INTERNATIONAL DESIGN CONFERENCE - DESIGN 2004
Dubrovnik, May 18 - 21, 2004.

DESIGN 2004

SIMULATION OF PRODUCT LIFE CYCLE: METHODOLOGICAL BASIS AND ANALYSIS MODELS

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Keywords: life-cycle design, advanced FMEA, duration, useful life, recovery

1. Introduction

In the context of product design and development, Design for Environment or Green Design consists of the study of the principle characteristics of the architecture (layout of the construction system, modularity, geometries, jointing systems, materials) with the principle aim of reconciling the requirements of environmental quality (improvement in the use of resources, limitations to environmental impacts of production, use and end of life, recovery of resources) with those of conventional design (performance, structural safety, ease of production, costs) [Billatos and Basaly 1997]. From this viewpoint, the instruments and methods of Life Cycle Design are of particular interest. These consist of a design intervention which incorporates all the phases of the product's life cycle (development, production, use, maintenance and repair, retirement, recovery) in the entire design process, from the phase of concept definition to that of detailed design development [Alting 1993].

Operating within this field of reference, therefore, the need is to provide the designer with tools for the evaluation and optimization of design parameters determining for product performances (conventional and environmental) over the arc of the entire life cycle.

The aim of the present study is to define a methodological scheme and relative analytical tools in support of the design process, allowing the management of design choices (both at the level of product layout and that of the specifications of individual components), in relation to the product's conventional (functionality, safety, reliability, cost) and environmental performance over its life. Proposing variations in the design choices (reorganization of the architecture, modification of component geometries and materials), these tools must allow the simulation of the resulting life cycle so that it is possible to compare the various alternatives and identify the solutions that best optimize appropriate performance aims. With particular regard to the simulation of the final phases of the life cycle, i.e. use and retirement, the performance aims to be optimized must be related not only to the design choices but also to factors of deterioration which can alter the behavior of the product and its components over time.

2. Approach to the problem and methodological structure

With these aims, we propose a method of simulating product behavior over its life cycle and the relative analytical tools, to obtain, for every possible set of design choices:

- indications on the duration, safety and criticality of single components and of the overall system, on varying the time of use;
- indications on possible failures, and evaluations of the resulting servicing costs;

- indications on the residual life of components, evaluation of their possible reuse, and quantification of the resulting potential extension of the system's useful life;
- evaluation of the environmental impact associated with the main phases of the life cycle.

The principle difficulty consists of correlating design parameters with product performance in its life cycle after production. This requires not only a modeling of the life cycle, but also an appropriate modeling of the product, as a basis for simulating its behavior in response to different design choices.

The importance of life cycle modeling in the process of product development, in relation to the environmental impact, has already been evidenced [Zust and Caduff 1997]. Also some approaches to life cycle simulation have been outlined, with particular reference to modular products [Tomiyama et al. 1997], or in more general terms [Kato et al. 2001].

The first deals with approaches defining life cycle models according to elementary activities which aid the inventory phase of Life Cycle Assessment, in accordance with the previsions of ISO14040 standards. The second proposes simulation schemes which provide particular information on the product's environmental impact (quantifying the flow of materials discharged or translating the impact of end of life into economic terms) without detailing the correlation with the principle design parameters. Further, while introducing the temporal variable governing the simulation, these schemes rarely study in depth this concept in relation to the phenomena of performance decay, and to the consequent effect on the system's efficiency [Hata et al. 1997].

As summarized in the scheme of Fig. 1, the development of the method proposed here makes use of some tools, opportunely correlated with indices expressing the decay of performance over time:

- a model of the constructional system, based on the behavior of functional sub-groups;
- some significant functions which express the system's performance in relation to the possible strategies of improving the life cycle under examination: optimization of the useful life (through servicing operations on the system); the recovery of resources at end of life (through the reuse and recycling of components).

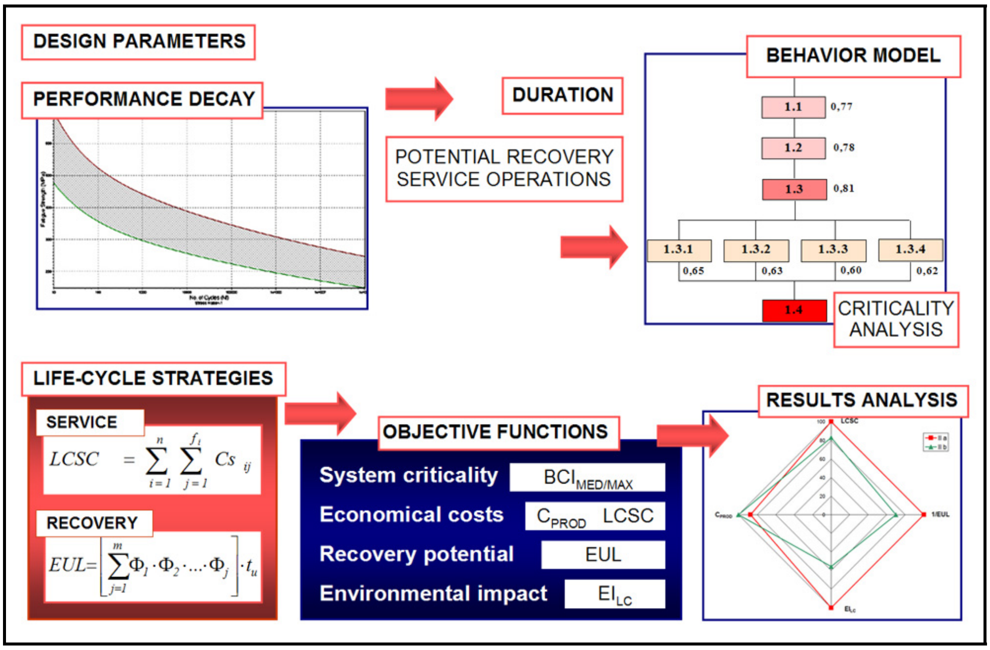

Figure 1. Methodological structure and tools

With the support of these tools it is possible to outline a simulation procedure allowing the evaluation, already in the design phase, of the product's possible behavior in the intermediate and final phases of the life cycle (use and end of life), according to the main design choices and the time of use. This behavior must be evaluated using objective functions, relevant to the aims of optimal product design. They must quantify the behavior of the product in relation to three main aspects: the level of functional efficiency and safety of the constructional system; the costs of the product in relation to the main phases of the life cycle; the environmental impact of the whole life cycle and the recovery potential of the resources used.

3. Product model and analysis tools

Again referring to the scheme in Fig. 1, we can consider in more detail the principle points.

To correlate the set of design choices and product performance, the methodological approach proposed here is based on Advanced FMEA, scheduling the development of a product behavior model based on its functioning rather than on its structure [Eubanks et al. 1997]. This is based on the definition of the principle elementary functionalities of the constructional system, on the set of determining variables required for the behavior under examination to take place (initial state) and final variables reached after the function has taken place (final state), and of the performance characteristics regulating the behavior, which can generally be expressed using mathematical models.

With regard to the evaluation of variations in the system's performance over time, in the method proposed here, this is calculated in relation to different typologies of decay phenomena: independent from load conditions (e.g. aging of the materials) and dependent on the load conditions (e.g. fatigue). Taking into consideration a defined set of materials, characterized by decay curves, it is possible to evaluate the indices which give information on the duration of components (DI) and on safety (DCF) over the life cycle. On these bases, the simulation of the system's functionalities allows the identification of possible failures and their classification in terms of their effect on components, to derive the criticality of the system through analysis of the configuration of the model (blocks in series/parallel), the danger of a failure, and the residual performance level.

This information directly influences possible strategies for improving the environmental performance of the life cycle considered here: optimization of the useful life (through servicing operations on the system) and the recovery of resources at end of life (through the reuse and recycling of components). In this regard, reference is made to the calculation models already available both for the evaluation of the economic impact of servicing systems during their useful life [Gershenson and Ishii 1993] and for the planning of recovery cycles at end of life [Giudice et al. 2003]. The indicators proposed by these models are, respectively, the life cycle service cost (LCSC) and the extension of useful life (EUL).

3.1 Model of system behavior

As mentioned above, design choices and product performance are correlated using a model of the system's behavior based on Advanced FMEA [Eubanks et al. 1997]. This model defines the principle elementary functionalities of the constructive system, the determining variables required for the behavior under examination to take place, the final state after the function has taken place and the performance conditions regulating the behavior. Fig. 2 shows the reference scheme for a system based on a principle functionality, broken down into elementary behaviors in series and in parallel.

Each elementary behavior is defined by: the components directly involved in the behavior; the mathematical models expressing the performance conditions which regulate the behaviors, generally consisting of functions linking performance conditions Pf_j to operating conditions, to fixed and variable geometric parameters and to the properties of the materials (pre-conditions); the performance limits Pf^*_j, which, compared with Pf_j, make it possible to establish whether the behavior takes place correctly (post-conditions).

3.2 Evaluation of performance deterioration

Simulating the system's behavior requires an evaluation of the variations in its behavior over time. While distinguishing between the two different typologies of decay phenomena (independent from and dependent on load conditions), it is generally possible to ascribe the phenomenon to material performance diagrams (Fig. 3) where the time variable t represents real time for the phenomena of the first type, and the real time of use for phenomena of the second type.

Once the materials making up the system have been chosen, each characterized by the corresponding decay curve, it is possible to evaluate the indices providing information on the duration of the components and on the level of safety over the time of use, and thus over the life cycle.

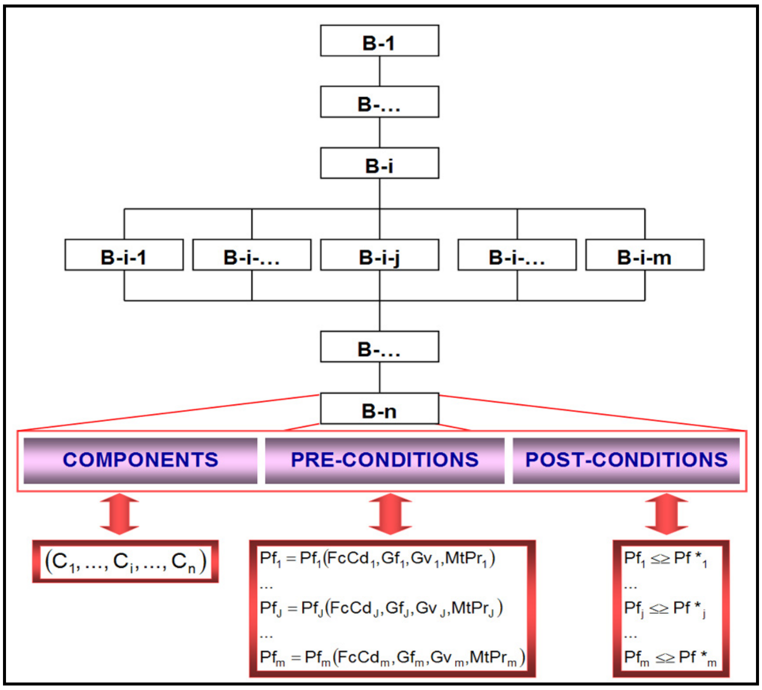

Figure 2. Model of constructional system: Reference scheme

3.2.1 Duration index

With regard to the first aspect, an index of the duration of the component DI is introduced. This is defined as the ratio between the estimated physical life of the component t_r, determined by the performance required Pf_r, and the fixed useful life t_u, which is a design requisite:

$$DI = \frac{t_r}{t_u} \tag{1}$$

Having fixed the duration of the useful life t_u, this index DI depends on t_r, i.e. both of the material, since the decay curve varies with this, and of the component geometry, which determines the working conditions and therefore the required performance Pf_r.
Its value provides indications on the component's operating conditions over the arc of the useful life and allows the quantification of both the need for servicing operations and the possibility of reusing the component. In the case where DI<1, we can anticipate the need to substitute the component f times over the entire arc of the useful life, with:

$$f = int\left(\frac{1}{DI}\right) \tag{2}$$

If 1<DI<2, the component can be used only once. In the case where DI>2, the component can be reused r times, with:

$$r = int(DI) - 1 \tag{3}$$

3.2.2 Dynamic criticality factor

Considering the variation in a component's level of safety over time, and again referring to Fig. 3, the dynamic criticality factor DCF is introduced:

$$DCF = \frac{Pf_0 - Pf}{Pf_0 - Pf_r} \tag{4}$$

where Pf_0 is the component's initial performance, Pf is that corresponding to the generic time t, and Pf_r is again the required performance.
This index quantifies the increase in the component's criticality during its use, and for $t = t_u$ expresses the criticality corresponding to the end of use (in this case the notation DCFu will be used).
If Pf_u indicates the performance level corresponding to the end of useful life, it is seen that:

- if $Pf_u > Pf_r$ then DCFu<1, therefore the component is not critical;
- if $Pf_u < Pf_r$ then DCFu>1, therefore the component is critical, and is the more critical the higher the value assumed by DCFu.

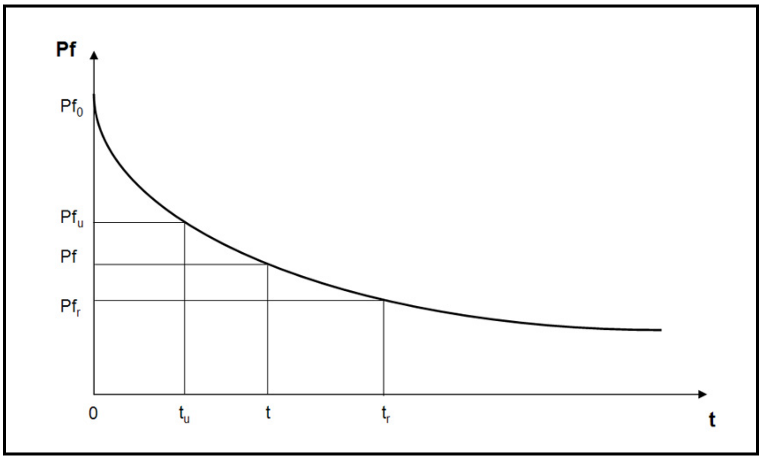

Figure 3. Decay of performance: Reference diagram

3.2.3 *Behavior criticality index*

As above, according to the system model introduced, each of the system's behaviors is determined by a set of components. Indicating the generic component correlated to the behavior with C_i, and the corresponding value of the dynamic criticality factor at end of use with $DCFu_i$, the behavior criticality index BCI is defined as:

$$BCI = c \cdot max(DCFu_i) \tag{5}$$

where $c \in [0,1]$ is a further factor expressing the criticality of the behavior under examination in relation to the functionality of the whole system (if a non-behavior results in the total arrest of the system, this must be classified with a high c factor, given the import of the failure).
The higher the value of BCI, the more critical the behavior under examination, both for the effect of its failure on the system and for the decrease in performance level, quantified by the dynamic criticality factor. The distribution of the values assumed by BCI for each behavior on varying the design parameters allows an analysis of the criticality of the system under examination.

3.3 Analysis of life cycle improvement strategies

The values assumed by the indices of performance decay introduced above directly condition the possible strategies for improving the environmental behavior of the life cycle: optimization of the useful life (through servicing operations) and recovery of resources at end of life (through component reuse and recycling). To quantify these behaviors, we propose the following mathematical reference models.

3.3.1 Life cycle service cost

The strategies for optimizing the useful life of products include interventions of diagnosis, maintenance, repair, substitution and any other operations which may be necessary to guarantee the correct functioning of the system. For an evaluation of the effect that design choices can have in terms of suitability for servicing operations, we can use mathematical models which express the life cycle service costs [Gershenson and Ishii 1993]. Given a component requiring several service operations, the cost of the j-th service operation on the i-th generic component is given by:

$$Cs_{ij} = tl_{ij} \cdot cl_{ij} + c_i \tag{6}$$

where tl_{ij} is the time of intervention, cl_{ij} the cost of the intervention per unit time and c_i the cost of the component or of the material required in the intervention.

Considering as service interventions the substitution of failed components, for a system consisting of n components C_i, the total life cycle service cost LCSC is expressed by:

$$LCSC = \sum_{i=1}^{n} \sum_{j=1}^{f_i} Cs_{ij} \tag{7}$$

where f_i is the number of substitution interventions anticipated for the j-th component, defined by (2).

3.3.2 Recovery cycles and extension of useful life

The problem of planning recovery cycles in relation to the duration of the components has already been treated by the authors [Giudice et al. 2003] where we proposed a calculation model which takes account of the environmental impact of producing the i-th component, α_i. This can be expressed in terms of the eco-indicators of the materials and processes, evaluated according to the Eco-Indicator 99 method [Goedkoop and Spriensma 2000]:

$$\alpha_i = ei_i^{mat} \cdot p_i + \sum_{s=1}^{v_i} ei_{is}^{prss} \cdot p_{is}^{prss} \tag{8}$$

where ei_i^{mat} is the unitary eco-indicator for the material constituting the i-th component, p_i the weight of the component, v_i the number of manufacturing processes in the component's production cycle, ei_{is}^{prss} the eco-indicator for the s-th manufacturing process of the production cycle per unit of the principle manufacturing parameter, and p_{is}^{prss} is the principle parameter of the s-th manufacturing process.

Considering it possible to anticipate a number of recovery cycles m, the recovery fraction which can be associated with the j-th cycle, in terms of environmental impact, can be expressed as:

$$\Phi_j = \frac{\sum_{i=1}^{n} r_{ij} \cdot \alpha_i}{\sum_{i=1}^{n} \alpha_i} \tag{9}$$

where r_{ij} is a binary coefficient, which assumes unitary value only in the case where the i-th component is reusable at the j-th cycle. This is therefore easily expressed as a function of r, the number of possible component reuses, given by (3).

Hypothesizing a constant duration of all the reuses, equal to the fixed duration of the first use t_u, the function quantifying the extension of useful life is defined as:

$$EUL = \left[\sum_{j=1}^{m} \Phi_1 \cdot \Phi_2 \cdot \ldots \cdot \Phi_j \right] \cdot t_u \tag{10}$$

This function, which expresses the extension of the life of original components within the life cycle of the product, can be considered an indicator of saving in resources, according their different environmental impact.

4. Definition of objective functions

As above, the product's behavior in the life cycle must be evaluated in relation to its functional capacities, to the economic costs and to the environmental performance. With this aim, and with reference to the mathematical models proposed so far, we propose the following objective-functions:

- a criticality index of the constructional system, identified in the mean or maximum values assumed by the BCI indices expressing, through (5), the criticality of each behaviors of the system;
- the product's costs over the life cycle, which, ignoring the costs of product retirement, can be quantified by the production and servicing costs, the latter expressed by the function LCSC (7);
- the potential extension of useful life of the resources used in the system through the recovery of components, expressed by the function EUL (10);
- the environmental impact of the life cycle, quantified by the sum of the impacts associated with the phases of production, use (servicing) and retirement.

The last function requires a further development of the mathematical models, as discussed below.

These objective-functions, evaluated for each design choice, are suitable for treatment using multi-objective analysis, with the ultimate aim of determining which solution best satisfies the entire spectrum of performances sought.

4.1 Environmental impact of life cycle

The function expressing the environmental impact of the life cycle EI_{LC} is defined as the sum of three terms, each relative to the main phases of the cycle: production, use (servicing), and end of life.

$$EI_{LC} = EI_{PROD} + EI_{SRV} + EI_{EOL} \tag{11}$$

The first term can be expressed as the sum of the environmental impacts associated with the production of the individual components α_i (8):

$$EI_{PROD} = \sum_{i=1}^{n} \left(ei_i^{mat} \cdot p_i + \sum_{s=1}^{v_i} ei_{is}^{prss} \cdot p_{is}^{prss} \right) \tag{12}$$

The environmental impact of use, assimilable to the impact associated with service operations, can be defined on the basis of the servicing costs model LCSC (7), considering that every substitution of a failed component corresponds to an environmental impact equal to that of the component's production.

$$EI_{SRV} = \sum_{i=1}^{n} \sum_{j=1}^{f_i} \left(ei_i^{mat} \cdot p_i + \sum_{s=1}^{v_i} ei_{is}^{prss} \cdot p_{is}^{prss} \right) \tag{13}$$

The last term of (11), relating to the product's end of life, is composed of three terms depending on whether, at end of life, the components are retired or recovered through the reuse or recycling:

$$EI_{EOL} = EI_{DISP} + EI_{RCL} + EI_{RS} \tag{14}$$

With reference to the parameter of reuse r expressed by (3), we introduce a further binary coefficient ρ, which assumes unitary value only in the case where r ≥ 1, otherwise it is zero.
Passing to the definition of the first term of (14), this can be expressed as follows:

$$EI_{DISP} = \sum_{i=1}^{n} EI_{DISP_i} = \sum_{i=1}^{n} ei_{DISP_i} \cdot p_i \cdot (1+f_i)\cdot(1-\xi_i)\cdot(1-\rho_i) \tag{15}$$

where ei_{DISPi} is the environmental impact of disposal per unit weight, p_i the weight of the component, ξ_i the recyclable fraction of the material forming the component, and f_i is the number of anticipated substitutions during use, expressed by (2). Analogously:

$$EI_{RCL} = \sum_{i=1}^{n} EI_{RCL_i} = \sum_{i=1}^{n} ei_{RCL_i} \cdot p_i \cdot (1+f_i)\cdot(\xi_i)\cdot(1-\rho_i) \tag{16}$$

where ei_{RCLi} is the environmental impact of the recycling process per unit weight and the other terms are as defined above.
The two expressions (15) and (16) are not zero only for components which cannot be reused (ρ_i=0).
The last term of (14) refers to the environmental impact at the end of life, due only to reusable components (ρ_i=1), and is expressed by:

$$EI_{RS} = \sum_{i=1}^{n} EI_{RS_i} = \sum_{i=1}^{n} (-\alpha_i)\cdot r_i \cdot \rho_i \tag{17}$$

where again α_i is expressed by (8) and r_i by (3). This term, therefore, expresses a recovery of environmental impact, as the sum of production impacts associated with reusable components.
Again, all the eco-indicators considered are evaluated according to the Eco-Indicator 99 method.

5. Simulation and analysis of results

The simulation procedure follows the development of the models proposed and it's summarized in Fig. 1. As intended, it is based on a direct relation between the design parameters, which constitute the variables to be optimized, and the objective-functions (Section 4) which quantify the product's performance in the main phases of the life cycle. This relation is structured using the behavior model of the system (Section 3.1), and is expressed analytically using the indicators of component duration and failure derived from the deterioration of performance over time (Section 3.2).
To illustrate the application of the methodology, we present a summary of the results obtained on a mechanical system, a 4 speed gear box (Fig. 4).

5.1 Behavior model of system

From an analysis of the machine's operation, it is possible to define the system model which, in this case, is very simple and can be reduced to elementary behaviors, largely in series. Only one behavior, that representing the transmission of torque according to the gear engaged, breaks down into four sub-behaviors in parallel, corresponding to each gear.
The scheme of the model is partially represented in Fig. 5, evidencing the information associated with the behavior 1.1 (transmission of the torque from the motor shaft to the clutch): the components involved, the mathematical models expressing the required functionality (in this case the structural strength), and the verification of the final state of the behavior.

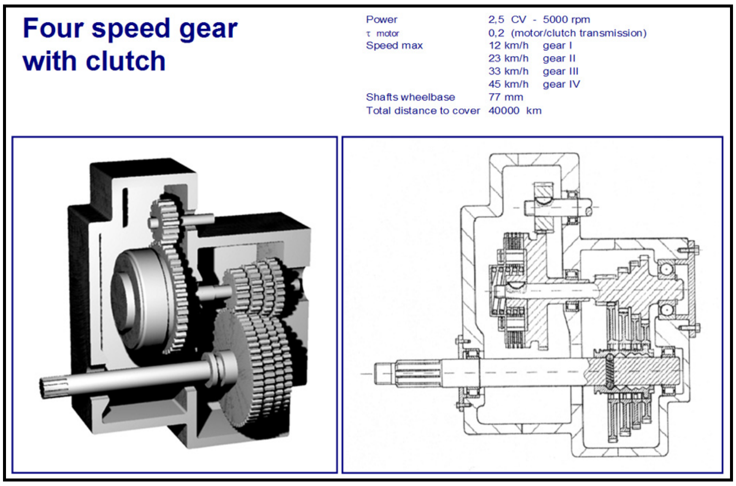

Figure 4. Case study: Gear box

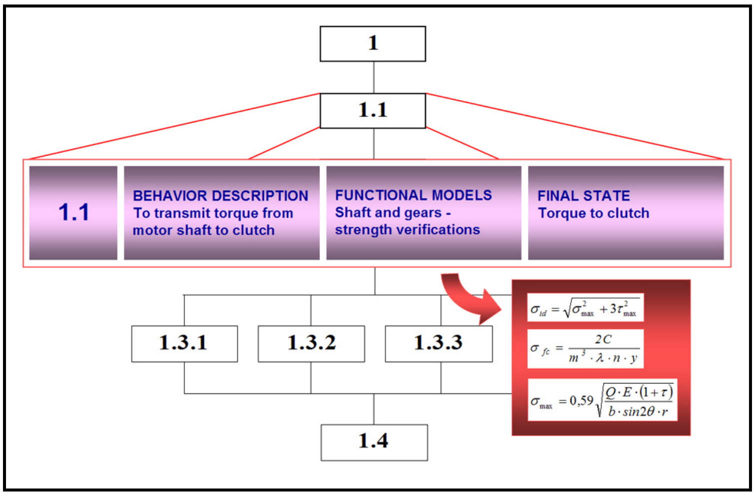

Figure 5. Model of system behavior

5.2 Performance evaluations and analysis of criticality

Having developed the behavior model, the analysis continues with the simulation of the functional performance of individual components over the life cycle of the system.

On the basis of the design requirements (summarized in Fig. 4), on varying the design choices (in particular materials and geometric parameters), it is possible to determine the loading conditions of each component and its required duration. In this regard it is necessary to consider some details. The components making up the system are subjected to fatigue loading. The gear box is destined for a motor vehicle and if the number of kilometers the vehicle is expected to travel is set as a design datum (vehicle mission), it is possible to determine the number of loading cycles of each component. In this case, therefore, all the time variables t introduced above (Section 3.2) are to be understood as loading cycles, and the decay of performance is expressed by the resistance to fatigue curves of the materials.

Table 1 presents some evaluations for a first design alternative I, defined by the choice of materials and the specification of geometric parameters.

For each component, the table gives: the chosen material; the number of expected loading cycles t_u related to the fixed mission; the required performance level Pf_r (mechanical strength in MPa); the number of loading cycles t_r guaranteed by the chosen material, in relation to Pf_r (t_r assumes a value of infinity when Pf_r is below the fatigue limit of the material). The same table then shows the corresponding values assumed by the indicators introduced in Section 3.2. In particular, when the duration index DI (1) assumes a value of infinity, r assumes 2 as conventional maximum number of possible reuses. Moreover, given that in this first design alternative the motor shaft is considered a single piece with the corresponding 4 gear wheels, all five components assume a value of the number of expected substitutions f equal to the maximum value assumed by each single component (reported in brackets), and a value of r equal to the minimum.

Table 1. Design alternative I

	material	t_u	Pf_r (σ_{fc})	t_r	DI	f	r	DCFu
motor shaft	AISI 1015	8,59E+08	49,2	infinite	**infinite**	**0**	**2**	**0,77**
clutch box	AISI 1015	1,72E+08	110,9	infinite	**infinite**	**0**	**2**	**0,91**
motor gear	AISI 1030	8,59E+08	153,5	infinite	**infinite**	**0**	**2**	**0,96**
clutch spring	AISI 1080	3,20E+06	345,1	3,12E+06	**0,98**	**1**	**0**	**1,01**
primary shaft	AISI 1015	1,72E+08	115,1	infinite	**infinite**	**(0) 5**	**(2) 0**	**0,90**
gear 1 - primary shaft	AISI 1015	1,72E+08	160,2	3,23E+07	**0,19**	**(5) 5**	**(0) 0**	**1,03**
gear 1 - secondary shaft	AISI 1030	3,54E+07	195,7	1,23E+07	**0,35**	**2**	**0**	**1,05**
gear 2 - primary shaft	AISI 1015	1,72E+08	161,9	3,20E+07	**0,19**	**(5) 5**	**(0) 0**	**1,04**
gear 2 - secondary shaft	AISI 1030	3,54E+07	182,8	3,11E+07	**0,88**	**1**	**0**	**1,01**
gear 3 - primary shaft	AISI 1015	1,72E+08	156,9	6,15E+07	**0,36**	**(2) 5**	**(0) 0**	**1,02**
gear 3 - secondary shaft	AISI 1030	3,54E+07	203,9	5,30E+06	**0,15**	**6**	**0**	**1,07**
gear 4 - primary shaft	AISI 1015	1,72E+08	134,9	infinite	**infinite**	**(0) 5**	**(2) 0**	**0,96**
gear 4 - secondary shaft	AISI 1015	3,54E+07	144,5	1,00E+08	**2,83**	**0**	**1**	**0,96**
secondary shaft	AISI 1015	3,54E+07	149,9	1,00E+08	**2,83**	**0**	**1**	**0,98**
inner spring	AISI 1080	3,20E+06	363,1	1,07E+06	**0,33**	**2**	**0**	**1,04**
mesh mechanism	AISI 1015	8,85E+06	188,6	1,87E+06	**0,21**	**4**	**0**	**1,06**

On the basis of the values assumed by the factor DCFu for each component, it is then possible to analyze the distribution of the criticality index of the behaviors BCI, evaluating their maximum value (indicating the most critical behavior) and estimating the mean criticality of the entire system (for design alternative I, mean BCI is equal to 0,80).

5.3 First analysis of the behavior in life cycle

Again referring to Table 1, from the values assumed by f and r, it is possible to predict the system’s poor performance, both in terms of the use phase (high number of component failures and substitutions) and the end of life phase (little possibility of component reuse). This is confirmed by the values assumed by the functions LCSC and EUL introduced in Section 3.3, and evidenced by comparison with design alternative IIa, which predicts better values for f and r, and for the mean BCI also (0,78), while production costs remain substantially the same. This is principally due to a better choice of materials.

The values assumed by LCSC and EUL are further improved in design alternative IIb. This design differs from IIa only in that the motor shaft and gears are no longer considered a single unit, but able to be disassembled (this modification does not result in variations in the behavior model and criticality of the system). In this case, the failure of a single gear does not require the substitution of the whole shaft-gear unit (improving LCSC), nor does it limit the possibility of reusing other components of the unit (improving EUL). The modification does, however, lead to an increase in the production cost.

All these results are summarized in Fig. 6, where the values of the functions under examination have been normalized (reciprocal of EUL is considered to have to minimize all the functions).

5.4 Analysis of the environmental impact of life cycle

Finally, it is possible to evaluate the environmental impact of the entire life cycle EI_{LC} for the more interesting design alternatives IIa and IIb, using the mathematical models introduced in Section 4.1. Also in terms of this objective-function, alternative IIb is better than IIa (-44%), paralleled by a limited increase in production cost (+15%), as evidenced in Fig. 7 (EI_{LC} is expressed in mPt, according to Eco-Indicator 99 method).

Finally, the radar diagram of Fig. 8 gives an overview of the effectiveness of the two design alternatives considered, in terms of the four most significant objective-functions (to be minimized): production cost, servicing costs, the reciprocal of extension of useful life and environmental impact of the life cycle.

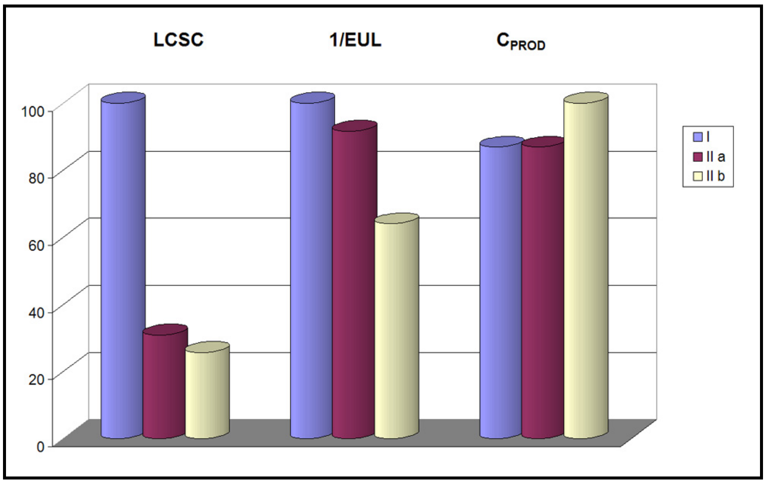

Figure 6. Comparison between design alternatives I, IIa and IIb

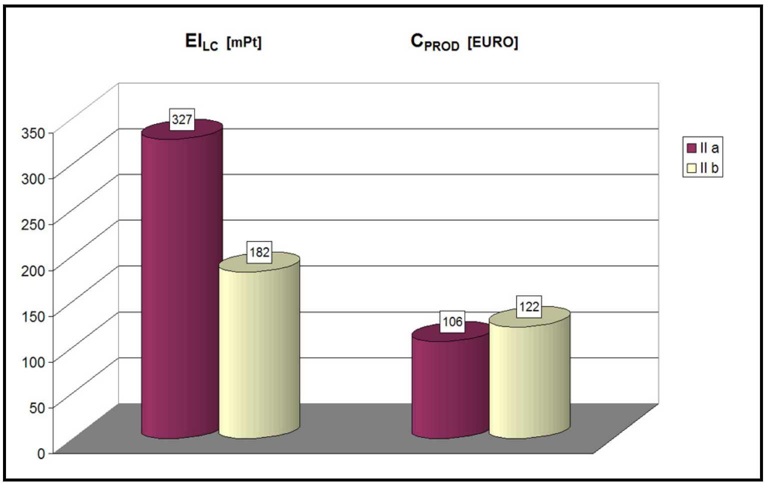

Figure 7. Comparison between design alternatives IIa and IIb

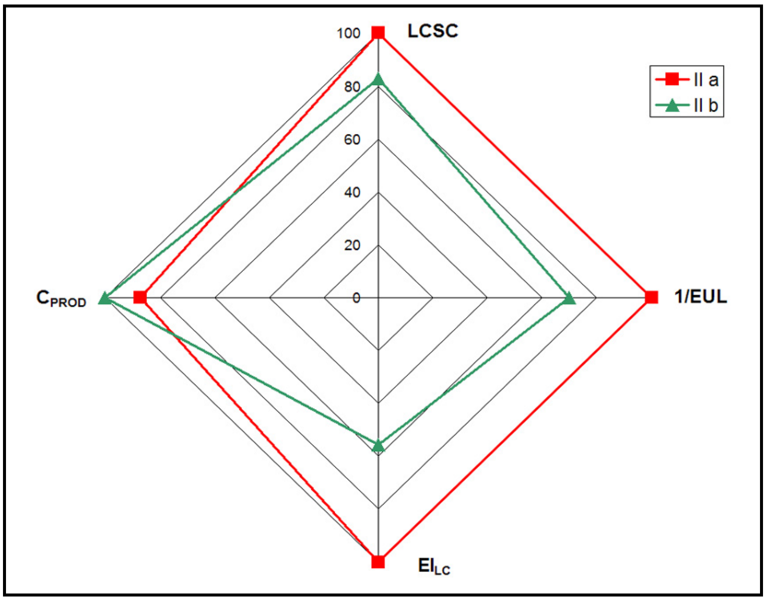

Figure 8. Comparison between design alternatives IIa and IIb: Radar diagram

6. Conclusions

Operating in the context of Life Cycle Design, it is necessary to define analytical procedures and tools aiding design and allowing the management of design choices (both at the level of product layout and at that of the specifications of single components) in relation to the conventional (functionality, safety, cost) and environmental performances of the product over its whole life cycle.

In the method proposed, the direct relation between design choices and final performance is obtained through a behavior model of the product. The proposed model allows the simulation of the life cycle in terms of phenomena of decay in performance of the materials (due to external factors or loading conditions). As shown by the case study reported, the simulation method and analytical tools can be applied to obtain, for each design alternative examined: indications on the duration, safety and criticality of single components and of the overall system, on varying the time of use; indications on possible expected failures and evaluations of the resulting servicing costs associated with the life cycle; indications on the residual life of components, evaluations of their possible reuse, and quantification of the resulting extension of the system's useful life; evaluations of the environmental impact associated with the principle phases of the life cycle, from production to retirement.

Analyzing this broad spectrum of information, evaluated for each design alternative, it is possible to determine, already in the design phase, which solution can best satisfy the required performance over the life cycle of a product.

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