Journal of Cleaner Production 42 (2013) 1–18

Contents lists available at SciVerse ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Benefits and limits of a Constraint Satisfaction Problem/Life Cycle Assessment approach for the ecodesign of complex systems: a case applied to a hybrid passenger ferry

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ARTICLE INFO

Article history:
Received 27 April 2012
Received in revised form
1 October 2012
Accepted 26 October 2012
Available online 5 December 2012

Keywords:
Ecodesign
Complex system
Life Cycle Assessment
Constraint Satisfaction Problem
Ship design

ABSTRACT

This article aims to respond to the absence of ecodesign tools for products in the early stages of the design process especially in the domain of complex systems. A complex system has numerous interdependent sub-systems, each of these having several design alternatives and variable conditions of use which affect the choice of technological solutions and environmental performance. A complex system is also one which evolves throughout its life cycle, interacting with the external environment. These characteristics rapidly result in a great number of configurations which must be assessed in order to identify the optimal system for the environment (using many criteria and over the whole of the life cycle). To ecodesign such a system in the early stages of the design process, we have investigated, from the literature, 3 different methodological approaches, each of which uses Life Cycle Assessment (LCA). Approach 1 is the intuitive approach of the designer based on simple rules or on a Pareto combined with LCA. Approach 2 is based on Design of Experiments (DoE) combined with LCA and in approach 3 the Constraint Satisfaction Problems (CSP), based on the calculation of intervals, are combined with the LCA. These three methods (Pareto/LCA, DoE/LCA and CSP/LCA) have been tested in an ecodesign project for a complex system: a hybrid passenger ferry. The results of each method are evaluated according to the following criteria: time consumed, training, exploration of fields of possibility, interpretation of results and reusability. These results show that the CSP/LCA approach has certain advantages, in particular for exploring the fields of possibilities, interpreting results and the time saving through reusing results obtained for similar systems.

1. Introduction

Integrating the environmental dimension into system design is a delicate process. Indeed, a complex system consists of an interdependent whole made up of heterogeneous subsets; this means that designing a complex system involves making sure that the various functions, techniques and technological solutions are integrated in the appropriate manner while respecting the best possible environmental performances over the system's life-cycle (Agarwal and Mukkamala, 2005). Today, traditional approaches to ecodesign make it possible either to carry out environmental evaluations for remedial ends (LCA) (Hauschild et al., 2005), or to guide the designer towards improved solutions using «guidelines» (Wimmer and Züst, 2003). Both these approaches most often lead to local under-optimisations which are unsuitable for the design of complex systems. It is thus necessary to implement new practices of eco-design which are better suited to designing complex systems.

A passenger ferry is an example of a complex system with numerous interdependent sub-systems, several possible alternatives for the design of each sub-system and variable conditions of use affecting the choice of technical solutions and environmental performances; it is also a system which changes throughout its life cycle (wear and tear, refitting) and which interacts with the external environment (Aiguier et al., 2011), (Cilliers, 1998).

The reduction of energy consumption relies on a combination of solutions: technological change, redefining users' needs, reducing performance requirements to the minimum necessary, using renewable materials etc.

In this article, we propose an original methodological approach which allows to identify an optimal solution to the problems of

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http://dx.doi.org/10.1016/j.jclepro.2012.10.048

configuring complex products. The overall objective is to include environmental optimization step as soon as possible in the early stages of the design process. Today the Life Cycle Assessment method is widely used in industry to evaluate products in detailed design. But it is not suitable for use in "conceptual design stage" in part because of the amount of information needed to evaluate early concepts. So, we use an approach by constraints: Constraint Satisfaction Problems (CSP). The aim of the approach is to obtain environmentally optimized configuration during the conceptual design phase as stated by Pahl and Beitz (1996) or into the phase of concept development as defined by Ulrich and Eppinger (2000). The general idea of this paper is to assess comparatively 3 approaches: Pareto/LCA, Design of Experiments (DoE)/LCA and CSP/LCA.

In Section 2, we define the characteristics of a complex system. In Section 3 we give an overview of tools for ecodesign and environmental improvements, and we give specifications for a method of ecodesign for complex systems. In part 4, we present three theoretical X/LCA approaches for the conception of complex systems: Pareto/LCA, DoE/LCA and CSP/LCA. In part 5, these three different approaches are applied in the context of a new hybrid technology passenger ferry; in the final part of the article, we discuss the results and performances of these approaches according to the specifications laid out in part 2; we then introduce future developments for the CSP/LCA approach.

2. The Design of complex systems

Designing a complex system is difficult problem for several reasons (Cilliers, 1998), including the following:

- A great number of sub-systems and alternative solutions

Designing a complex system involves taking into account the product configuration, that is, determining the components which make up its architecture. This configuration will remain fixed throughout the product life cycle. For complex systems, the diversity of solutions quickly results in a vast number of combined solutions.

- Interdependent sub-systems

Knowledge of each element of a complex system independently does not enable us to predict the behaviour of the system as a whole. In other words, according to the definition of complexity (Cilliers, 1998), (Vautier, 2001), (Bocquet et al., 2007), (Aiguier et al., 2011), the system becomes more and more complex. In this situation, analytical approaches do not give an adequate view of the use of such systems. One of the main reasons for this is that such approaches fail to differentiate between the final demands on and initial conditions of an element of the system. Other approaches are therefore needed to go beyond the local optimisations, that are optimisations of each sub-system independently, currently in use. Moreover, the total optimisation of a system may require local sub-optimisations (Fussler and James, 1996).

- Different modes of operating

A complex system is subject to conditions of use or demands expressed by the stakeholders: traders, customers, legislators etc. According to the conditions of use, it is then necessary to determine various operation modes. Energy consumption depends on the use which is made of the system. In the automobile sector, these conditions of use are made clear by NEDC cycles (New European Driving Cycle). These cycles are made up of several low speed urban cycles and a high speed non-urban cycle. The fact that vehicles are designed for optimal functioning in an urban cycle and a non-urban cycle does not take account of users' actual usage, which is likely to be mainly urban or mainly non-urban.

- A system which changes throughout its life cycle

It is not easy to make a long term forecast of the life cycle of a complex system during its design phase. This difficulty applies particularly to lifetime, maintenance and end-of-life.

Complexity results in various levels of cycles of use which combine use phases and maintenance phases. Moreover, a large number of criteria will affect how the system is used (frequency, hours of functioning, ways it is used, seasons etc.).

The long lifetime of certain complex systems requires maintenance phases with programmed replacement of certain components planned right from the design phase. Beyond a certain time frame, component characteristics become less sure. This implies an additional difficulty when predicting the system's behaviour over the long term.

- A system which interacts with its environment

Cilliers (1998) states that "The complex systems are usually open systems, i.e. they interact with their environment. As a matter of fact, it is often difficult to define the border of a complex system. Instead of being a characteristic of the system itself, the scope of the system is usually determined by the purpose of the description of the system, and is thus often influenced by the position of the observer."

3. Overview of the currents state of ecodesign tools

3.1. Tools and methods of ecodesign

Highly exhaustive syntheses of many ecodesign tools are available in the literature; we cite the works of Alting and Legarht (1995), Zhang et al. (1997), Gungor and Gupta (1999), Baumann et al. (2002), Hauschild et al. (2005), Ilgin and Gupta (2010), Bovea and Pérez-Belis (2012). On the basis of these overviews, we analysed the tools then classified them into two categories: tools for simple systems and tools for complex systems (Table 1).

3.2. Tools and ecodesign methods for complex products

3.2.1. Pareto/LCA approach

The first approach relies on a «Pareto»/LCA combination. It can be generically broken down into 6 consecutive phases (cf. flowchart 1 Fig. 1).

The «Pareto»/LCA approach consists of an intuitive optimisation of systems or sub-systems which appear to have the highest impacts. According to Pareto's empirical law, about 80% of effects are the result of 20% of causes; by focussing on this 20% of the system, the designer can hope to achieve a significant reduction in environmental impacts. In the approach, the designer makes use of his or her implicit understanding of the system. This intuitive reasoning consists of feeling the way to optimising the elements of the principal sub-systems in order to achieve a global improvement of the performances of the system as a whole. After identifying the sources of major impacts and seeking alternative solutions, LCA must then be reiterated. For each iteration, the objective is to refine the definition of the new system and reduce its impacts on the life cycle. This very «natural» approach is nevertheless very time-consuming. Moreover, focussing on 20% of the system limits the