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Sustainable life cycle design using Constraint Satisfaction Problems and Quality Function Deployment

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Abstract

In many ecodesign problems, finding solutions that complete the design requirements while bettering multiple performances (environmental impacts, costs, etc.) is no trivial task. Design-aid tools using optimization methods are efficient to address these issues but fail to encompass the whole life cycle of products and customer attractiveness aspects. This article describes an original method using CSP optimization and QFD to generate an optimized model of a product during the early design stages. Scores from the QFD matrix are used to weight the sub objectives of the optimization so that the solving is strongly dependent on the customers' demands. As a consequence, the method allows a better integration of customer needs during the design process. To optimize multiple performances, the variables of the model are used to create impact functions corresponding to environmental impacts, costs, etc. of every life cycle phases of the product's parts. As a result, the optimized model is the one with the best performance scores while answering best the variety of customers' needs. The methodology is applied to the design of an innovative inflatable dinghy. Results show that the use of QFD generates a fewer improvement of the environmental performance compared to an environmentally focused optimization (10% vs 18%) but it guarantees that the product will better meet customers' needs. Hence, the product should more likely be accepted and purchased and have a positive impact on the performances of the whole market.

Keywords: Ecodesign; Optimization; Quality Function Deployment; Life Cycle Assessment; Sustainability

1. Introduction

Design requirements, in terms of functionality, costs, environmental performance, security, etc. require a great deal of complex thinking to optimally design a product. [1, 2]. During the design stages, this translates into the need of setting a great number of variables influencing the product and its life cycle. Optimization methods, first used by mathematicians and computer scientists, have been proven to be efficient tools to help designers dealing with numerous design variables simultaneously [3] These methods, thanks to the computing performance of the hardware used, allow exploring the whole of the design space and identifying, using algorithms for the search of optimal solutions, solutions that fulfil the requirements [4]. On the other hand, in the scope of an ecodesign approach, life cycle assessment (LCA) methods [5, 6] have proven insufficient to answer the various needs of designers [7]. As a consequence, researchers such as Azapagic and Clift [8-10] associated in various ways LCA and optimization methods to create more efficient design-aid tools. Firstly used for the optimization of manufacturing processes [3], optimization methods are now used in many design problems and considering all the life cycle phases of products [11].

Because they make it easy for the designer to change the values of the variables, constraints-based optimization methods are used to easily compare several design alternatives of a product [12, 13]. This easy simulation is also an important source of information for decision makers to help them compromising between environmental performance, cost, functionality, etc. [14].

However, the existing methods fail to encompass the whole life cycle of products and customer attractiveness aspects [11].

The method developed here, named EcoCSP-QFD, aims at

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optimizing the design of products along three axes, in order to obtain the best ratio between functionality and multi criteria performance: (i) by taking into account the whole of the life cycle [15], (ii) by influencing the service life duration of the product, (iii) by increasing attractiveness for customers. To demonstrate the pertinence of our method, we apply it to a design problem: the innovative inflatable dinghy case.
The second section of this paper details the problems related to ecodesign and optimization. The third section presents the EcoCSP-QFD method. The fourth section gathers the results after applying the method to the case study. The last section presents our conclusions.

2. Ecodesign complexity and optimization

The functions of a product, as defined in its specifications, structure the design process as well as the manufacturing stage [16]. It is also the functions that define a great part of the use and maintenance phases of the product [17]. In the end, the end of life scenario of the product can depend of the residual level of its functions [18, 19]. We see that a product's functionality and its evolution over time influence the whole of its life cycle. In addition, having visibility on the use and end of life phases early during the design process is useful to optimally design the product and define the best levels of functionality [15, 20]. These relations of interdependency that exist between functionality, design process and life cycle have to be taken into account to optimize the performances of the product.
As we see, the definition of the product's functions is a crucial step that structures the following design process [16, 21]. The functions that appear in the product's requirements often guide designers and engineers when making choices between several technological solutions [22]. As a consequence, authorizing functional negotiation during the design process (allowing designers to adjust the levels of the functions) can be a way of bettering the product's performances because of a better match of the technological solutions with the functional levels required [23, 24]. The aim is for the designer not to only optimize the product design anymore but to optimize both sides of the pair: functionality and design solutions. Luttropp [21] states that functional negotiation can and will bring win-win situations where the environmental performance is improved while the levels of the most important functions are raised (and eventually remove the useless functions).
Determining the optimal duration of the service life (SL) of a product is a recurrent design problem [25-28]. If the problem is seen from the impacts perspective (whether they are environmental, economic, etc.), the SL calculation will take into account the marginal impact costs and benefits of maintaining the product longer compared to the impact costs and benefits of replacing it [29]. In other words, after a certain service time, a product may become more expensive (in terms of impacts) to maintain compared to the impact savings made if replaced by a new one (minus the impacts related to the end of life of the old product). A difficult aspect of the SL optimization is that in a business to customer model the company loses its control over the product's SL when it is sold. Indeed, the decision of throwing away the product is taken by the customer alone and depends of numerous parameters [30]. As a consequence, modelling the SL can be done using more or less realistic hypothesis regarding the usage practices during the SL (for example considering that the customer will keep the product until normal wear and tear caused by the recommended usage practices put it out of order).
An ecodesign strategy cannot limit itself to reducing environmental impacts without considering attractiveness for the customers. It is indeed poorly profitable, on the economic side as well as on the environmental side, to heavily invest to better a product's performances if it does not generate sufficient sales [31]. An optimization method for ecodesign must not only influence environmental aspects but also the key functions that are preponderant in the attractiveness for customers. Quality Function Deployment (QFD) [32, 33] was created to include customers' demands in the design process by defining and prioritizing their interrelations with the product's specifications. Since then QFD has been modified to be more adapted to ecodesign problems. Zhang [34] proposed a method called Green-QFD that integrates life cycle principles to optimize the environmental performance of the manufacturing phase of products. Later, Masui et al. [35] developed the QFD for Environment (QFDE) method by incorporating environmental aspects into QFD.

3. The EcoCSP-QFD method

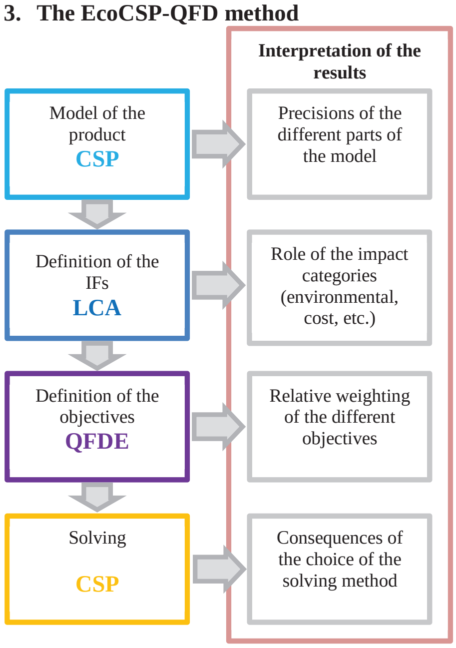

Fig. 1. The EcoCSP-QFD method

3.1. The CSP model

The starting point of the EcoCSP-QFD method is modelling the product/system considered [36-38]. CSP models use a set of variables X such as lengths, surfaces, masses, etc. To each one of these variables X_i is attributed a domain D_i which represents the range of its possible values. Variables are linked to one another by mathematical functions called constraints C. Altogether, variables, domains and constraints shape a mathematical representation of the real product including all the design solutions. The model is not limited to the product itself; Yannou et al. [39] include to their model variables related to the users (gender, level of skill…) that influence the product design. Solving a CSP means: for each