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Optimization approach for attractive and sustainable products

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Abstract

Reducing environmental impacts from the earliest stages of products/ systems design is a major challenge. We suggest a paradigm shift, which involves a hybrid ecodesign approach based on the modelling of systems by constraints based on the Constraint Satisfaction Problem formalism with more traditional environmental assessment methods to decide which design choices to be made. This approach has been applied to characterize a product architecture of a vacuum cleaner focusing on the durability of the products. Then attractiveness of the product has been optimized on 3 functions leading to a functional negotiation.

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Keywords: Eco-design ; Optimization ; CSP ; Early design stage ; Attractivity

1. Introduction

Drastically reducing environmental impacts from the earliest stages of products/ systems design... this is the absolute and urgent imperative if the planet, with its high demographic imbalance and its generalized production/ consumption pattern, is to remain viable in the short term.

With the benefit of hindsight, we know that the traditional ecodesign methods developed over the past 30 years are not appropriate because they reason by setting the functional definition of the systems under consideration (performance, lifetime) and simplistically apprehend the complexity of these new systems, which generally results in a marginal reduction in impacts.

The systems to be designed are becoming increasingly complex because, structurally, they are composed of many subsystems, associated in a platform and range logic, which are often coupled and operate in several operating modes. Then, the products become connected, and more generally the interactions with their environment become a design object,

the system under consideration is no longer the isolated product but the macro-system associated with the functionality. Finally, the complexity comes from the environmental constraints themselves.

The environmental assessment that results from a Life Cycle Assessment (LCA) does not encapsulate itself in a single indicator but requires the measurement of many distinct and complementary categories of impacts. In ecodesign, the interest is no longer to optimize locally one dimension of the product life cycle but to consider all the dimensions of the product life cycle as well as the infrastructure supporting the associated services. When considering multiple life cycles, functional improvements (upgrades) or a dynamic assessment of environmental impacts, the systems to be designed must be considered over an extended time period. Several questions illustrate the complexity relating from ecodesign issues, such as rebound effects or dynamic effects.

This paper is structured as follows. A brief overview of the state of the art is presented in section 2. In section 3 we will present the methodology and in section 4 the case study and

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experimental results. Finally, we will comment on the main results and conclude on the actions to be implemented.

2. State of the art

The methodological breakthrough proposed in this article makes it possible to overcome the obstacles induced by complexity to achieve sustainable systems with high added value for all stakeholders (note that in this article the sustainable development aspect is limited to improving the environmental impact and attractiveness for the customer). This new eco-design paradigm is an essential link in the creation of new foundations for industrial excellence and the development of innovative systems that are more advanced because they synthesize a large number of constraints. All these qualities open the opportunity to invest in new markets (upgradable products, shared-use products, products integrating connected objects).

Our approach is original because the current ecodesign methods are mainly aimed at simple systems (generic methods such as simplified LCA, EcoPas, LIDS Wheel or more specific methods such as Design for (Df) recycling, Df remanufacturing, Df upgrading, Df low energy in use, Df ecologistics, Df cleaner production).

In summary, these conventional ecodesign methods do not allow all possible architectural solutions to be explored, within an acceptable time frame; for example, many approaches have been developed in the literature to help the designer identify and select the right materials as a set concept [1], [2], [3], [4], [5]; the shortcoming of these approaches is that they do not take into account the multiple interconnections with the product on which they are dependent [6].

In addition, they reason according to a principle of fixed functional unit, which greatly hinders the optimization of the sustainability of a complex system. Improving the attractiveness of a product can be achieved by taking better account of customer requirements. This should make it possible to design a product that meets the best their expectations and is therefore likely to be highly successful on its market. Among the most commonly used techniques are those of the Quality Function Deployment (QFD) [7], QFD for Environment [8], Environmentally Conscious QFD [9].

3. Method

In this article, we propose to reverse the process of ecodesign reasoning, by rigorously aggregating from the outset all the constraints associated with environmental impacts in order to specify the design problem in a systemic way and to be able to launch a systematic and computerized exploration process for solutions that simultaneously satisfies all the objectives at once. Technically, this new eco-design approach is based on mathematical modelling. All the constraints of the problem can thus be grouped into a Constraint Satisfaction Problem (CSP) and their resolution can be based on generic algorithms in the field of constraint programming and global optimization.

This modeling makes it possible to integrate constraints when looking for solutions as elements that generate choice

and not as validation criteria. This modeling allows to define Product Architecture (ArP) and Life Cycle (ArCV) synthesis problems [10].

Some members of the engineering community have used this tool in their research. They demonstrated that the use of CSPs could be interesting in areas such as pre-design [11], solving design problems [12], [13], optimization [14], [2], product platform configuration [15]. The effectiveness of CSP approaches is also proven in modelling the product use phase [16].

This resolution paradigm consists of 2 distinct phases: 1) mathematical modelling of the problem (variables, domains, constraints and objective function(s)) and 2) resolution using generic algorithms for exploring the research space. The formulation of an objective then guides the exploration in order to calculate the best solutions with regard to this criterion.

This part of the modelling aims to define the values of certain design variables. These design variables have a major link with environmental impacts through the variation in the lifetime of the element concerned. They correspond, for example, to the choice of materials, the dimensions of certain components or the number of components.

The analysis of environmental databases makes it possible to establish relationships between these design choices and the service life obtained.

4. Case study

The proposed method has been applied to the eco-design of a vacuum cleaner. This vacuum cleaner has been modelled in a simplified way (Fig. 1) as a product consisting of a protective housing, a motor for suction, a battery for energy and an electronic board for the control part. We then modelled each of the components using constraints in order to explore in depth a large number of alternative solutions. For simplicity, the environmental impacts modelled are based on the "Eco-Indicator" (Recipe) expressed in milli-points (mPt).

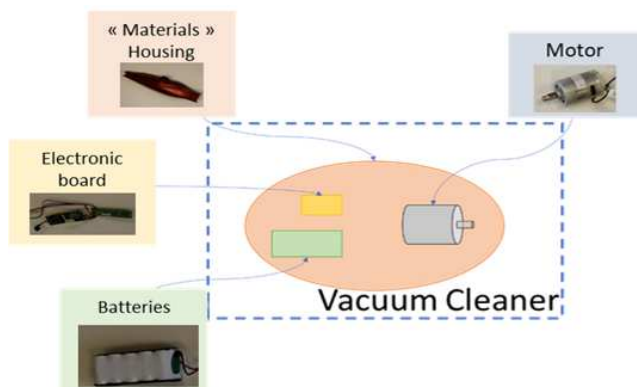


Fig. 1. Simplified model of vacuum cleaner

4.1. Product configuration

The "housing" module is a passive module, the environmental impact of the module is related to the type of material chosen and the quantity (mass) specified. These two data are our design variables. The service life (DV_housing) is a function of the thickness of the housing (Fig. 2).

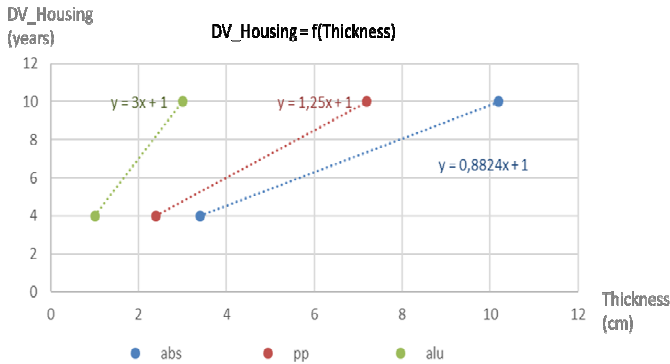


Fig. 2. Characterisation of the housing module lifetime

The component model, created using CSPs, consists of a table of possible materials for the module, design variables (thickness, material density, strength), criteria variables (physical lifetime, mass, environmental impact) and constraints.

Table 1. Materials table

| Type | Density (Kg/ m3) | EI* (mPt/kg) | a |
|---------------|------------------|--------------|--------|
| 1 (ABS) | 1060 | 223 | 3 |
| 2 (PP) | 920 | 99,3 | 1,25 |
| 3 (Aluminium) | 2700 | 782 | 0,8824 |

Design parameters:

- Materials {ABS, PP, Aluminium}
- Thickness = [1 ; 10] cm
- Area 5000cm2
- DV_Housing = [4 ; 10] (years)

Constraints:

$$DV_{housing} = a \cdot Thickness + 1 \tag{1}$$

$$EI_{housing} == M_{housing} \times EI_{mat} \tag{2}$$

The constraint (1), linking lifetime to thickness, is an assumption we have made to illustrate our approach.

The "Motor" module is an active module because it consumes energy during use. The environmental impact of the module is related to the mass of the component, the materials used and the power during the use phase. These three data are

our design variables. The "physical" life of the motor depends on the type of technology used (brushed or brushless motor) and the power.

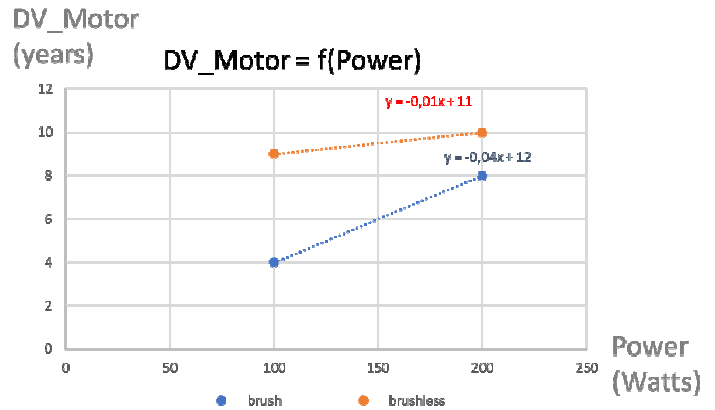


Fig. 3. Characterisation of the motor module lifetime

Design parameters:

- Technologies {Brushless, Brushed}
- Power = [100 ; 200] Watts
- DV_Motor = [4 ; 10] years

Table 2. Motors table

| Type | EI* (mPt/kg) | a | b | c | d |
|---------------|--------------|------|----|-------|-------|
| 1 (brushed) | 551 | 0,04 | 12 | 0,625 | 237,5 |
| 2 (brushless) | 551 | 0,01 | 11 | 0,625 | 237,5 |

Constraints:

$$DV_{motor} = - a \cdot Power + b \tag{3}$$

$$M = c \cdot Power + d \tag{4}$$

$$EI_{motor} == M_{motor} \times EI_{mat} \tag{5}$$

$$\text{If type} == 2 \text{ then add PCB} \tag{6}$$

The constraint (3), linking lifetime to power, is an assumption we have made to illustrate our approach. The constraint (4) characterizes the mass as a function of the power. A Boolean constraint (6) must be specified to model the brushless motor control board.

The "PCB" module is a continuous active module because it contains energy-intensive electronic components in use. The environmental impact of the module is related to the surface of the board, the materials used and the electronic components that compose it. By hypothesis the "physical" lifetime of the board depends on the type of technology used and decreases as the number of electronic components increases (thus the surface area of the board increases).

* Environnemental Impact

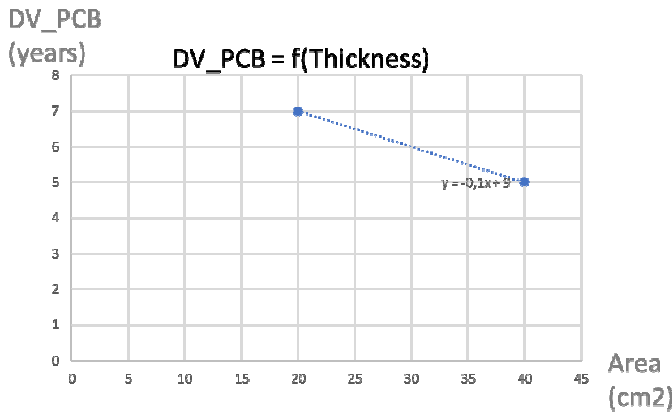


Fig. 4. Characterisation of the control board module lifetime

Design parameters:

- Technologies {...}
- Area = [10 ; 40] cm²
- Thickness = 0,2cm
- Electronic board for « brushless » motor {0 ; 1}
- DV_PCB = [4 ; 10]

Table 3. PCB table

| Type | Density (g/cm ³) | EI* (mPt/kg) | a | b |
|------|------------------------------|--------------|------|---|
| 1 | 1,850 | 229 | 0,11 | 9 |
| 2 | ... | | | |

Constraints:

$$DV_PCB = -a \cdot Area + b \tag{7}$$

$$EI_PCB == M_PCB \times EI_mat \tag{8}$$

The constraint (7), connecting the lifetime to the area, is an assumption that the reliability of the board decreases as the number of electronic components increases (i.e. with the area).

The battery module is a discrete active module. First, it is an active module because it allows the storage of energy during the use phase. It is also a discrete module because the amount of energy stored depends on a discrete number of cells. The batteries are characterised by a specific energy (Wh/kg) that determines the autonomy of the device. A battery consists of several cells whose format is defined by a voltage (V) and a capacity (Ah). The lifetime of a battery depends on the number of charge/discharge cycles (Fig. 5). For example, after 500 charge/discharge cycles, a Lithium-ion battery has only 80% of its initial capacity.

The environmental impact of the module depends on the materials used (Nickel, Lithium, Lead) and the number of cycles of the cells used

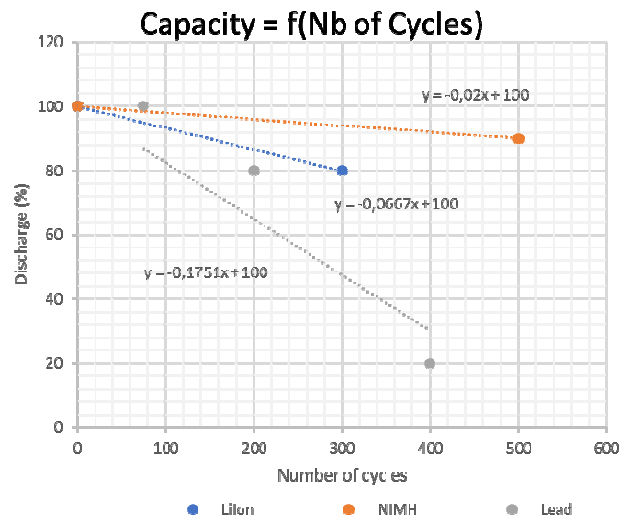


Fig. 5. Characterisation of the battery module lifetime

Design parameters:

- Technologies {Pb, Li-ion, NIMH}
- Number of cells = [0 ; 100]
- Capacity
- DV_Batteries = [4 ; 10]
- Number of cycles = [100 ; 1500]

Table 4. Batterie table

| Type | Voltage (Volts) | Capacity (Ah) | Density (Wh/kg) | a | EI (Pt/kg) |
|------------|-----------------|---------------|-----------------|-------|------------|
| 1 (Li-ion) | 3,6 | 2 | 170 | 0,067 | 1,1 |
| 2 (Ni-MH) | 1,2 | 0,8 | 180 | 0,020 | 2,6 |
| 3 (Plomb) | 6 | 1,3 | 31 | 0,175 | 4,2 |

Constraints:

$$\text{Residual capacity} = -a \cdot \text{Nb of cycle} + 100 \tag{9}$$

$$EI_bat == M_bat \times EI_mat \tag{10}$$

The constraint (9), linking the residual capacity of the battery to the number of cycles, is an assumption we have made to illustrate our approach.

4.2. Product attractiveness

The requirements identified as important for customers using a vacuum cleaner are lightness, speed of vacuum cleaning and autonomy.

For each requirement an attractiveness score is defined by a score from 0 to 100Pts.

The lightness is quantified by the total mass of the vacuum cleaner.

- The search for the product configuration minimizing the mass results in a product of 1.83 kg.
- The search for the product configuration maximizing mass results in a product of 4 kg.

By hypothesis we will consider that between these 2 values the attractiveness varies linearly according to the equation 11:

$$ATT_{mass} = - 30.1 * Mass + 155.2 \tag{11}$$

For a fixed suction system, the vacuum cleaning time is a function of the power.

By hypothesis, the passage time is reduced by 10% for every 100 watts of suction power added.

- The search for the product configuration minimizing the cleaning time gives a cleaning time of 16min.
- The search for the product configuration maximizing the cleaning time gives a cleaning time of 18min.

By hypothesis we will consider that between these 2 values the attractiveness varies linearly according to the equation 12:

$$ATT_{Power} = -3333*duration + 1000 \tag{12}$$

The autonomy is equal to the energy stored by the battery divided by the power of the vacuum cleaner.

- The search for the product configuration maximizing the autonomy gives an autonomy of 24.6min.
- The search for the product configuration minimizing the autonomy gives an autonomy of 19.2min.

By hypothesis we will consider that between these 2 values the attractiveness varies linearly according to the equation:

$$ATT_{autonomy} = 1111*d_{auto} - 355 \tag{13}$$

Among the 3200 solutions evaluated (Figure 18), solutions 1244, 1706, 1728, 1761, 1772, 1838, 2322 and 2344 are not dominated, so they form the set of solutions to the bi objective problem.

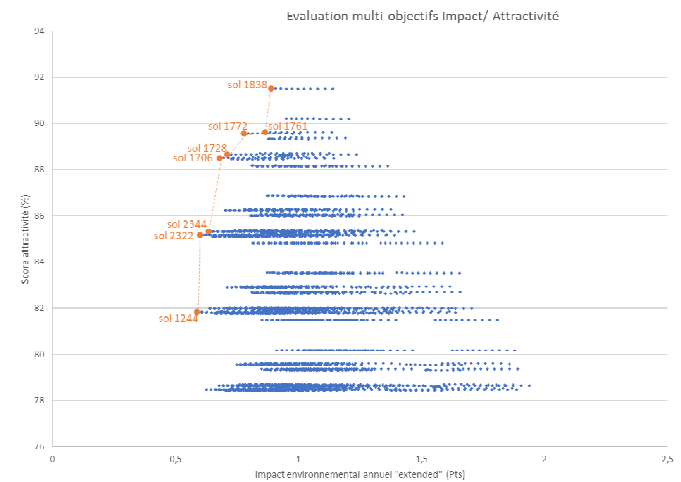


Fig. 5. Solution set (Pareto Front)

Table 5 details the optimal solutions. The solution 1706 is the lightest, the solutions 1244 and 1706 have the greatest autonomy and the solution 1838 has the greatest suction power. The solution 1244 is the least environmentally damaging and the solution 1838 is the most attractive.

Table 5. All the solutions to the bi objective problem.

| Variable | Sol 1244 | Sol 1706 | Sol 1728 | Sol 1761 | Sol 1772 | Sol 1838 | Sol 2322 | Sol 2344 |
|---------------------------|-----------|----------|-----------|-----------|-----------|----------|-----------|-----------|
| Housing material | PP | ABS | ABS | ABS | ABS | ABS | ABS | ABS |
| Housing mass (kg) | 3 | 1 | 1 | 1 | 1 | 1 | 2 | 2 |
| DV_Housing (years) | 8.5 | 4 | 4 | 4 | 4 | 4 | 7 | 7 |
| PCB area (cm2) | 15 | 10 | 15 | 15 | 15 | 10 | 15 | 15 |
| DV_PCB (ans) | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 |
| Battery type | NiMH | NiMH | NiMH | NiMH | NiMH | NiMH | NiMH | NiMH |
| Energy stored (Wh) | 43.2 | 43.2 | 47.0 | 53.8 | 53.8 | 66.2 | 43.2 | 47.0 |
| DV_Batterie | 8.2 | 8,2 | 8 | 8 | 8 | 8 | 8.2 | 8 |
| Motor type | Brushless | brushed | Brushless | Brushless | Brushless | brushed | Brushless | Brushless |
| Motor power (W) | 108 | 108 | 120 | 140 | 140 | 180 | 108 | 120 |
| DV_Motor (ans) | 6.8 | 6.8 | 6.2 | 8.8 | 5.3 | 8.1 | 6.8 | 6.2 |
| EI per year (mPts) | 587.2 | 678.6 | 710.2 | 863.5 | 778.2 | 887.9 | 600.4 | 633.9 |
| Attractivity (%) | 81.8 | 88.5 | 88.7 | 89.6 | 89.6 | 91.5 | 85.2 | 85.3 |

5. Conclusions and perspectives

We presented a methodological approach based on Constraint Problem modeling (CSP) and constraint propagation resolution supplemented by an optimization algorithm.

Combined with the life cycle analysis tool, CSP reasoning makes it possible, first, to model the product/ system and the constraints associated with environmental impacts and, second, to systematically explore "Product Architectures" in order to proactively reduce environmental impacts and to deal with complex systems. The solutions obtained in the case study cannot be apprehended in a traditional product development process, this reinforces our belief that it is necessary to generalize the use of a numeric tool in order to

generate and evaluate a maximum of architectures coupled with eco-design tools so as not to miss innovative and environmentally efficient solutions.

In addition, our approach is based on taking into account the attractiveness of the functions for users by optimizing the combination of value addition and environmental impacts. While life cycle analysis is based on a fixed functional unit, our approach leads to "functional negotiation" in the specification.

One of the aspects not currently addressed is the prioritization of functions. Indeed, in order to be able to express functional attractiveness as a constraint, it is necessary to prioritize functions by giving weight to the different functional parameters of the problem.

A. Popoff [17] describes an "ECO-CSP-QFD" method that combines CSP and QFD reasoning to generate an optimized

model of a product at the beginning of its design. In the first phase of the QFD method, customer requirements are used to prioritize the technical characteristics of the product that will satisfy them. The QFD matrix scores obtained are then used to weight the sub-objectives so that the resolution takes into account customer requests. As a result, such a method allows for a better integration of the client's needs during the design process.

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