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COMPARISON OF ENVIRONMENTAL CHARACTERISTICS OF FUNCTIONALLY EQUIVALENT DEVICES BY WEIGHTED PRODUCT METHOD

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1. Introduction

The problem of designing eco-friendly devices has become one of the most relevant issue for engineering and all scientific disciplines that deal with environmental aspects must contribute to aid designers to find the best solution to problems.

Each industrial device generates an environmental impact, which may be large or small and that requires to be quantified. A challenging target may consist in the assessing devices with the aim to select and use products that are as sustainable as possible (in terms of material employed, energy resources spent, recyclability, etc.) and that, simultaneously, are able to perform correctly the function for which they were designed for, do not forgetting to remain attractive.

The assessment can be performed comparing some sustainability indicators. The process can be pursued comparing the environmental performance of similar products, and so reducing the efforts connected to a full Life Cycle Assessment, that necessarily must be made ex-post, when the product is at least in the prototypal phase, even if the process can be also activated when designers are working in the embodiment design phase.

In any case, the analysis of a group of functionally equivalent devices can be based on the evaluation of several environmental performance indicators (EPIs) that have been subscribed among all stakeholders involved in the search for a sustainable solution.

Strictly related to the elaboration of EPIs, Multi Criteria Decision Making (MCDM) techniques can be used for the purpose to select the best solution.

The paper proposes to employ, among MCDM techniques, the Weighted Product Method (WPM) in order to compare the environmental impacts of several functionally equivalent products. The technique performs a pairwise comparison of all devices, in term of a certain number of environment performance indicators. Since each EPI enhances one environment aspect and each one has a proper unit of measure, it has been necessary to use a method able to compare different solutions on the basis of a-dimensional terms. WPM was chosen for its intrinsic simplicity of use, for the elementary operations involved, and its easy interpretation, also by people, not necessarily skilled in operational research methods.

In the same time, as drawback, WPM has certain rigidity, because it admits that all selection criteria must be selected and implemented in strict relation to the global solution that must be found. For our purpose, if we consider to find the solution as “lower is better”, in term of environmental impact, all the indicators must follow the same law.

The methodology is structured as follows: a set of functionally equivalent products are disassembled in their basic components and each element is assessed on the basis of a set of environmental indicators used to describe its life cycle in a simplified manner. Then, partial results from components appraisals are aggregated for each device to obtain an overall impact index for each product. At this point, a pairwise comparison among devices has to be made in order to select the best one in terms of minimum environmental impact. A graph of comparisons is drawn to organize the couples of design solutions to be compared, a vector of weights is selected (according to the will of designers or project constraints) and WPM assessment can be run. The entire methodology is applied to a case study.

2. Literature review

The issue of products assessment has had a wide literature during the last decades, mainly based on LCA methodology, that calculate impacts and return a product benchmarking according to some impact categories such as: Global Warming Potential, Ozone Depletion, Eutrophication, Acidification, Ecotoxicity, Photochemical Smog, etc. Typically, the comparison is displayed by means of a column chart where designer can evaluate a device, but a single best product solution may be difficult to be determined [Finnveden et al. 2009].

Since the introduction of ISO 14031 [ISO 14031 1999], the attention to sustainability moved toward a more deep involvement of all organization from “company, firm, enterprise” till “authority or institution” to perform an environmental performance evaluation.

Hermann [Hermann et al. 2006], integrates three methodologies such as Life Cycle Assessment, Multi Criteria Analysis and Environmental Performance Indicators to select the correct alternative for one industrial production.

The MCDM techniques [Triantaphillou et al. 1998] are frequently used in several fields such as: Computer Science, Management, Decision Science, Engineering and, in the latest years, also in Design problems, for the assessment of the product environmental performance. Pohekar and Ramachandran [Pohekar and Ramachandran 2004] have reviewed the MCDM techniques: WSM (Weighted Sum Method), WPM (Weighted Product Method), AHP (Analytical Hierarchy Process), PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation), ELECTRE (Elimination and Choice Translating Reality), TOPSIS (Technique for Order Preference by Similarity to Ideal Solutions), CP (Compromise Programming), MAUT (Multi-Attribute Utility Theory). They have reviewed the techniques that can be applied to sustainable energy planning, adding to the previous also the Multi-objective optimization and Decision Support System (DSS).

Further refinement is introduced by Gao [Gao et al. 2010], where the selection of a green product design scheme was done by using the fuzzy TOPSIS.

More on sustainability, MCDM techniques are applied to select the best alternative for demolition and waste management [Roussat et al. 2009]. In this case, alternatives are represented by different waste treatment strategies that are compared on some criteria related to sustainability and economics. The employed approach is the so called ELECTRE III.

Recently, exergy has been proposed as the unique environmental metric for sustainability. Duflou [Duflou et al. 2011] and Coatanéa [Coatanéa et al. 2007] have proposed the use of exergy for the environmental assessment of the manufacturing phase, for which several data can be obtained, or extrapolated, from consolidated and efficient databases.

3. Evaluating products on the basis of environmental performance indicators

Following the approach underlined on the ISO 14031, a policy about sustainability can produce better results if a wider set of stakeholders is involved in the process. As basic point for product evaluation based on environmental impacts, it is necessary to identify a set of parameters that characterize a product and describe it in terms of its lifecycle. According to this approach a set of strategic Environmental Performance Indicators (EPIs) must be considered [Dewulf and Duflou 2003]. The EPIs must be selected with a certain degree of awareness. They must be in strict relation with the phases of life cycle, they must be measurable, and it should be possible to accumulate EPI scores of subsystem to an overall product EPI score. The EPIs chosen should not be extremely numerous, because their main task is to create a common humus on which a circular discussion can be continuously activated on their relevance and verification.

In this approach a set of seven EPIs has been used:

1. Mass (M). It indicates the quantity of material employed. It is present as a component specification or it can be determined when a component has been designed, as a cad model, computing the volume and specifying density (kg, g, etc.);
2. Presence of Hazardous Substances (HS). It represents the quantity of toxic substances present in the component (kg, g, etc.);
3. Global Warming Potential (GWP) of the component. It indicates how much GHGs (Green House Gases) contribute to global warming due to the construction process of a product part. In practice, it is measured in kilograms of CO_{2eq} by a LCA tool, where material and process, at least, have to be specified;
4. Impact index in Manufacturing phase (IM). It measures the impact produced during component construction approximately. It is expressed in mPts (millipoints);
5. Transport index (TR). It measures the distance (in km) from supply sources of a component in case it is provided by a vendor, otherwise it is the distance from supply sources of raw materials that have to be worked;
6. Energy index in Use phase (EU). It indicates the maximum energy consumption and it is provided by constructors. Generally, it is measured in Wh, kWh, kJ, etc);
7. Lack of Recyclability (LR). It is the quantity of not recyclable materials and it is calculated as a quantity (in kg, or g., or as a ratio: the weight of not recyclable materials divided by the total weight of the component).

These indicators are quite common in environmental evaluation. Although some of them are present in different eco-design methodologies, they were used jointly in this context in order to check these EPIs in a lifecycle perspective. Mass indicator (M) and the presence of (HS) are related to Raw Material stage; Global Warming Potential (GWP) and the Impact in Manufacturing phase (IM) are related to Production stage. Transport Index (TR), Energy index in Use phase (EU) and Lack of Recyclability (LR) are directly associable to Transport, Use and Disposal stages.

The information related to the seven EPIs must be given to perform the assessment. Table 1 provides a synoptic description of the indicators with two possible scenarios: in case components were originally designed by teamwork or when the components (in itself or as equivalent part) are already present on the market. Further in the table, the units of measure in which the impacts are assigned and some sources where indicators can be found, are suggested.

Table 1. Environmental performance indicators that characterize each product component

EPI	Component Type	Scenario	Unit	Source
Mass (M)	Designed Component	Calculated as CAD Model Volume *Density (of material employed)	kg; g	Designer
	Equivalent Component	Mass of the component	kg; g	Technical Sheet
Hazardous Substances (HS)	Designed Component	Designers choose materials and/or manufacturing cycles. HS may be employed and fixed quantities are allowed	kg; g	Check on RoHS tables [Directive 2002/95/EC, 2003]
	Equivalent Component	Designers estimate materials, cycles and HS	kg; g	Technical Sheet
Global Warming	Designed Component	Designers selected materials, processes and substances	kg CO_{2eq}	- LCA tool - IPCC 2007

Potentials (GWP)	Equivalent Component	Starting from technical sheet, designers go back to the impacts	kg CO_{2eq}	- Gabi Database - other LCA tool - IPCC 2007 [Pachauri and Reisinger 2007]
Impact in Manufacturing phase (IM)	Designed Component	When materials and manufacturing cycles are selected, IM indicates impact for production. Material quantity is multiplied by the indicator in tables "Production" and "Processes" on EI '99	mPts	ECO INDICATOR '99 (EI '99) Database [Goedkoop and Spriensma 2001]
	Equivalent Component	Physical characteristics of component are analyzed	mPts	ECO INDICATOR '99 (EI '99) Database
Transport (TR)	Designed Component	Distance from procurement source of Raw Material	km	Vendor
	Equivalent Component	Distance from procurement source of component	km	Vendor
Energy in Use phase (EU)	Designed Component	Maximum Power	kWh; Wh; kJ	Designer
	Equivalent Component	Maximum Power	kWh; Wh; kJ	Technical sheet
Lack of Recyclability (LR)	Designed Component	Designers estimate how much material may not be recycled	kg; g or number	Designer
	Equivalent Component	Designers estimate how much material can not be recycled	kg; g or number	Material Technical Sheet

4. Comparing functionally equivalent products

Suppose to have a group of *m* design solutions that perform the same main function and that stakeholders must carry out an environmental evaluation on these functionally equivalent products in order to choose the device with the minimum environmental impact. At this point, in the analysis such discordance among different *m* solutions may be ascertained, that the selection of the best product alternative may be difficult to be identified, because one product architecture may present low environmental impacts according to some EPIs, and a second solution may be excellent in terms of other indicators. This situation of uncertainty is very common when multi-dimensional comparisons are carried out and it could be considered a critical activity. For this reason it is useful to perform the analysis by a MCDM technique. This approach is suitable when the task to compare products is characterized by:

- more alternatives available for a decision maker;
- multiple decision criteria that, in general, may be in conflict with each other;
- criteria characterized by different and incommensurable units;
- weights of importance assigned to criteria.

4.1 WPM applied to eco-design problems

The approach employed to assess functionally equivalent products and to solve cases of assessment uncertainty is the Weighted Product Method (WPM), which seems to be a suitable way to compare different products on the basis of multiple criteria. Its application, in fact, offers benefits in term of low computation compared to more complex methods MCDM, the employment of little number of criteria (there is no need to arrange them hierarchically such as in the AHP) and it allows technicians to compare products characterized by indicators which can assume different values, and are characterized by different units.

As the objective of the comparison is the selection of the device characterized by the minimum environmental impact, the WPM technique is proposed to rank the design alternatives and choose that with the least one.

The designer (or teamwork), at this point, takes in consideration *m* design solutions S_j (j = 1,.., m); each solution S_j is characterized by an array of EPIs composed of seven components called $\mathbf{D_j}$, where $\mathbf{D}_j = [d_1,.., d_h,.., d_7]$; each term d_h contained in $\mathbf{D_j}$ is the cumulated value that each single "h" EPI has in the solution S_j and it is calculated as follows:

$$d_h = \sum_{i=1}^{n_j} I_{ih} \tag{1}$$

where n_j *represents the number of components of the solution* S_j *and* $\mathbf{I}_i = [I_{i1},.., I_{ih},.., I_{i7}]$ (with h = 1,…,7) is the array *where the* seven *EPIs related to each component* i *of solution* S_j *are stored.*

According to the purpose to compare different alternatives, in the general WPM formulation all arrays $\mathbf{D_j}$ can be grouped in a 2-dimensional array $\mathbf{D_{jh}}$ where each single term d_{jh} represents the cumulated value of h-th EPI evaluated in the S_j design solution.

All solutions are pairwise compared. Each solutions couple (S_k, S_l) is compared by evaluating the ratio:

$$P(S_k/S_l) = \prod_{h=1}^{7} (d_{kh}/d_{lh})^{w_h} \tag{2}$$

where *w* is the array of weights associated to the indicators and w_h is the weight associated to the h-th indicator.

Generally, a result can be equal, greater or less than 1, but the situation where $P(S_k/S_l) < 1$ makes the alternative *k* more preferable than *l* in our context, because the global solution follow a law like "lower is better". Each design solution is compared with the others multiplying a sequence of ratios, one for each decision criterion. Each ratio is raised to power on the basis of the weight that the designer has given to the corresponding criterion in the vector *w*.

If *m* alternatives have to be compared, the process of analysis will forecast that the number of couples C that has to be matched is:

$$C = m*(m-1)/2 \tag{3}$$

The formulation above (3) [Biggs et al. 1986], moreover, allows us to state that C is the minimum number of couples to be compared by means of the WPM. This result is true, in fact, if we represent *m* alternatives in a graph G, C is the number of arcs that makes G a complete directed graph.

For example, in the case of four design alternatives (*m* = 4) designers can generate the sequence of six comparisons C = 6 (1-2, 1-3, 1-4, 2-3, 2-4, 3-4) quite easily, but all permutations are allowed. The result from comparison of each couple has to be analyzed and stored to determine the best solution. At the end, the alternatives are sorted from the best to the worst, according to the partial results obtained. The best solution characterized by the minimum impact will be selected. In any case must be considered that formula (2) presents some characteristics:

- It allows designers to solve uncertainty through a dimensionless problem, thanks to the ratios of the same criterions evaluated on two different alternatives;
- It has to be used after designer has defined that all criteria are costs or benefits, exclusively. In our context all the EPIs are cost types, then, the rule "lower is better" is adopted;
- Finally, it gives the possibility to assign different weights w_h to each indicator, then, designers may prefer more a criterion than another, increasing or decreasing its value.

4.2 Exceptions in WPM assessment

In order to carry out WPM analysis correctly, some problems of failure have to be considered. As the element $P(S_k/S_l)$ is the result of a multiplication of ratios, the presence of a performance d_{jh} equal to zero has to be managed carefully, according to the strategy proposed in this section. Obviously, no problems of failure are present if the relation (4) is verified, after EPIs have been cumulated for each device:

$$d_{jh} \neq 0 \quad \text{for } h = 1, \ldots, 7, \text{for all } S_j \tag{4}$$

In case of the presence of some $d_{jh} = 0$ during the confrontation of two design alternatives S_k and S_l, designers must avoid that these situations of inconsistency occur:

a) A ratio where the term $d_{kh} = 0$ and the term $d_{lh} \neq 0$, so $(d_{kh}/d_{lh}) = 0$;
b) A ratio where the term $d_{kh} \neq 0$ and the term $d_{lh} = 0$, so $(d_{kh}/d_{lh}) = \infty$;
c) A ratio where both terms $d_{kh} = 0$ and $d_{lh} = 0$, so $(d_{kh}/d_{lh}) = (0/0)$ = Not determined!

Every time such a situation occurs, the ratio, related to the h-th indicator equal to zero, must not be included in the WPM assessment, otherwise equation (2) fails.

In any case must be underlined that if one indicator has zero values ($d_{jh} = 0$) in solution S_j, this means that the associated EPI is not present and this has an intrinsic relevance when environmental comparison is carried out: solution S_j has reached the lowest value for h-th indicator.

When $d_{jh} = 0$, designers must, however, integrate the assessment as follows, because a set of cases may occur. In cases a) and b):

1) a product alternative S_k owns one or more $d_{jh} = 0$, whereas another S_l verifies the equation (4) and confrontation is won by S_k;
2) a product alternative S_k owns one or more $d_{jh} = 0$, whereas another S_l verifies the equation (4) and confrontation is won by S_l;
3) both product alternatives S_k and S_l have one or more indicators equal to zero, but they are related to different indicators.

In the case 1), it is possible to state that S_k is preferable to S_l; in the cases 2) and 3), designers have to decide about the best alternative according to the relevance of the performance related to that indicator not included in the WPM.

In the case c) both design solutions present a 0 related to the same indicator, so the ratio must not be considered when WPM is run and the result will depend only on the result given by the term $P(S_k/S_l)$.

5. A case study: Clothes pegs

A test case is proposed to provide an example of environmental assessment by means of WPM. The method is applied to compare the environmental impacts of five clothes pegs, which perform the same main function (to hold clothes on a wire during drying), although they have different architectures, materials and proper characteristics. All the products were disassembled in their basic components and analysed. In Figure 1 the analyzed devices are showed.

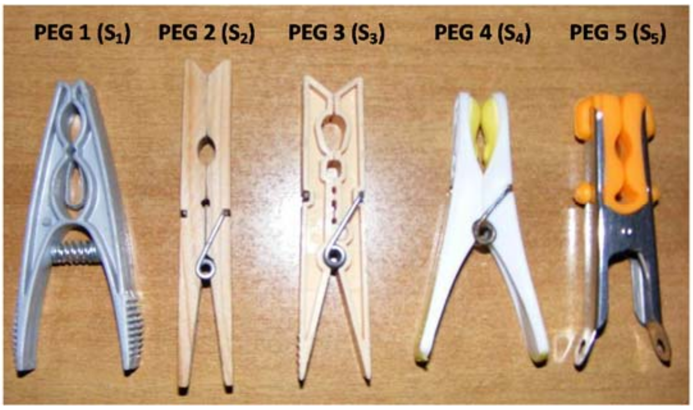

Figure 1. The group of clothes pegs considered in the case of study

In Table 2, solution S_3 is disassembled as example. The I_{ih} values of environmental performance indicators have been calculated for each component, specifying also the quantities, the materials and the manufacturing processes used and the cumulated indicator $\mathbf{D_j}$ for whole solution S_j, obtained by applying the equation (1). The analysis was carried out for all the four pegs.

The vector of cumulated values for solution S_3 is $\mathbf{D_3}$ = [9.6, 0, 0.026, 2.681, 0, 30, 0.96]. The sum of impacts $\mathbf{D_j}$ for each other peg (S_1, S_2, S_3, S_4, S_5) is displayed in Table 3.

By observing the five one dimensional arrays $\mathbf{D_j}$ it is not possible to select the best device in terms of environmental performance, so the WPM can be applied. The teamwork must decide the weights, stored in vector *w*, to be assigned to each criterion, on the basis of design constraints (or strategies). In this particular case study, *w* is composed as follows: *w* = [0.1, 0.1, 0.2, 0.25, 0.05, 0.1, 0.2].

It must be underlined that the weight associated to an indicator has the task to control the value of the ratio between two solution in relation to that indicator. Higher weights amplify the ratio, lower weights damp the ratio. In any case the sum of the weights is equal to 1.

Table 2. Analysis of PEG 3 (S_3)

	Component	Quantity	Material	Main Processes	I_{ih} (EPI)						
					M (g)	HS (g)	GWP (kg CO_{2eq})	IM (mPts)	EU (Wh)	TR (km)	LR (g)
S_3	1 (Base 1)	1	Polyethilene	Injection Moulding	3.5	0	0.007	1.229	0	10	0.4
	2 (Base 2)	1	Polyethilene	Injection Moulding	3.5	0	0.007	1.2285	0	10	0.4
	3 (Spring)	1	Steel	Cold drawing and Bending	2.6	0	0,012	0.2236	0	20	0.16
D_3	-	3	-	-	9.6	0	0,026	2.6806	0	30*	0.96

* in case of two or more components have the same source, kilometres of transport are considered for only one item.

Table 3. Array D_{jh} of aggregated indicators for all design alternatives S_j

	M	HS	GWP	IM	EU	TR	LR
S_1	8.0	0	0.026	3.770	0	50	0.80
S_2	8.8	0	0.023	0.437	0	60	0.09
S_3	9.6	0	0.026	2.680	0	30	0.96
S_4	10.2	0	0.026	3.024	0	220	1.02
S_5	25.5	0	0.145	3.810	0	120	2.55

It must be underlined that the weight associated to an indicator has the task to control the value of the ratio between two solution in relation to that indicator. Higher weights amplify the ratio, lower weights damp the ratio. In any case the sum of the weights is equal to 1.

During the analysis, in all pegs, not relevant data about hazardous substances (HS) were detected and no energy in use phase (EU) can be considered. The number of products is $m = 5$, then, the number of comparisons is C = 5*(5-1)/2 = 10.

Figure 2 shows the graph of comparisons that designers can draw in order to organize the comparisons for this specific case study. The nodes are represented by the five design alternatives (S_1, S_2, S_3, S_4, S_5), whereas the arcs represent the comparisons to be made.

According to the graph in Figure 2, it is possible to start the comparisons among the design solutions with the couple S_1/S_2. An example of WPM computation is displayed below to show how the mathematical model works. Hence, applying eq. (2) and considering that the second and the fifth indicators are null, these indicators must be omitted from the computation, and the comparison gives:

$$P(S_1/S_2) = (8.0/8.8)^{0.1} \times (0.026/0.023)^{0.2} \times (3.770/0.437)^{0.25} \times (50/60)^{0.1} \times (0.80/0.09)^{0.2} = 2.651$$

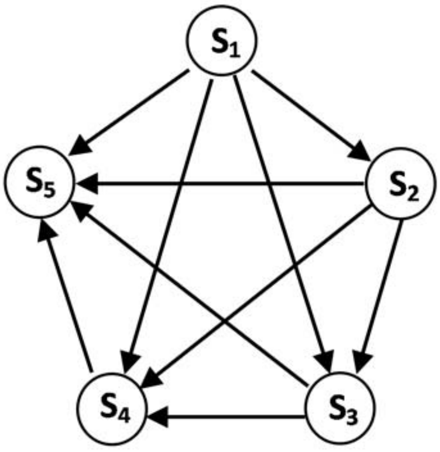

Figure 2. Comparison graph for the five clothes pegs

The remaining nine comparisons are carried out and results obtained are shown in Table 4.

Table 4. Results by WPM among the all ten comparisons

Comparison	Value	Result	Comparison	Value	Result
$P(S_1/S_2)$	2.651	S_2	$P(S_2/S_4)$	0.318	S_2
$P(S_1/S_3)$	1.085	S_3	$P(S_2/S_5)$	0.172	S_2
$P(S_1/S_4)$	0.844	S_1	$P(S_3/S_4)$	0.778	S_3
$P(S_1/S_5)$	0.458	S_1	$P(S_3/S_5)$	0.421	S_3
$P(S_2/S_3)$	0.409	S_2	$P(S_4/S_5)$	0.542	S_4

The results obtained by WPM show that $S_2 < S_3 < S_1 < S_4 < S_5$ (where "<" stands for "better than", being the law "lower is better"), so S_2 is the most preferable peg in term of environmental impacts, because it wins the highest number of comparisons (four, respect to all the other solutions). Examining the columns of values in Table 4 it is possible to observe that if two design solutions are similar the result of eq. (2) is near to 1 (as in the case of $P(S_1/S_3)$ or $P(S_1/S_4)$) or the solutions are very different each other, and the result of eq. (2) is much higher or lower then 1 (as in all other cases).

More insights can be pursued, performing a quantitative analysis of the results. At this moment it is known only the ranking of solutions, but not the difference among the environmental performances. Computing the mean value of all the comparison, performed by each solution, it is possible to evaluate how remarkable is the victory, by means of the following equation:

$$\overline{P}_j = \frac{1}{m-1}\sum_{\substack{i=1 \\ i\neq j}}^{m} P(S_j/S_i), \quad \forall\, j=1,\dots,m \qquad (5)$$

Table 5. Number of victories and mean values of comparisons for each solution S_j

	S_2	S_3	S_1	S_4	S_5
Victories	4	3	2	1	0
Mean Value of Comparisons	0.319	1.141	1.260	1.539	3.054

Solution S_2 is near 4 time better than S_3, the immediate follower. The worst is S5 with the highest mean value.

6. Conclusions

The paper has discussed the possibility to perform a sustainability benchmark among different solutions, related to functionally equivalent devices, by means of the Weighted Product Method on the basis of seven Environmental Performance Indicators. Among the Multi Criteria Decision Making techniques, WPM has been employed taking advantage of its simplicity and low efforts of computation.

The general organization of the procedure has been presented, discussing the main steps of the methodology that designers have to follow. It has been applied to a case study. The assignment of the weights has been suggested as a liberal choice of the design team, a specific subsection was dedicated to the exceptions during the WPM run and a strategy has been described in order to guarantee that the assessment can be performed in any case.

In future works, the WPM will be integrated into a global procedure able to consider the whole product life cycle, in which not only the environmental aspects of components are considered, but also the product performance in terms of flows of energy and material, during product operation.

The method proposed in this paper will be used in order to solve the uncertainty in the selection among alternative design solutions, in a more complete procedure to assess sustainability. The final task of this procedure will be to employ it since the early phases of product development, when concepts must be compared, even if the evaluation cannot be other than almost rough.

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