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► To cite this version:

Nicolas Tchertchian, Dominique Millet, Pierre-Alain Yvars. How to improve environmental performance by negotiating functional specifications of complex system?. 21st CIRP Conference on Life Cycle Engineering, Jun 2014, Trondheim, Norway. pp.449-454, <10.1016/j.procir.2014.06.088>. <hal-01065137>

HAL Id: hal-01065137

<https://hal.science/hal-01065137v1>

Submitted on 18 Sep 2014

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How to improve environmental performance by negotiating functional specifications of complex system?

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Abstract

This article aims to present an approach based on a combination of life cycle analysis methods (LCA) and problem solving by constraint satisfaction (CSP). This original approach makes it possible to vary the design of the different dimensions of the functional units of a complex system and thus to make it easier to identify the best architecture along with the best functional definition of the system. Our approach (EcoCSP) presented allows to negotiate performance to move towards an environmental optimum corresponding to a set of acceptable specifications. The EcoCSP approach is implemented to define the functional performance of a green passengers' ferry.

1. Introduction

In respond to the environmental crisis that arose in the late 70s, the concept of sustainable development has been proposed. In order to implement such development, it is not enough to make superficial reductions of environmental impacts; it is necessary to thoroughly redefine products and their expected performances in such a way that the consequences are compatible with sustainable development.

Various authors (Daly 1973; Simonis 1985; Williams et al. 1987; Herman et al. 1989; Ayres and Kneese 1990; Freeman 1992) have mentioned the radical nature of the technological transformation that needs to be effected in order to improve the environmental performance of a product or system: they have recommended reducing the proportion of material in the economy using expressions such as X Factor, eco-efficiency, industrial ecology, functional economy, dematerialization, product service-system etc.

Current methods of Eco design such as life cycle analysis and other assessment methods derived from this, such as environmental guidelines and checklists, are generally not suitable for systems that are increasingly complex. Complexity generated by complex systems induces issues in terms of modeling, prediction or configuration. Contribution of current ecodesign methods is limited to very localized optimizations (substitution of materials by more "sustainable" one, adding renewable energy sources, more robust design, etc.). It appears therefore necessary to implement new ecodesign practices, more suitable for the design of complex systems.

Any increase in complexity results in the multiplication of technical solutions and thus of possible alternatives. In such cases, design becomes a long process of negotiation within the design team. This negotiation is generally based on an initial definition of the system's specifications – specifications

that are rarely questioned during the design process. In this article, we focus on the necessity for the actors concerned to generate a functional negotiation, that is to say, to select the « right » functions, then the characteristics of the system in order to optimize its environmental performance.

In the following section of this article we deal with the problem of defining functional units in Life Cycle Assessment of complex systems. In the third part of the article we give a theoretical introduction to the EcoCSP method; this method combines CSP and LCA in order to identify the optimal architecture of a system by negotiating the functional unit so that an environmental optimum may emerge. In section 4, the EcoCSP approach is applied in the context of designing a new passenger ferry with hybrid technology. Our conclusion in section 5 summarizes the contributions of EcoCSP approach.

2. Functional negotiation

2.1. Improving environmental performances by reassessing product functions

A design project can be characterized by the degree of modification of the product. We propose, based on the works of Brezet 97, Millet 97, Abrassard 01 and Van den Hoed 97, three project categories:

- Superficial improvement of components
- Redefinition of the product architecture with a fixed functional unit
- Improving performance by redefining the number and scope of the functional specifications

These 3 categories translate into 3 different levels of design team intervention in the system. The first involves a slight modification of the product (component materials and fastenings) and procedures (Millet et al., 2009). The second results in modifications of the product architecture and the procedures affecting the life cycle (Tchertchian et al., 2013).

Finally, the third demands a functional and innovative reinterpretation of both the product and its life cycle.

Current methods of Eco design such as life cycle analysis and other assessment methods derived from this, such as environmental guidelines and checklists, merely identify the causes of environmental problems in order to redesign the product while keeping its functionalities unchanged; this is in contradiction to strategies of radical environmental improvement (X Factor) that necessitate a complete reassessment of product functionalities. Achieving a higher degree of sustainable development requires finding a balance between acceptable impacts and necessary functions. Luttrupp (2005) presents different ways of reaching this balance: he favors reducing environmental impacts while increasing the level of the product's functional performance - a win-win situation that eliminates all unnecessary functions. On the other hand, he is critical of the « green fix » strategy (using new materials while keeping all the functions) that result in short term, temporary optimizations; he also judges inefficient the « linear down » strategy (improving environmental impact by downgrading or eliminating functions).

2.2. The problem of defining the functional unit in the LCA method

Life cycle analysis (LCA) is a method of environmental assessment of a product or service over the whole of its life cycle, that is, from the phase of extracting the raw materials and manufacturing the product until the end of life (landfill, recycling, reuse etc.), including distribution, use and maintenance. The methodological framework of LCA is regulated by ISO 14040; this distinguishes 4 phases – defining the objectives and the perimeter of the study, taking the inventory of the life cycle, assessing the impacts of the life cycle and interpreting the results). The phase of defining the objectives and perimeter of the study requires the definition of a functional unit. The functional unit is the « quantified performance of a system of products to be used as the unit of reference in a life cycle analysis » (ISO 14044, 2006b). The definition of this functional unit is crucial. Indeed, in cases where the LCA study aims to analyze the potential impacts of different options, it is imperative that all the options assessed fulfill the same function in order to be comparable (Jolliet et al., 2005). Now, by constraining the designer to reason by iso-functionality, the LCA methods and its derivations naturally hinder thinking about products that might have a better balance between environmental cost and functional gain (Luttrupp 06). In general, the available tools, amongst them LCA, are based on a single criterion: the main function expressed in the form of a functional unit (Lagerstedt 03). This means that very different products or concepts can be compared.

3. EcoCSP approach

The EcoCSP approach is a further development of the CSP/LCA approach proposed by (Tchertchian et al. 2013). This approach is based on a combination of 2 methods « Constraint Satisfaction Problem »/Life Cycle Assessment.

3.1. Constraint Satisfaction Problem

A CSP (Constraint Satisfaction Problem) is defined by (Montanary, 1974):

- $X = \{x_1, x_2, x_3, \dots, x_n\}$, a set of variables, n being the number of variables of the problem.
- $D = \{d_1, d_2, d_3, \dots, d_n\}$, a set of domains. Each domain, associated to a variable, can be discrete or continuous.
- $C = \{c_1, c_2, c_3, \dots, c_p\}$, a set of constraints, p being the number of constraints of the problem.

A constraint is an explicit relation between two or more variables and imposes restrictions on area of possible values for variables of the problem. It should be any type of mathematical relation (linear, quadratic, non-linear, Boolean...) covering the value of a set of variables. Solving a CSP consist instantiating each variable of X , and at the same time satisfying the set of problem constraints C .

3.2. CSP solving process

A CSP can be solved using different kinds of algorithms, more or less effectives. A simplistic approach is based on the generate-and-test algorithm which systematically generates each possible values assignment and tests if it satisfies all the constraints. The most common algorithm for performing systematic search is based on backtracking: it incrementally attempts to extend a partial solution toward a complete solution, by repeatedly choosing a value for another variable. The late detection of generate-and-test and backtracking algorithms being their main disadvantage, various consistency techniques have been implemented. The consistency-enforcing algorithm makes any partial solution of a small sub-network extensible to some surrounding network. Thus the inconsistency is detected as soon as possible. The consistency techniques range from simple node-consistency and the very popular arc-consistency to full, but expensive path consistency. As Chenouard (2007) points out, using CSP in preliminary design has the advantage of great flexibility for expressing knowledge and modifying models; it resolves generic problems. This is a sought after characteristic in design, for it expresses knowledge without defining how it should be dealt with. CSP makes it easier to manipulate and reuse such knowledge.

3.3. The EcoCSP approach : A development of the CSP/ACV approach

The methodology of life cycle analysis uses a normalized functional unit (UF_n), to facilitate comparisons among systems that show unequal performances. The state of the art review and Reap's compilation (2008) of the main problems posed by LCA, show that defining a functional unit is not sufficient for the radical improvement of the environmental performances of a complex system. The works of (Tchertchian et al., 2013) demonstrated the relevance of an approach combining CSP and LCA to define the best architecture of a complex system environmentally speaking. This fruitful research pointed to a way forward. Indeed, the

CSP approach allows us to modelise functional requirements as constraints; by exploring these as such, it is then possible to simulate the various architectural alternatives of a complex system while at the same time varying the functionalities of that system. We have called this approach EcoCSP. According to our convention, the nominal functional unit (FUn) of a product or system is generally made up of negotiable functions (FRsN) and non-negotiable functions (FRs \bar{N}) (functions that are necessary for the system to work, or for safety). The EcoCSP approach enables us to define a functional unit that is globally optimized (FUgo) by modifying the levels of performance of certain negotiable functions of the normalized functional unit. By specifying the level of performances of the system's negotiable functions in the right way, we obtain a globally optimized functional unit. (FUgo). By varying a negotiable function of the system locally, we obtain a locally optimized functional unit. (FUlo).

The EcoCSP approach, as shown in figure 1, is broken down into 3 phases, the first two being effected in parallel:

- The first phase consists of determining the technological associations that satisfy the system's environmental constraints. Generating alternative technological solutions (2) requires the creation of a library of components (3) that allows us to modelise all the possible architectures of the system. The system is then modelised by writing the algebraic relationships among components (4) and by formalizing the constraints (5). A loop is introduced that feeds into the component database (6) during the phase of constraint satisfaction (10 and 12). This makes it possible to propose technical solutions close to critical points – these being optimal points of functioning that allow to downsize components.
- The second phase (7, 8, 9) consists of identifying the negotiable functions (system functions that can be redefined in order to improve the system's environmental performance) and non-negotiable functions (functions that are fixed as necessary for the system to work correctly).
- The final phase (10 – 13) consists of generating architectures along with their related technical specifications. First of all, this is done by varying individual negotiable functions in order to identify which are significant; that is, which of them have an impact on the system's final environmental performance. After this, only those negotiable functions that are significant, are modified simultaneously.

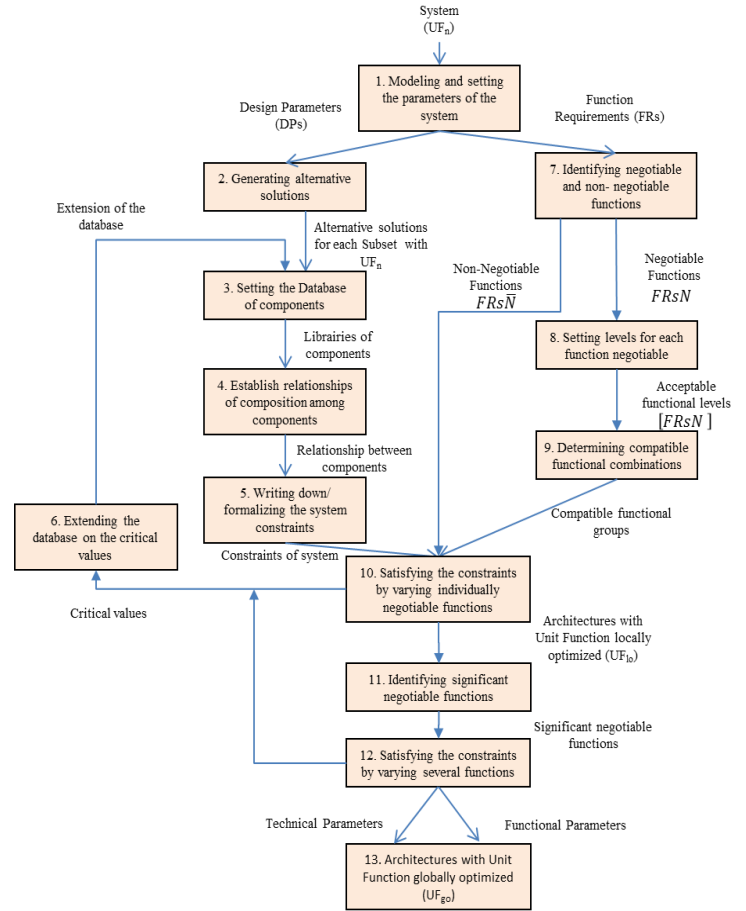


Fig. 1. Flowchart of the EcoCSP approach

EcoCSP allows judgments and choices to be made about functions on the basis of those functions that are deemed negotiable; the approach makes it possible to vary the system's performance in order to reduce environmental impacts.

4. Case study : Passenger ferry

4.1. Simplified modelisation

The system under study is a maritime passenger ferry that crosses the bay of Toulon. The ferry can transport 100 passengers. The Toulon ferry runs three lines 7 days a week over 300 days per year. Each ferry makes 24 bay crossings daily.

Taking account of various factors, 300 days of exploitation per year will be used as the functional unit. The ferry has a lifetime of 20 years. The diesel motors are replaced approximately every 12500 hours (or about 500 000 km).

For practical reasons, in this article we have deliberately simplified the system. The passenger ferry is thus broken down into 5 main sub-sets: hull and superstructure, power generation, propulsion apparatus, steering apparatus, energy and auxiliaries. Phases 1-5 in the general framework of the method (figure 1) and the main relationships governing the system are detailed in previous work (Tchertchian et al. (2013)).

4.2. Definition of negotiable functional parameters

Phases 7-10 of the method consist in determining the negotiable functions and among these the most significant (i.e. causing greater improvement).

In first part of the study, 6 scenarios are built by varying a single negotiable parameter (table 1): Speed, Passenger capacity, Number of mission, Insulation, Air Conditioning and the number of recharge (batteries). For each scenario the FU_{10} corresponds to transporting 2400 passengers per day.

Table 1. Negotiable functional parameters

Level	Parameters				
	P1: Speed max	P2: Nb of passengers	P3: Nb of missions	P4: insulation	P5: Air Conditioning
Current	12	100	24	No insulation	No AC
Acceptable	11,5	97	23	isolation	AC

In the second part of the study, FU_{go} scenarios are obtained by varying the six functional parameters simultaneously. In the following, 6 FU_{go} scenarios will be described according to a design of experiment L_8 (2^6) (table 2).

Table 2. Globally optimized functional unit scenarios

Parameters

Table 3. Results of the multicriteria assessment for architectures generated with FU_{go} scenario.

Scenario	Abiotic depletion		Acidification		Eutrophisation		GWP		Ecotoxicity		Photochemical	
	Unit		Unit		Unit		Unit		Unit		Unit	
	kg Sb eq	Gains/ S0	kg SO ₂ eq	Gains/ S0	kg PO ₄ ³⁻ eq	Gains/ S0	kg CO ₂ eq	Gains/ S0	kg 1,4 DB eq	Gains/ S0	kg C ₂ H ₄	Gains/ S0
S0	30128		13003		1393		1324661		6236588		672	
S1	27523	-9,5 %	12537	-3,7 %	1345	-3,6 %	1264583	-4,8 %	6159150	-1,3 %	641	-4,8 %
S2	28847	-4,4 %	11849	-9,7 %	1320	-5,6 %	1243347	-6,5 %	5847321	-6,7 %	621	-8,2 %
S3	31470	4,3 %	13833	6,0 %	1481	5,9 %	1394576	5,0 %	6559125	4,9 %	709	5,3 %
S4	31381	4,0 %	12955	-0,4 %	1410	1,1 %	1340310	1,2 %	6197649	-0,6 %	676	0,7 %
S5	32433	7,1 %	14715	11,6 %	1569	11,2 %	1462591	9,4 %	6916010	9,8 %	746	10,0 %
S6	33372	9,7 %	14548	10,6 %	1551	10,2 %	1462266	9,4 %	6788044	8,1 %	745	9,9 %
S7	29320	-2,8 %	12377	-5,1 %	1368	-1,9 %	1283601	-3,2 %	6097973	-2,3 %	644	-4,3 %

The function « objective » is to minimize the environmental impact over the life cycle (raw materials and manufacturing phase, use phase and maintenance phase. The end of life phase is not included). Each scenarios described above are assessed environmentally using the indicator of a single score EI99 in order to make the results clearer. We therefore provide a summary with the results of the multicriteria assessment with 6 environmental indicators, present in the CML method table 3.

4.3.1 Assessment of FU_{10} scenario

The first part of the case study compared 7 scenarios obtained by varying a single negotiable variable. These scenarios are assessed with reference to scenario 0, a scenario established using the CSP/LCA approach (figure 2). The transport of 2400 passengers per day is maintained in all seven scenarios. The functional unit is optimized locally according to the negotiated function. Speed, number of passengers and comfort are significant negotiable functions because their negotiation

Scenario	P1: Speed max	P2: Nb of passengers	P3: Nb of missions	P4: Insulation	P5: Air Conditioning	P6: Nb of charges	FU (Nb passenger s/day)
0	12	100	24	No insulation	No AC	1	2400
1	12	100	24	insulation	AC	12	2400
2	12	97	23	No insulation	No AC	12	2231
3	12	97	23	insulation	AC	1	2231
4	11,5	100	23	No insulation	AC	1	2300
5	11,5	100	23	insulation	No AC	12	2300
6	11,5	97	24	No insulation	AC	12	2328
7	11,5	97	24	insulation	No AC	1	2328

4.3. Simulations

First of all, the CSP/LCA approach is applied to the system considering the FUn (maximum speed 12 knots, 24 missions daily, 100 passengers per journey, heating for 6 months of the year). Applying CSP/ ACV the ship's architecture and its optimal state of functioning are determined by propagating constraints. This example was undertaken in C++ using the IlogCP constraint programming library (Ilog, 2006).

allows for a significant variation in the system's environmental impact. For example, a reduction of 4.2% in the maximum speed (corresponding to lengthening the journey by 3%), allows for a gain of 5%. The distribution of the number of passengers and the number of journeys has an influence on the system's performance. To respect the functional unit of 2400 passengers per day, two scenarios were assessed. The first corresponded to transporting 109 passengers over 22 missions and the second to transporting 93 passengers over 26 missions. While the first scenario allows to improve the environmental score by 4% the second generates 4.5% of extra impact for transporting 2400 passengers per day. Both scenarios have the same FU, but have very different outcomes. Similarly, improving comfort by better insulation, adding air-conditioning also generate new impacts. In order to reduce the impacts generated by complex systems in a sustainable way, it is necessary to obtain the right specification of negotiable functions ; this can be achieved either by modulating certain functions, or by making compromises between adding functions and reducing

certain performances. This leads to defining a globally optimized functional unit.

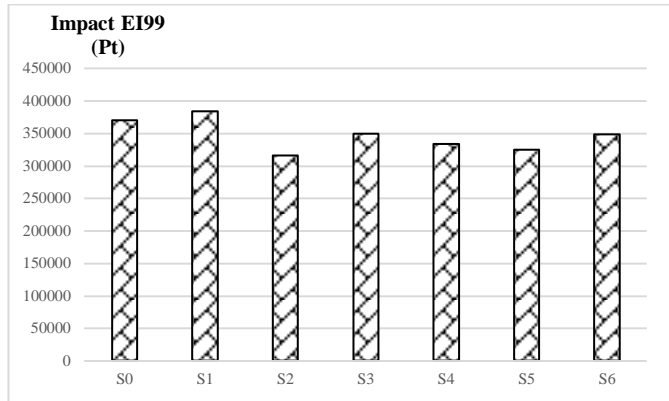


Fig. 2. Environmental Assessment for each FU_{lo} scenario

4.3.2 Assessment of FU_{go} scenario

While in the preceding sub-section the assessed scenarios respect the main function of « transporting 2400 passengers per day », in the second part of the study, seven scenarios were obtained by varying 6 significant negotiable functional parameters simultaneously, in accordance with the design of experiment in table 2. These six scenarios were assessed and compared to the reference scenario figure 3. The functional unit was globally optimized and the number of passengers transported per day varied between 2231 and 2400. Thus the impacts of the globally optimized functional unit was reduced by 3, 4 and 7%, depending on the scenario, compared with the nominal functional unit of the scenario of reference. Out of the seven modelised scenarios, five allow a reduction of environmental impacts of between 3 and 13% (depending on the component libraries used). A small reduction in system performance, defined by the globally optimized functional unit, results in an environmental gain that can be over 10%. In addition, this can allow for new functionalities to be added (air conditioning) or existing functionalities to be improved (increased comfort). It should be recalled that the scenarios that are not isofunctional with the initial scenario of reference, are no longer comparable with it.

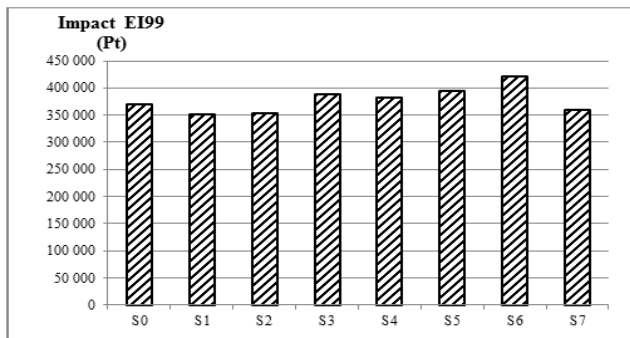


Fig. 3. Environmental Assessment for each FU_{go} scenario

Conclusions

In this article we have enriched the CSP/LCA approach by constructing the EcoCSP approach. This enables us to anticipate the configuration of a system's architecture by adapting the performances of negotiable functions. The complexity of couplings among sub-systems obliges the user to make use of « intelligent » tools, that by simulating many different scenarios, help the designer to fine-tune and choose the right technologies for sustainable systems. A slight downgrading of the performances related to these functions can generate substantial environmental gains. Reducing the system's performances or eliminating certain functions raises the question of outcomes for the passenger. For example, in this type of intercity transport, the number of passengers is not constant throughout the day. It fluctuates, and there are more people during rush hours. In the above simulations, the environmental gain is achieved to the detriment of « social » considerations; this is in contradiction to the concept of sustainable development.

The EcoCSP tool allows us to make functional judgments and choices to optimize negotiable functional performances and thereby reduce environmental impacts. Nevertheless, this does not mean we should neglect consideration of the social consequences that these choices have on the system's use.

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