extended approach to the design problem suggests a systematic consideration of integral design of products and the processes which make up their life-cycle, in accordance with the principles of Life-Cycle Design (LCD). This design approach takes into consideration all the phases of the life-cycle, from concept development to disposal, analysing and harmonising determining factors such as quality, costs, production feasibility, requirements of use, servicing and environmental aspects [1], [2]. The principle environmental objective, which is to optimise the distribution of the flows of resources over the product's whole life-cycle, can be followed by many strategies. Of particular importance are those concerning the recovery of components and materials at the end of the product's life [3]. These strategies, which allow closed resource flows over the product's life-cycle, and optimisation of the product's environmental performance, must be complemented by an analysis which evaluates the not insignificant life-cycle costs [4], [5].

2 Aims and objective

On the basis of the experience of manufacturers operating in the industrial plant sector, for some product typologies, resources were used at a low intensity in that some parts of a constructional unit were still efficient at the end of its conventional life span and, therefore, potentially could guarantee further durability, but were nevertheless discarded with the entire product. This evidenced interesting margins in which operations of component reuse could be applied. In the light of these considerations, the research was oriented towards the development of instruments able to translate some determining design choices into opportunities for component recovery by means of mathematical models which: simulate possible recovery cycles at the end of the product's life; quantify the benefit in environmental terms; analyse the relation between the increase in recovery flows and the resulting effects on life-cycle costs. The objective, therefore, was to develop a design method and tools which allow architectures to be compared and optimised, in terms of component separability and the distribution of their working life in the unit, for an effective and sustainable recovery of resources.

3 Design method

The design method identified can be summarised as in Figure 1. The first phase of defining the general architecture of the product, using instruments of traditional design, consists of identifying the main components of the system, their spatial and functional organisation, the jointing systems and the overall dimensions and materials of each component. This is followed by a phase where the conventional architecture previously defined is analysed in relation to the recovery strategies. This operation is directed at analysing the architecture evidencing the property of performance durability over time, and the joint constraints (reversible/irreversible) which condition the separabilty of single parts or sub-units from the rest of the assembly.

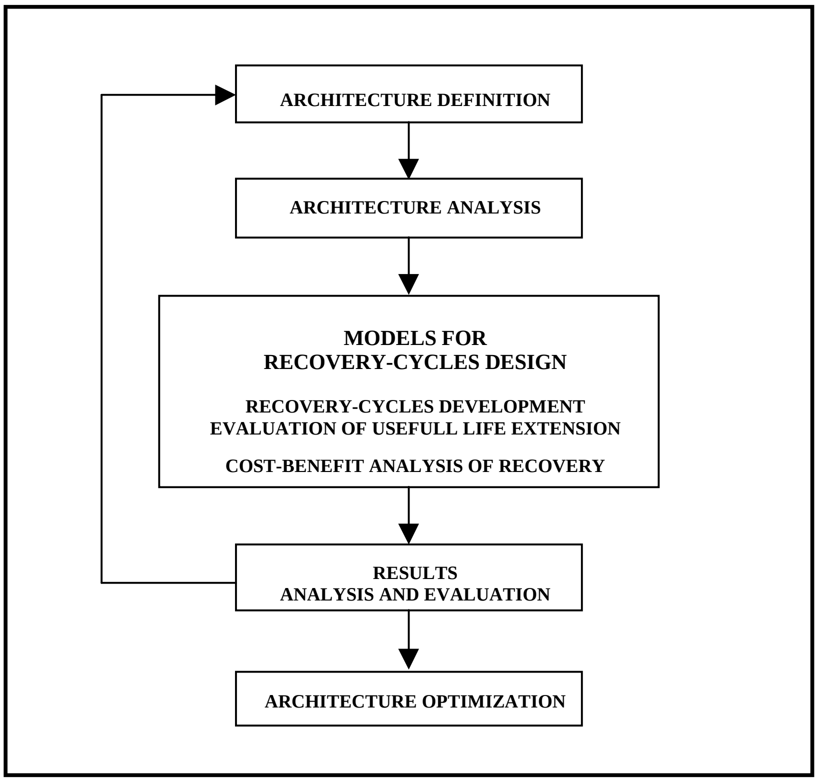

Figure 1. Design Method

The data obtained from the architecture analysis are then elaborated by calculation models, which define the possible recovery cycles and evaluate their environmental efficacy in terms of extension of the product's useful life. The next phase, evaluating the results given by the calculation models used, provides suggestions for a correct redesign of the architecture. The redefined architecture again undergoes the process of calculation, complemented by an appropriate cost-benefit analysis which can evaluate the economic cost of the operation of redesign, with the final aim of best harmonising the requirements of conventional design (functionality, safety, costs) with those of the environment.

4 Models for recovery-cycles design

The calculation models developed to aid the design of product recovery cycles, have the function of translating the architecture data into a measure of a component's suitability for reuse, calculating the outcome of the possible recovery cycles at the end of the product's ordinary working life, quantifying the advantages in terms of environmental protection, and analysing the impact of recovery on the life-cycle cost.

4.1 Evaluation of Recovery Fractions and Useful Life Extension

The analysis of the overall architecture, conceived according conventional design criteria, allows the identification of n principal components C_i making up the unit, each characterised by weight P_i. The Recovery Fractions define the recovery cycles in that they are functions of the components which take part in each recovery cycle, and can be expressed in two ways:

$$\Phi_j^P = \frac{\sum_{i=1}^{n} r_{ij} \cdot P_i}{\sum_{i=1}^{n} P_i} \qquad \Phi_j^\alpha = \frac{\sum_{i=1}^{n} r_{ij} \cdot \alpha_i}{\sum_{i=1}^{n} \alpha_i} \tag{1}$$

The first form Φ_j^P expresses the fraction of the total weight of the product reusable at the j-th recovery cycle. To better characterise these in terms of environmental impact, however, it is appropriate to express them according to the environmental impact associated with the production of each component, instead of the simple weights. This is possible using the eco-indicators available in the literature, which are used to quantify the impact involved in the production of the more common materials and in standard manufacturing processes [6]. Indicating the environmental impact of i-th component production by α_i, therefore it is possible to express the recovery fractions in the other form Φ_j^α. The term r_{ij} is the reusability of the i-th component at the j-th recovery cycle, and can be expressed as a function of two factors determining component's suitability for recovery and reuse: durability and separability. The durability D_i of the i-th component is the ratio (entire value) between the predictable duration of component (depending on design choices), and the duration of the product's conventional working life T. The separability of the i-th component at the j-th recovery cycle S_{ij} expresses the possibility of disassembling and separating the component from the unit in order to recover it. With regard to this last point, a qualitative analysis based on simple observation of the system's architecture could be complemented by an analytical approach to the problem of evaluating the separability of each component, or module, using appropriate models for the optimisation of disassembly procedures [3].

Already formulated by the authors [7], on the basis of previous suggestions [8], Useful Life provides a global vision of the product's entire life, beyond the limits of a single life cycle. It can be intended as the period of time for which the entire architecture or part of it is used in the same life cycle, and can be considered as an indicator of environmental performance over the entire life cycle. Extending the useful life, in fact, corresponds to a better use of the resources involved in the production phase. Referring to precedent formulation [7], and indicating the number of whole reuses by nr, and the maximum number of foreseeable recovery cycles for the entire unit by m: if at the conclusion of each use subsequent to integral reuses a recovery fraction Φ_j is recovered and again introduced into the cycle, hypothesising a constant duration of all the uses equal to T, the Extension of Useful Life EUL quantifies the overall extension of the life of the original components within the same product's life cycle:

$$EUL = \left[nr + \sum_{j=1}^{m} \Phi_1 \cdot \Phi_2 \cdot .... \cdot \Phi_j \right] \cdot T \quad (2)$$

According to the type of investigation required, the two forms of the recovery fractions expressed by (1) are introduced into (2).

4.2 Cost-Benefit Analysis of recovery

The Cost-Benefit Analysis model is based on the distinction made between two different production systems: first production, that is the product is manufactured from virgin raw materials only; second production, that is integrating the volumes of virgin raw materials with volumes recovered, to manufacture a product of second production. The cost of first production C^{I}_{PROD} is defined as the sum of the terms regarding the acquisition of the materials, the production of the parts and their assembly:

$$C^{I}_{PROD} = \sum_{i=1}^{n} \left(c_i \cdot P_i + C_i^{PP} \right) + \sum_{v=1}^{f} C_v^{ASS} \quad (3)$$

where: c_i is the unitary cost for the material making up the i-th component; C_i^{PP} is the production cost of the i-th component; f is the total number of junctions required in the structure; C_v^{ASS} is the cost of making the v-th junction. Introducing the cost of second production C^{II}_{PROD}, and the reusability of the i-th component at the j-th recovery cycle r_{ij}, the Production Cost Recovery after the j-th recovery cycle RC_{PROD_j} can be defined by:

$$RC_{PROD_j} = \frac{C^{I}_{PROD} - C^{II}_{PROD_j}}{C^{I}_{PROD}} = \frac{\sum_{i=1}^{n} r_{ij} \cdot \left(c_i \cdot P_i + C_i^{PP} \right)}{\sum_{i=1}^{n} \left(c_i \cdot P_i + C_i^{PP} \right) + \sum_{v=1}^{f} C_v^{ASS}} \quad (4)$$

At this point it is of particular interest to determine the condition for which an increase in the volumes of recovery, that is an increase in the recovery fractions (1), of undoubted environmental advantage, is also advantageous from the economic point of view. Such an increase can be obtained by modifying the architecture to allow recovery cycles which involve greater flows of the volumes making up the product. In the majority of cases, however, modifications of this type lead to an increase not only in the recovery of production cost (4), but also in the production costs themselves. Nevertheless, considering the possibility of reiterating the recovery over time, it can happen that the increase in the production costs is compensated for in some way over time. The model developed for an investigation of this type was inspired by a model used for a different purpose [9], already reformulated by the authors [10]. On the basis of the definitions of first and second production suggested above, the cost of the entire life of the product C can be defined, applying the following simplified ideal hypotheses: recovery reiterated over time, in a regime where, for all the recovery cycle programmed, the volumes involved in the different levels of recovery are always the same (therefore production cost recovery (4) is constant and written RC_{PROD}); the product is sold and recovered in a sufficiently short period of time that a null rate of interest can be assumed.

$$C = C^{I}_{PROD} + \sum_{j=1}^{m} \left(C^{II}_{PROD_j} + C_{REC} \right) = \left(1 + m - m \cdot RC_{PROD}\right) \cdot C^{I}_{PROD} + m \cdot C_{REC} \quad (5)$$

In (5) C_{REC} is a generic term of recovery cost, assumed constant for each recovery cycle.

Now assume that modifications are made to the architecture, so that they cause an increase in the production cost recovery RC_{PROD}. If δ indicates the increase in RC_{PROD}, and ε the corresponding increase in C^{I}_{PROD}, under the last hypothesis that the variation of the recovery costs are negligible ($C_{REC} \cong C^{*}_{REC}$), on the basis of (5) it is possible to obtain the new expression of the cost of the entire life C*:

$$C^* = \left(1 + m - m \cdot RC_{PROD} - m \cdot \delta\right) \cdot \varepsilon - m \cdot \delta \cdot C^{I}_{PROD} + C \quad (6)$$

As long as the increase in the recovery of production cost, although causing an increase in the production costs, leads to a condition of economic advantage over the entire useful life predicted for the product, it is necessary that $C^* \leq C$, which provides the following condition:

$$\frac{\delta \cdot \left(\varepsilon + C^{I}_{PROD}\right)}{\varepsilon} \geq \frac{1 + m \cdot \left(1 - RC_{PROD}\right)}{m} \quad \Rightarrow \quad \Psi\left(\delta, \varepsilon, C^{I}_{PROD}\right) \geq \Omega\left(m, RC_{PROD}\right) \quad (7)$$

Expression (7) represents the condition of economic advantage of the increase in recovery flows. The function Ω decreases on increasing the number of recovery cycles m. This confirms what was expected regarding the fact that the economic advantage of modifications to the architecture which lead to an increase in (4), is linked to the possibility of planning an elevated number of recovery cycles. Having evaluated the increase in production cost ε caused by any modifications to the architecture, expression (7) can be used to determine the minimum number of recovery cycles m which must be programmed to compensate the increase in ε. Vice versa, evaluating the number of possible recovery cycles m, from (7) it is possible to obtain the maximum limiting value which ε can assume for the condition of economic convenience to be achieved.

5 Recovery cycles design for heat exchangers

The experience of the manufacturers has shown wide margins for the application of recovery operations at the end of the working life of heat exchangers. The specific product seems particularly interesting in relation to the problems in question because it is characterised by construction standards developed according to principles of modular architecture [11]. This makes the product highly suitable for the recovery of some components at the end of its working life. Therefore the models developed for the design of recovery cycles were applied to the analysis and optimisation of heat exchanger architecture.

5.1 Recovery strategies at the end of working life

An investigation into the potentiality of the component recovery strategies was conducted with particular regard to the typology of heat exchanger coded CFU, with detachable shell (Figure 2). In particular cases (with the common parameters of overall volume and thermalpressure working conditions), after about 6 years of use metallographic analysis showed considerable deterioration in the metallurgical properties of the central module shell, good condition of the tubes (potentially reusable after rigorous cleaning) and excellent condition of the remaining components (front end module). In analogous tests, after a further 6 years of use of exchangers regenerated by substituting only the central module shell, the reused tubes showed deterioration, while the good condition of the remaining components suggested their suitability for a further and ultimate reuse.

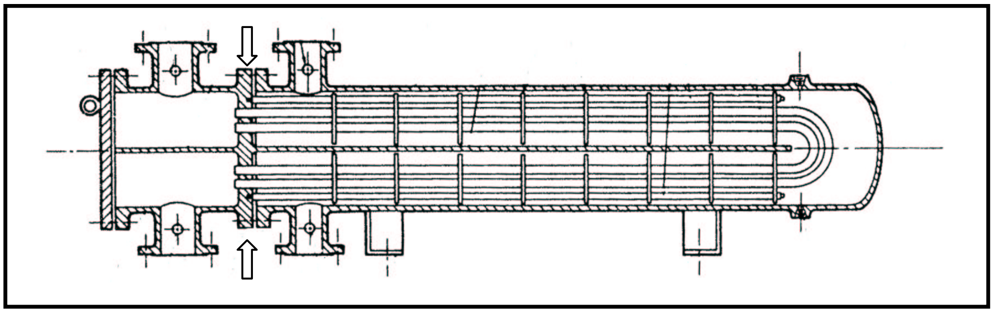

Figure 2. CFU architecture typology

5.2 Application of design method and evaluation of results

Following the design method reported in Figure 1, two possible recovery cycles and the components or groups of components which can be included were defined. The recovery fractions were calculated in terms of environmental impact, as expressed in the second form (1). The environmental indicators developed according to the Eco-indicator 95 methodology [6], were used in the calculation of environmental impacts α_i. Expression (2) was applied for the calculation of indicators of Extension of Useful Life. The first results were evaluated, and a design alternative which allowed an improvement in the efficiency of the recovery cycles was identified. Finally, the analytical instrument (7) was applied to analyse the effects this improvement would have on the costs of the life-cycle.

From the results of the analysis of conventional architecture CFU, it is clear that it would be appropriate to make the tube bundle separable from the front end stationary head module (see the junction highlighted by arrows in Figure 2), with a reversible flanged coupling which connects the central shell, tube plate and the front end shell. This results in an optimised architecture CFU*. The introduction of this modification allows a second recovery of the front end stationary head module, is therefore directed at a greater efficiency of the second recovery cycle. The results of the comparison between the two architectures, CFU and CFU*, can be summarised as follows.

In the first recovery cycle CFU* shows a slight decrease in the extension of useful life EUL compared to CFU (graph reported in Figure 3). Thus halting at the first recovery operation would mean that the optimisation was inefficient. This slight decrease is however fully compensated in the second recovery cycle, made more effective by a better modularity, with a consequent +7.4% increase in EUL for CFU* compared to the increase in conventional CFU. This underlines the importance of using an indicator which extends the evaluation over all the recovery cycles for a complete analysis of the efficiency of the recovery operation.

Application of the model for cost-benefit analysis makes it possible to relate the economic convenience of the architecture optimisation to the increase in production cost ε resulting form this optimisation, and to m_2 the number of recoveries possible after the first. In graph reported in Figure 4 this convenience is represented, for different values of ε (expressed as percentage values of the conventional architecture production cost), by the conditions under which the straight lines Ψ are above the curve Ω (independent of ε). Clearly, on increasing ε the point of parity moves towards higher values of m_2. In particular, in the case where only one recovery cycle can be programmed after the first, as in the case under examination, the condition of economic convenience is respected as long as the increase in ε remains below the limiting value ε_{lim} = 5.2% of the production cost of the conventional architecture. If ε exceeds this limit, at least two more recovery cycles after the first would be necessary to guarantee economic convenience.

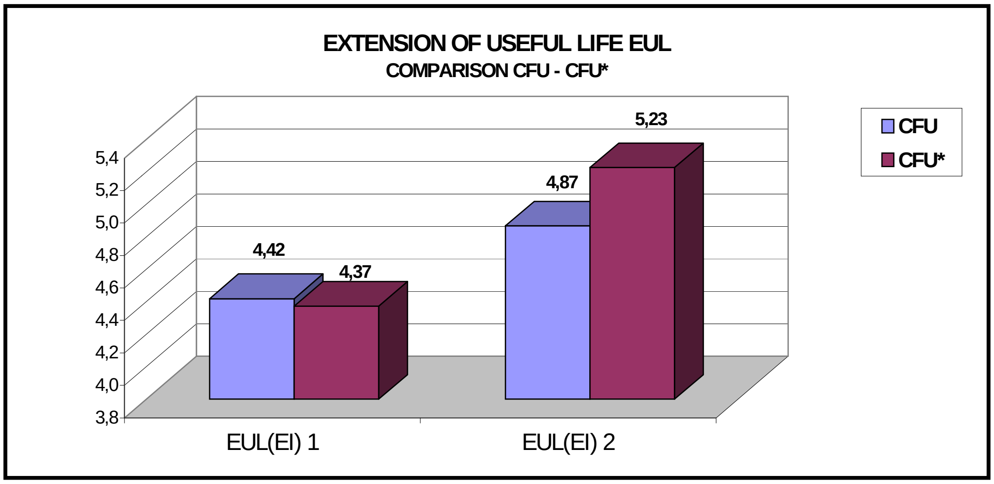

Figure 3. Extension of useful life (CFU vs CFU*)

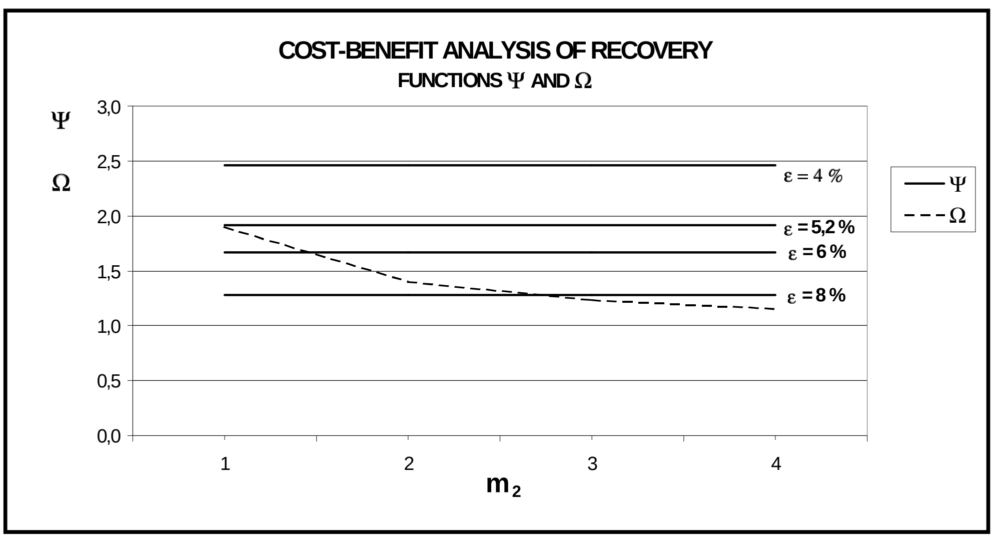

Figure 4. Cost-Benefit Analysis of recovery (Functions Ψ and Ω)

6 Conclusions

The study proposes a methodology and tools to aid designers in making the best choices in order to plan recovery cycles for a product at the end of its working life. Having outlined an effective design methodology for this purpose, calculation models were developed: to support the definition of the reusable parts of the architecture and recovery-cycles planning; to evaluate an indicator which translates the environmental effects of recovery cycles in terms of extension of the product's useful life; to determine the condition for which an increase in the volumes of recovery, of undoubted environmental benefit, is also advantageous from the economic point of view. Applied as an instrument of analysis and optimisation of the suitability for recovery of modules characterising the architecture of heat exchangers, the design method and calculation models proposed here seem to confirm the potential as an aid to optimise product architectures, to plan the best recovery cycles, and to investigate the relation between architecture optimisation and the resulting effects on life-cycle costs.

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