# The Use of DfE Rules During the Conceptual Design Phase of a Product to Give a Quantitative Environmental Evaluation to Designers

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**Abstract**
In order to help designers to understand and translate the environmental constraints into effective actions, methods and tools have to be developed to enable the generation of more environmentally benign design alternatives according to Design for Environment rules. This article explains how to use DfE rules earlier during the conceptual design phase, when the designers don't have simple qualitative tools or methods to evaluate their products. Two main actions have been realised: 1) to identify which kind of rules can be applied when designers only have a functional representation of their product 2). To create the necessary indicators to evaluate these rules depending on designers choices.

**Keywords**:
Environment, Conceptual design phase, DfE rules, quantitative environmental evaluation

## 1 INTRODUCTION

Product design decisions have significant impact on the environment all along the product life cycle. The main actor in these decisions is the designer which can make significant improvement to the product environmental impact by considering design for environment (DfE) rules during the design process. These rules have to be integrated specifically during the conceptual design phase [1] , when the designer has still the ability to easily modify the product while considering the environmental exigencies and the functional representation of the product [2]. But because of the nature of the functional representation [3] which doesn't have accurate data and detailed information about the final product, the implementation of the DfE rules is not easy.

To help the designer to consider DfE rules earlier during the design process, a tool is proposed that consists in a list of DfE rules usable during the conceptual design phase. In the next sections the recommended approach to use DfE rules earlier is presented with the rules that can be used. The model and indicators that contribute to the evaluation are also presented. Finally, a case study is presented to show how these elements can be used.

## 2 THE SUGGESTED APPROACH TO REALLY CONSIDER DFE RULES DURING THE DESIGN PROCESS

### *2.1. The current approach to consider DfE rules during the design process*

Many researches are concerned with the integration of the environmental constraint during the product design and the design of its related processes [4]. This leads to develop new design methods based on the consideration of the entire product lifecycle to reduce the environmental impacts [5]. A view of the current approach is presented figure (1).

In the early design phases designers can use guidelines as Ecodesign Pilot [6] to be guided in their choices. These guidelines are well adapted to the conceptual design phase but are not systematically used because they don't return usable quantitative indicators that could be analysed and compared to other design indicators at this stage of the design project.

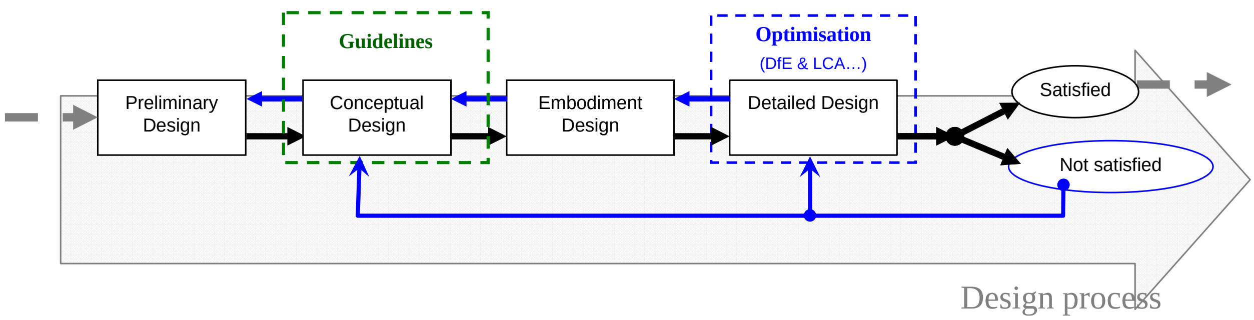


Figure 1: The current approach to design environmentally friendly products

So, the environmental impact of the product is mainly considered during the detailed design phase. At this stage, the necessary data are available (components, weights, material, joining techniques, manufacturing processes…) and Design for Environment (DfE) tools can be applied and Life Cycle Analysis (LCA) can be realised [7] [8]. After carrying out these analyses, the designers validate if the product satisfy or not the environmental requirements. Then if the requirements are satisfied, the design process continues. If not, the solution has to be reconsidered: with minor modifications for an optimization or with major modifications in the conceptual design phase, that conducts to a large waste of time.

### *2.2. The proposed approach to consider DfE rules during the design process*

In order to help the designer to optimize the environmental point of view during the design and to minimize the time of the design project, a simple environmental evaluation of the product has been define that will be carried out during the conceptual design phase and that can be extended until the detailed design phase (figure 2). Our objective is to propose an evaluating tool using first the element of the functional representation to return simple environmental indicators to the designer [9]. Then, for each step of the design process, an evaluation of the environmental requirements can be conducted to avoid too large trial/errors buckles during the design.

The developed indicators will not be related to an environmental impact assessment as a LCA because of the lack of product data at this stage. But a first estimation of the product environmental profile is possible by applying DfE rules. The objective is not to replace LCA at the end of the detailed design phase. It is to guide the designer earlier toward a good compromise for its product by simple estimations.

This is necessary to avoid significant modifications at the end of the detailed design phase.

So, in this article some rules that are used during the conceptual design phase are presented and it is explained how they can be used. A focus is done on the chosen product model that supports the evaluation process and the different indicators created in relation with the selected DfE rules.

## 3. DFE RULES TO BE USED DURING THE CONCEPTUAL DESIGN PHASE

The objective of this work is to apply DfE rules earlier during the design process, when designers need a quantitative tool to evaluate their propositions.[10] [11]. To do that, DfE rules have been selected and classified to be applied on a first definition of the product; that means on the functional representation of the product. [12]

### *3.1. DfE Rules classification*

A classification of the DfE rules has been proposed according to the product lifecycle phases which are defined by five main life cycle phases: Raw materials, production, transportation, usage and finally disposal phase[6]. So there are:

- Rules to choose the right materials.
- Rules to improve production processes.
- Rules to reduce the transportation.
- Rules to improve the use of the product.
- Rules to increase product durability.

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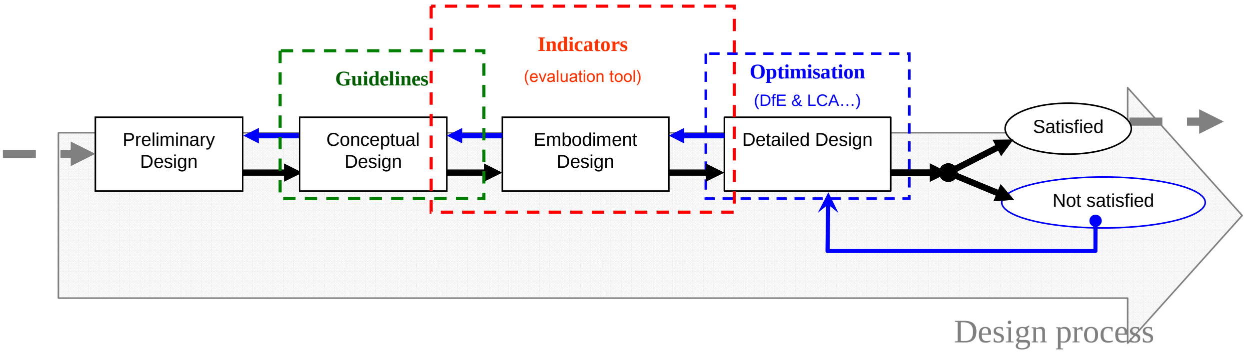



Figure 2: The current approach to design environmentally friendly products

**DfE Rules classification**

| Main group | Sub- group rule |
|---|---|
| **To choose the right materials.** | To select Material<br>To save material for component |
| **To improve production processes.** | To save material for component during the production processes<br>To save Energy during the production processes<br>To improve the assimilability of components (product assembly) |
| **To reduce the transportation.** | To improve the packaging<br>To improve the transportation |
| **To improve the use of the product.** | To improve the maintenance<br>To optimise the product functionality<br>To optimise the energy consumption in use phase<br>To reduce waste in use phase |
| **To increase product durability** | To improving the disassembly<br>To improving the remanufacturability<br>To improve the recyclability |

Table (1): the Main group et sub-group for DfE rules.

For each DfE rule group there are sub-groups related with specific technical points to guide designers more precisely during the product definition. Indeed, the rules presented in these sub groups can guide the designers to integrate environmental constraints but also different other concepts in parallel of product design development (remanufacturing, disassembly, maintenance,…). They are defined according to practical design guide and translated to be adapted to the conceptual design phase. Table (1) shows some of these groups and sub-groups

For each set of these sub-groups, there are two types of rules that have been identified: the technical rules and the environmental rules (figure 3). This classification is related with functional requirements [1] and environmental exigencies [13-15] that are defined in the requirement list.

### 3.2. Technical rules

The technical rules are used to cover technical requirements which have to be satisfied by the product during its lifecycle to be environmentally friendly. When the designer defines the type of product (Mechanical, Electrical, Electronic …) [6] and proposes an end of life scenario, he needs some rules to guide the design process and to take into account the technical aspects. These rules propose general ideas related with component material, product structure, product assembly and disassembly axes, joining techniques and disassembly, pollutants, etc.… These rules are inspired from DfX approaches [16] [17], such as design for disassembly (DfD) [18], design for remanufacturing (DfRem) [19]. They are supposed to guide the designer to adapt the product technical requirements during each life cycle phases: from materials suggestions and proper production processes until the definition of the product end of life scenarios.

### 3.3. Environmental rules

The difference between the environmental rules and the technical rules is that the technical rules are means to propose technical ideas, to solve technical issues, to find functional solutions, to adapt proposed approach like DfRem, and environmental rules are more related to the environmental standards and exigencies. They are related to the life cycle requirements for the whole product: energy consumption, environmental impact, end of life scenario, product durability [6]…. They are supposed to guide the designer to adapt the product environmental requirements during each life cycle phases. These rules aim to improve the conceptual design process by giving goals to designers, rather than improving technical issues.

### 3.4. Examples of DfE rules

In this paragraph, we illustrate for each group of DfE rules examples for technical and environmental rule:

- ***Rules to choose the right materials.***

**Objective**: The objective of this first group is to guide the designer in materials choices and to determine the effect of their presence in the product.

**Technical rules**

"TO USE RECYCLABLE RAW MATERIAL"

"TO MINIMISE THE NUMBER OF TYPE OF MATERIALS IN THE PRODUCT"

**Environmental rules**

"TO ADAPT THE MATERIAL TO THE LIFE OF THE PRODUCT"

- ***Rules to improve production processes***

**Objective:** The objective of this second group is to optimise the materials consumption and the level of energy used in production processes by adapting cleaner production strategies.

**Technical rules**

"TO USE STANDARDIZED ELEMENTS, PARTS, AND COMPONENTS FOR EASY PRODUCT ASSEMBLY".

**Environmental rules**

"TO AVOID HAZARDOUS MATERIALS AS AUXILIARY OR PROCESS MATERIALS".

- ***Rules to reduce the transportation.***

**Objective:** The objective of this third group is to optimise the product packaging and the transportation impacts.

**Technical rules:**

"TO ADAPT MODULAR STANDARDS SHAPES FOR REUSABLE PACKAGING".

"TO PREFERABLY USE RENEWABLE RAW MATERIALS FOR PACKAGING".

**Environmental rules**

"TO MINIMISE THE PRODUCT TRANSPORTATION".

- ***Rules to improve the use of the product.***

**Objective:** The objective is to minimise the impact of the product and of its consumables in use.

**Technical rules:**

"TO MINIMIZE THE ENERGY CONSUMPTION IN USE"

**Environmental rules**

"TO INCREASE THE LIFE TIME BY DESIGNING PRODUCT FOR SEVERAL USAGE PHASES"

"TO EXTEND THE USAGE TO SEVERAL USERS IN THE SAME USAGE PHASE"

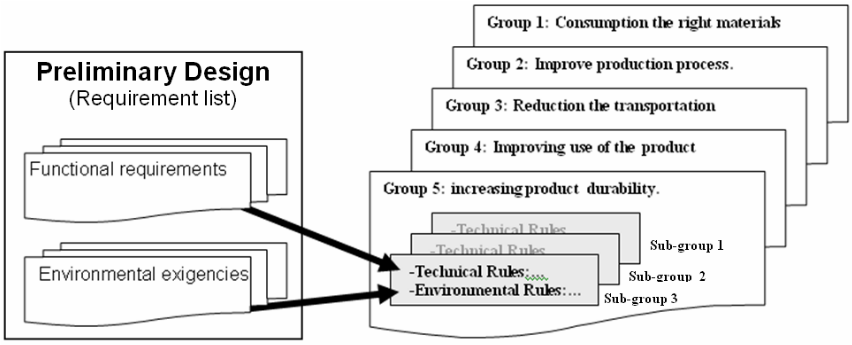



Figure (3): Types and groups for the DfE rules usable during the conceptual design phase

- ***Rules to increase product durability.***

**Objective:** The objective of this group is to minimise the waste and to adopt the best end of life strategy for the product.

**Technical rules:**

"TO IMPROVE DISASSEMBLABILTY OF THE PRODUCT".

**Environmental rules**

"TO PREFER CLOSED LOOP END OF LIFE STRATEGIES".

## 4. The DfE indicators to be used during the conceptual design phase

As presented in the previous paragraph, numerous DfE rules exist to evaluate a product. To improve the use of these rules during the design process we have:

- Identify the product model that can support these rules during the conceptual design phase.
- Define factors related to the design rules and weighting factors to evaluate the preliminary solutions from an environmental point of view.

### *4.1. The product model used during the conceptual design phase*

The product model has been chosen regarding the simplest combination needed to obtain a structure of the product. The simplest structure consists of two components and one relation (figure 4). It is the (C, R, P) [20]model for Component, Relations between the components and Product.

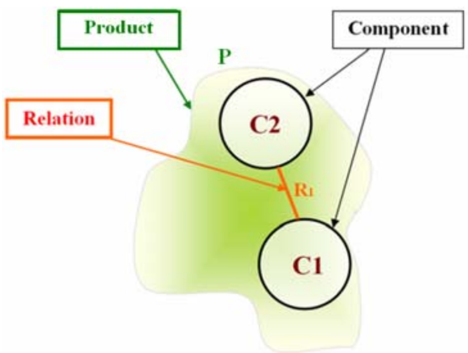



Figure (4): The (C,R,P) model

### *4.2. Indicators*

To evaluate the design choices, a triple indicator has been defined (Kc, Kr, Kp) related to the (C, R, P) model. For each of these three indicators, a value is assigned, related to specific characteristic. Some of these indicators have numerical values (weight, number…) and some of them are described by a literal formulation (material, EoL…).

A symbolisation for these indicators has been proposed (figure 5). They are presented with the letter (K), and their group is specified with the second letter (C, R or P). The third letter is a (P) if the indicators have specific relations with polluting components. At the end of the indicator appears the abbreviation for the characteristic considered, in small letters.

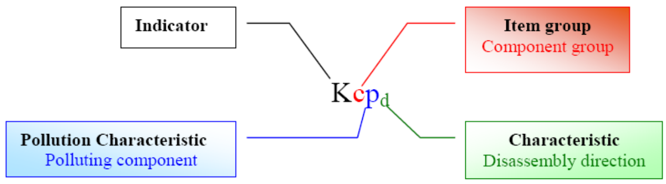



Figure (5): Indicators' symbolisation

For example:

- **Kc**da belongs to the component characteristics groups and gives information on the component disassembly axis.

- **Kr**type belongs to the relations characteristics group and gives information on the Type of relations. There are general types and the designer chooses the relation type from the list presented table (2).

- **Kp**pcn belongs to the product characteristics group and characterizes the number of polluting components in the product. As an example, for the product illustrated in the example table (2), the indicator value of **Kp**pcn is equal to 3 (**Kp**pcn =3).

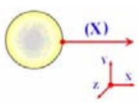
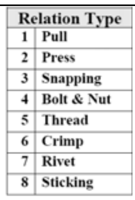
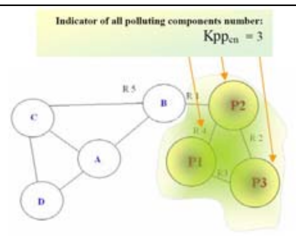
| | Components Group | Relation Group | Product Group |
|---|---|---|---|
| **Name** | Disassembly axis | Relation type | Number of polluting components |
| **Symbolisation** | **Kc**da | **Kr**type | **Kp**pcn |
| **Value** | **Kc**da = *List (X, Y, Z)* | **Kr**type = *List (x1, x2, x3…)* | **Kp**pcn =*Value(real numeral)* |
| **Illustration** |  |  Relation Type<br>1 Pull<br>2 Press<br>3 Snapping<br>4 Bolt & Nut<br>5 Thread<br>6 Crimp<br>7 Rivet<br>8 Sticking |  |

Table (2) Example of three indicators

### *4.3. Factors*

The factor is an evaluated item that is linked to a DfD rule. The factor is evaluated by a formula that uses the indicators presented in the last section and is valued as a real number belonging to an interval [0-1].

The symbolisation system of factors looks like the indicator's symbolisation system (figure 6). The factors are represented by a letter (F) and their group is specified with the second letter C, R or P. The third letter is a (P) if the indicators have specific relations with polluting components. At the end of the indicator appears the abbreviation for the rule considered, in small letters

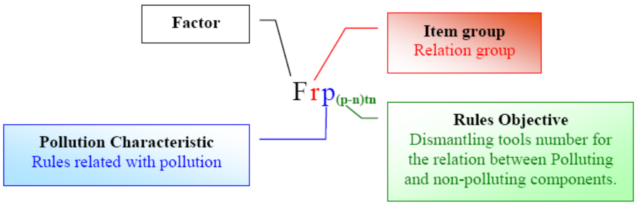



Figure 6: Factor symbolisation

As an example for the factor calculation, we will consider the factor **Fp**psd (**Similarity direction factor for the disassembly of Polluting components).** This factor belongs to the Product characteristics group (**P**). It is related to the number of pollutant components (**Kp**pcn) and to the number of components which have the same disassembly direction (**Kc**pd) :

**Fp**psd= ***interval*** [0-1] = Max (**Kc**pd) /.(**Kp**pcn) (1)

- **Kc**pd.: Number of polluting components having the same disassembly direction.

- **Kp**pcn: Number of polluting components.

The figure (7) represents an example to calculate the **Fp**psd . In this example there is a product model with seven components, three of them are pollutants. In the first assumption each component has its own disassembly direction, and **Fp**psd = 1/3

In the second example two from three pollutants components have the same disassembly direction, and Fppsd = 2/3

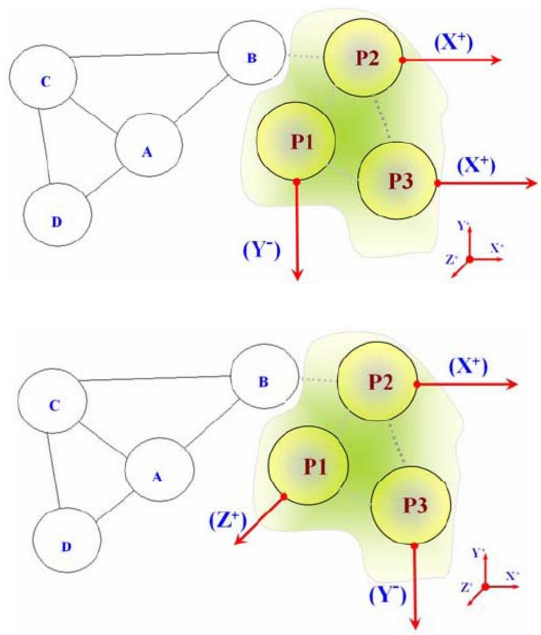



Figure 7: Example to calculate the **Fp**psd

### *4.4. Factor total and Weighting indicators*

After assigning factors to rules by factors and obtaining the value for each factor, the main factor (FACTOR TOTAL) can be clculated This factor total is specific for the whole product and represents the aggregation in one value of all the factors. The factor total value can be evaluated by giving each factor a different weighting value (the value of the weighting indicator related with designer point of view) and by dividing the total with the sum of the weightings.

$$Fp_{tot} = \textit{interval}\ [0\text{-}1] = \frac{\sum_{i=n}^{i=1} I_i * F_i}{\sum_{i=n}^{i=1} I_i} \qquad (2)$$

**Fp**tot: Factor total for the whole product (P)

**$I_i$:** Weighting indicator for the factor (Fi)

**$F_i$** : Factor of one realised rule

**n**: Number of used factors

For giving a proper justification for the values of factor, it is very important to link these factors with obvious criteria: links with known database (standards, limits and reference indicators), reference to the specialty of each product and the experience of the designer (designers and researches related with new product, processes or materials). The value of the weighting indicators is defined by the designer itself. He chooses the value according to the customer's needs and the designing specification.

In this research the scale of weighting indicator will be assumed as a scale of ten (X /10); the most important will take 10 and less important will take 0 depending on the designer point of view.

The factor is an evaluated item that is linked to a DfE rule. The factor is evaluated by a formula that uses the indicators presented in the last section and is valued as a real number belonging to an interval [0-1].

The symbolisation system of weighting indicator looks like the indicator's symbolization system (figure 8). The weighting indicators are represented by a letter (I) and their group is specified with the second letter (R, C or P). The third letter is a (P) if the indicators have specific relations with polluting components. At the end of the indicator appears the abbreviation for the main specific characteristic of the weighting indicator considered, in small letters

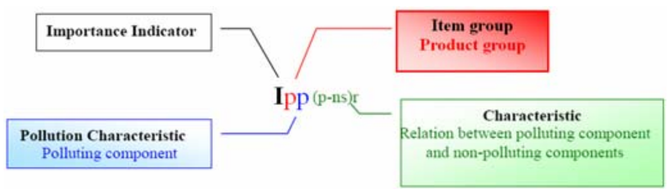



Figure 8: Weighting indicator symbolisation system.

The next figure (figure 9) shows that the factor value (**Fp**tot) is finally represented as a percentage to be compared with the proper limits of the design requirements. Whenever the value of (**Fp**tot) is near to (0) that means the level of applying the DfE rules is not satisfied, and whenever this value is near to (100) that means the design apply the DfE rules. Figure (9) represent a proposed scale to illustrate the final result of total value (**Fp**tot). The arrow underneath shows the **Fp**tot value.

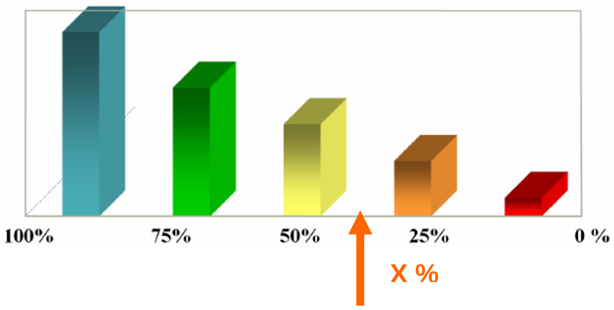



Figure 9: Factor total limits to evaluate the satisfaction.

The objective of a single factor formulation is to provide the designer a first estimation for his design. This estimation is related to how much the design adapts the aspects of environment during the conceptual design phase. We will see an application of this evaluation in the next section.

## 5. Case Study

In this case study, the design of a refrigerator is considered. The main components of this refrigerator have been defined during the conceptual design phase as in the Table 3. During the design process, a functional block diagram has been established (figure 10) and shows the functional components and their relations that are necessary to define the (C,R,P) characteristics.

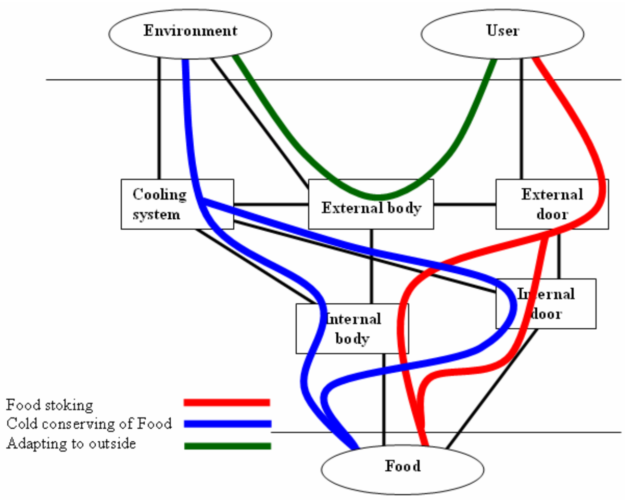



Figure (10): The FBD for the refrigerator

| | Component | Material type | EoL scenario |
|---|---|---|---|
| C1 | External door | Steel | Recycling |
| C2 | Internal door | Polystyrene | Incineration |
| C3 | External body | Steel | Recycling |
| C4 | Internal body | Polystyrene | Incineration |
| C5 | Cooling system | multi-materials | Not clear yet |

Table (3): Components materials and end of life for the refrigerator

To illustrate our approach, we will consider in this example the rules related to the group "**Rules to choose the right materials:**

### *5.1. First case*

In this case and relating to the first rule, "MINIMISING THE NUMBER OF TYPE OF MATERIALS IN THE PRODUCT" .we can define the factor:

**Fp**ms : (factor of **Product material similarity**):

This factor is related with each components material type by the indicator;

(**Kc**$_{Mat}$); *Component material Indicator.*

The value used in this factor is the number of components which are made of the same material (mono-material). The equation which gives its value is formed as following:

**Fp**ms **(material number)=*Internal(0-1)*=** (**Kc**$_{Mat}$)**/ (Kp**nc**) (3)**

While taking into account that:

**Fp**ms**(1) + Fp**ms**(2) + Fp**ms**(3) +…= 1** **(4)**

**Kp**ms : Product material similarity.

**Kp**nc : Number of components

**Fp**ms(1) :Percentage of material number (M1) in the product (P).

**Fp**ms(2) : Percentage of material number (M2) in the product (P).

**Fp**ms(3) : Percentage of material number (M3) in the product (P).

…

In our case study; Fpms= 40% (2/5) and this value can refer to two materials (Steel and Polystyrene). When the designers follow the rule and increase the number of component which have the same material in his design (by example change the external door material into "Polystyrene instead of Steel) the factor value becomes: Fpms=60% (3/5). This shows that the product design now applies the rule with a percentage of 60% after modifying the external door material. Next figure (Figure 11) shows through the satisfaction scale the result and the increase in the satisfaction level.

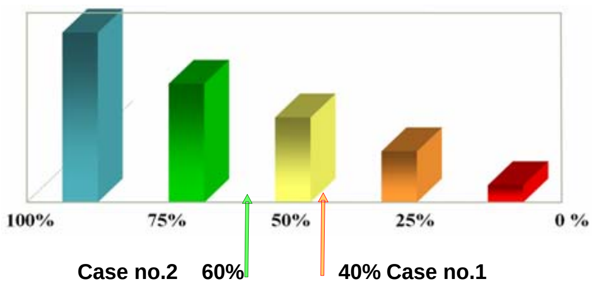



Figure (11): Satisfaction scale for the first DfE rule

### *5.2. Second case*

Relating to the second rule, "USING RECYCLABLE RAW MATERIAL" we can define the factor: **Fs**EoLns: (**Product similarity factor of components' EoL number**).

This factor is related to the number of components (**Kp**cn) and to components which have the same type of end of life (KcEoL).

Each type of EoL has its own factor. This factor helps in giving an indication of the EoL number independently to the total number of component that have the same EoL.

For each type of EoL there is separated indicator. As for the last factor, the value used in this factor is the highest number of components which have the same EoL. Then we can write;

**Fp**EoLns =***Internal (0-1)*** **= (Kp**EoLns**) / (Kp**cn**)** **(5)**

While taking into account that:

**Fp**EoLns(1) **+ Fp**EoLns(2) **+ Fp**EoLns(3) **+…= 1** **(6)**

**Kp**EoLns : Product's EoL number similarity Indicator.

**Kp**cn : Components number indicator.

**Fp**EoLns(1) : Percentage of components number which have EoL(1) in the product.

**Fp**EoLns(2) : Percentage of components number which have EoL(2) in the product.

**Fp**EoLns(3) : Percentage of components number which have EoL(3) in the product.

…

In our case study; **Fp**EoLns= 40% (2/5) and this value can refer to the two EoL scenarios (Recycle and Incineration). When the designer follow the rule and apply it by using recyclable materials EoL scenario instead of the incineration scenario in his design, this will increase the factor **Fp**EoLns. By example, changing the internal door and internal body into recyclable instead of incinerate Polystyrene, the factor value is **Fp**EoLns=80% (4/5).

Figure 12 shows through the satisfaction scale that the result have increased from non-satisfied to good level.

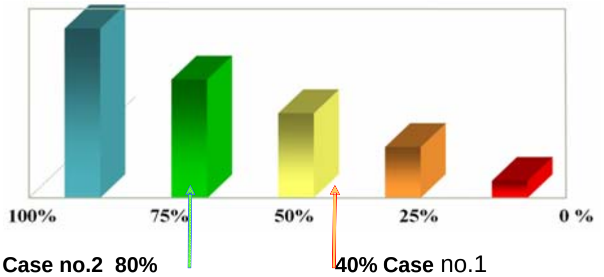



Figure (12): Satisfaction scale for the second DfE rule

## 6. Conclusion

During the last phases of the design, it is not easy to take into account the environmental criteria since the product is already carried out and because any modification on it generates additional delays or over-costs. But actually, environmental aspects are mainly considered during the detailed design phase, by taking into account the end of life scenarios and product life cycle analysis. For all these raisons, a method has been proposed to help the designer to take into account the environmental exigencies by early estimation during the conceptual design. This estimation is based on DfE rules that have been translated into valuable factors. Two main contributions have been realised :

- the environmental exigencies have been translated into rules (DfE rules), and the rules that can be applied in the conceptual design phase have been detailed.

- these rules have been translated into factors. Each factor is evaluated to identify if the rule is respected or not and to obtain a general estimation with one total factor for the product and all the rules.

Detailed analysis should still be realised later in the design process to validate/optimise the product. But with this first proposed approach, designers are guided toward a valuated goal and should be more concerned with environmental aspects.

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