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# AXIOMATIC DESIGN FOR THE DEVELOPMENT OF ECO-SUSTAINABLE METAPRODUCTS

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## ABSTRACT

The eco-design approach for new product development is becoming progressively more and more important for market and legislative reasons especially in advanced markets (EU USA, East Asia, etc.).

This paper analyzes through Axiomatic Design (AD) the potential capability of the meta-product approach connected with the use of a tailored Smart Eco-design Platform, for the improvement of the eco-sustainability of products. The approach, proposed by the authors to eco-design, introduces the meta-product level (or Functional System level) as the reference level for detecting and developing the optimal design through the use of AD. The first axiom aims to define the Design Matrix of the Functional System in order to detect its best configuration. The purpose is to avoid an optimization without appropriate knowledge in terms of interaction meta-product-resources. Then the Functional Requirements definition, used in AD, could represent the ideal index for the ease of sharing information and knowledge on a wide scale among different industrial sectors.

The development of the Smart Eco-design Platform could encourage the use of this approach in real product development. In this way it could be possible to develop a system of products with an overall higher level of eco-sustainability optimization, i.e. a system that needs less consumption of energy and material during all the products life cycles.

A case study about the improvement of a functional system composed of a refrigerator and a kitchen cabinet is included in the present paper to explain clearly the proposed approach.

**Keywords**: eco-design, Functional System, design approach, product development, meta-product.

## 1 INTRODUCTION

Scientific research and industrial results have been developing with a focus on effective eco-design approaches for new product development [Cappelli *et al*,. 2006; Collado-Ruiza, *et al.,* 2010; Roche *et al*., 1999; Waage, 2006]. Through these activities, good technical knowledge about the science and the characteristics of different materials and their level of environmental impact has been developed and collected in many commercial databases (e.g. Ecoinvent, Idemat, ETH-ESU, ELCD, etc.). In addition, many indices, measurement methods and technological guidelines have been introduced to measure and manage the environmental impact performances of a large set of industrial products [Riess *et al*., 1999 and Le Pochat *et al*., 2007]. All of these skills are strongly connected with a smart use of raw materials (reduction of weight, recyclability and management of hazardous materials), of energy ($CO_2$ emission reduction and energy efficiency) and the reduction of waste (scrap and hazardous materials).

An analysis of the current state of the art shows that the impact of eco-design activities for the development of new product are mainly limited by the following two main critical issues. On one hand, a single product point of view is used for eco-design analysis and considerations. In fact, traditional approaches obtain a first level of optimization through the progressive extension of the use of the knowledge (transformed in useful information for designers and process managers) in the overall supply chain of each product [Zhu, *et al*., 2010]. In this way it could be possible to obtain design solutions for each product which is able to optimize the environmental impact of a supply chain with different levels of complexity. The potential result is of undoubted value but it could be considered as a first level of optimization for the Eco-design Approach. As a matter of fact, the usual Eco-design Approach optimizes the single product independently of the system synergies related to the products that belong to the same meta-product during their life cycle. On the other hand, the sharing and the use of eco-design knowledge and experience in a large set of the industrial sector results in complexities for industrial users. Consequently, only a few industrial sectors (for instance the automotive one) have successfully introduced eco-design activities in their new product development processes with different levels of effectiveness [Johansson, 2002]. One of the most important root causes of this aspect is that all of the information is organized in a database based on the Technical Characteristics of the products that are often very different (per sector) from each other.

In this scenario, International Standards and local legislation become more accurate year by year and diffuse into each industrial sector.: e.g. EU Directive 2009/125/EC (Energy Using Product – EUP); 2002/95/CE (RoHS); 2002/96/CE (WEEE); 2006/12/EC (Waste). For this reason, Eco-design becomes more necessary year by year for an always larger set of industries.

The aim of this paper is to analyze, through AD, the potential impact related to the introduction of a Functional System approach to eco sustainability analysis of meta-products (product of products) as the optimal design level to develop extended eco-sustainability of products. The optimal design is obtainable using a Smart Eco-design Platform that collects all of the needed information to define a correct design considering the Functional Requirements connected with the sustainability of the system.

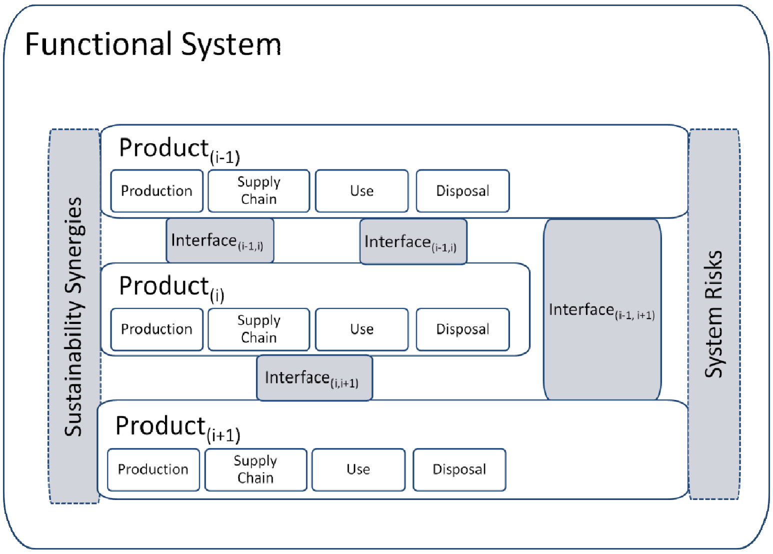


**Figure 1. Functional System composition: information studied in traditional approach (white boxes) and information added in the new approach (gray boxes).**

## 2 FUNCTIONAL SYSTEM APPROACH

As described previously, a critical issue for the eco-design approach is connected with the need for an expanded definition of the eco-sustainability of a product [Deutz *et al.*, 2010 and Lofthouse *et al.*, 2006]. In particular we suggest the consideration that the most suitable life cycle for each product is strongly connected with both the particularity of each product and also with the meta-product. We defined a "Functional System" as a meta-product composed of many products (Figure 1) that converges to the same set of functions. The Functional System is the central concept of each eco-design analysis; it is the measure of the performance delivered by the system under study. This unit is used as a basis for calculation and also as a basis for comparison among different systems fulfilling the same function. This set of functions is connected with a specific set of customers or consumer needs considering both B2B (Business to Business) and B2C (Business to Consumer) market spaces. Each product could belong to a different Functional System in a different part of its life cycle, considering production, use and disposal.

The traditional single-product approach doesn't show the Design Matrix of a meta-product that could indicate many improvement paths to identify the optimal solution. Without the meta-product functional scheme it is not possible to detect and consequently to solve many FR/DP correlations linked with the Functional System perspective (products interfaces, system synergies and system risks) because so many potential improvements are not used to obtain a more ideal meta-product.

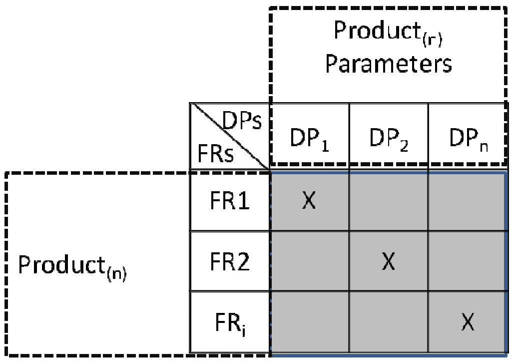


**Figure 2. Example of the Design Matrix for a single product.**

In particular it is important to apply the traditional approach and knowledge about Life Cycle Assessment (LCA) to the extended complex environment that is the Functional System. In fact, the introduction of the Functional System concept will create the potential to achieve a higher level of optimization for eco-designed product. This optimization through Functional System analysis assures that more degrees of freedom will be taken into account and more conceptual and physical resources will be introduced for the implementation of better eco-designed solutions.

Therefore without Functional System analysis it would be impossible to obtain the necessary information for an important reduction of the environmental impact of products. As shown in Figure 2, the Design Matrix of a single product could contain an insufficient level of information for the selection of the optimal sustainable solution. (The design could appears uncoupled.)

Instead it is necessary to extend the usual single product point of view to a meta-product one, i.e. from product environmental impact to Functional System one in order to identify the overall Design Matrix characteristics (Figure 3).

In this way, the focus of eco-design actions is moved to the most critical aspects for the system sustainability. These critical aspects arise from the large amount of attention on single products and also from the boundaries (between the different products that compose the Functional System) considering both sustainability synergies of the system and system risks. In this scenario the evaluation of the interfaces among all of the products, the management of these interfaces and the level of holistic integration among the always new products becomes relevant for the eco-sustainability of each Functional System.

## 3 SMART ECO-DESIGN PLATFORM

The approach introduced by this scientific paper aims to become the current state of the art in Eco-design methods and technical capabilities. The integration of all of these aspects could be obtained through the development of a framework able to detect and classify all of the necessary information. This architecture, called the "Smart Eco-design Platform" consists of all of the knowledge about the correlations among the Customer & Consumer Functional Requirements ($C^2$FRs), the Design Parameters of the Products (DPs), the Environmental Information (EIs) based on each specific eco-design technical experience related with the Functional System and the sharing of the overall knowledge (Figure 4).

So this platform can create and manage all of the knowledge about materials and best practices connected with the Eco-design capability considering the complex Supply Chain of the set of products linked with a specific Functional System.

The Smart Eco-design Platform helps to generate the Design Matrix of a Functional System and to identify the design improvement for the Functional System. By means of

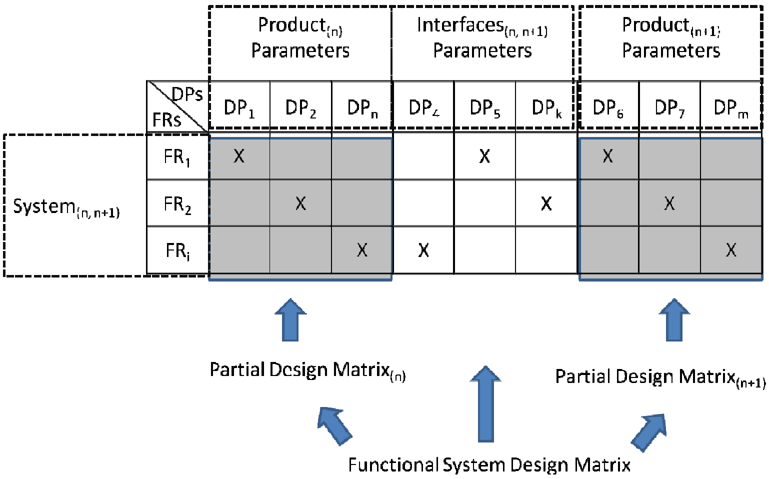


**Figure 3. Example of a Functional System.**

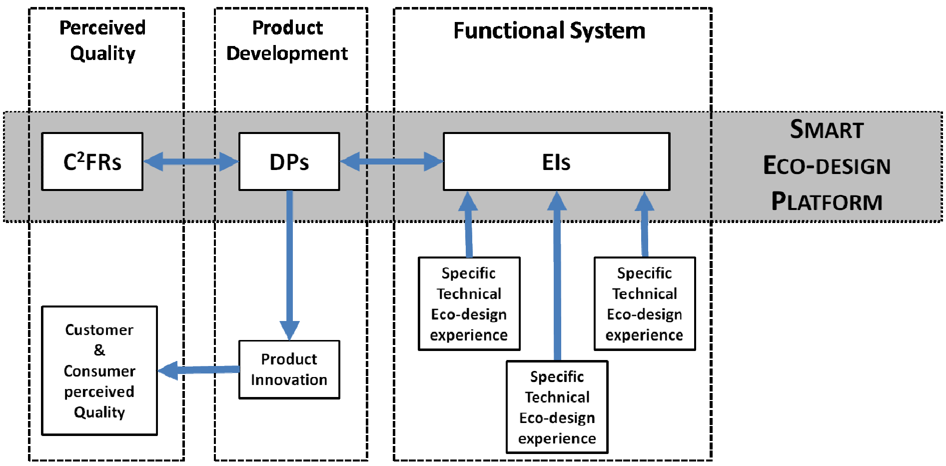


**Figure 4. Smart Eco-design Platform internal and external connections.**

these improvements it will be possible to develop innovative architecture and paradigms for the Functional System

Consequently it could assure a new higher level of performance to the customer and consumer of the products in terms of perceived quality.

The creation of this platform can manage and share the specific technical knowledge for all of the multiproduct supply chain of the Functional System (Figure 5). The common approach for the sharing, the collection and the analysis of the data is based on the AD Functional Requirements definition [Suh, 2001], considering both customer & consumer needs. This passage has an important impact on the described critical issue of Eco-design implementation, i.e. the difficulties in sharing the information in a wide range of either. A Platform based on Functional Requirements is clearly more general and user friendly for users that come from different industrial sectors.

The knowledge developed and diffused by the Smart Eco-design Platform allows the creation of a solution with a larger product flexibility and with a longer life time of the product. In particular, it is possible to define a more intelligent use of raw materials and energies based on resources sharing inside the Functional System. One of the primary impacts is the development of knowledge in the long-term and short-term C2FRs for each Functional System. This could be used for different products to reach longer life-times. In fact, the products could be optimized through a specific technical capability in coupling of technical characteristics with different time-governance of C2FRs. Therefore it could be possible to define a modularity considering different C2FRs and their connection with technical characteristics of each product. This knowledge permits the reduction of the use of materials and energy connected with the oversize of one or more technical characteristics during the development process (Figure 6).

In particular, the time governance is detected and analyzed using AD. This Design Matrix of the Functional System is able to identify and to solve the most conceptual critical FR/DP correlations (Figure 7). These correlations are usually related to an overconsumption of energy and a higher production of scrap and hazard materials. Then the first axiom of AD helps to evolve the products to an higher level of recyclability and reuse.

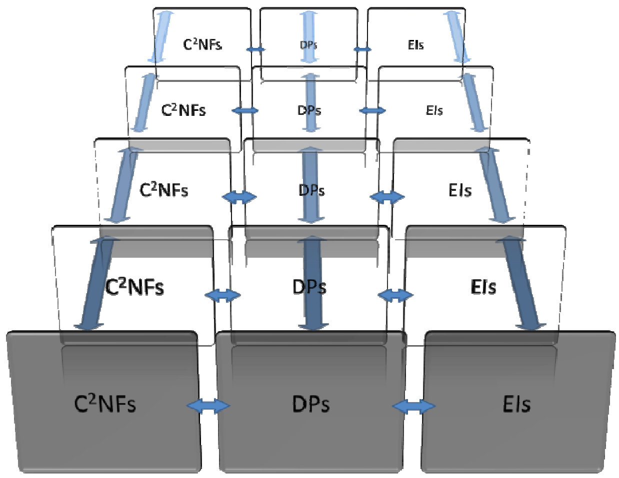


**Figure 5. Multilayer structure of Smart Eco-design Platform for Functional System.**

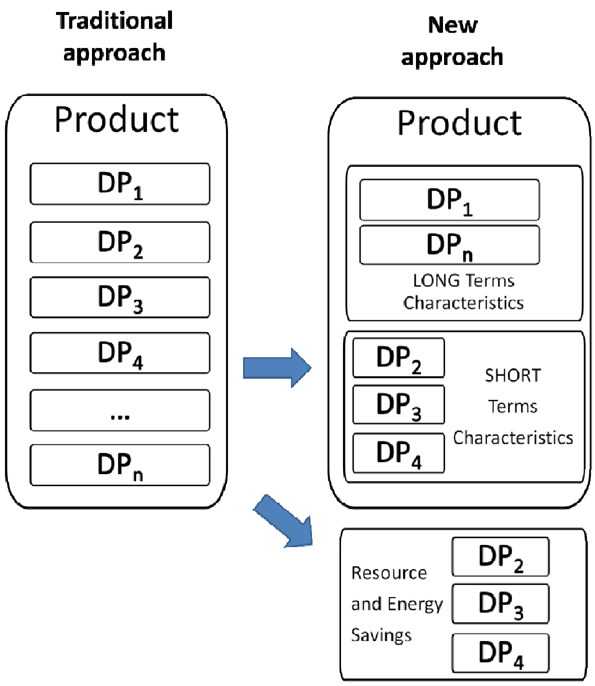


**Figure 6. Overdesign detection.**

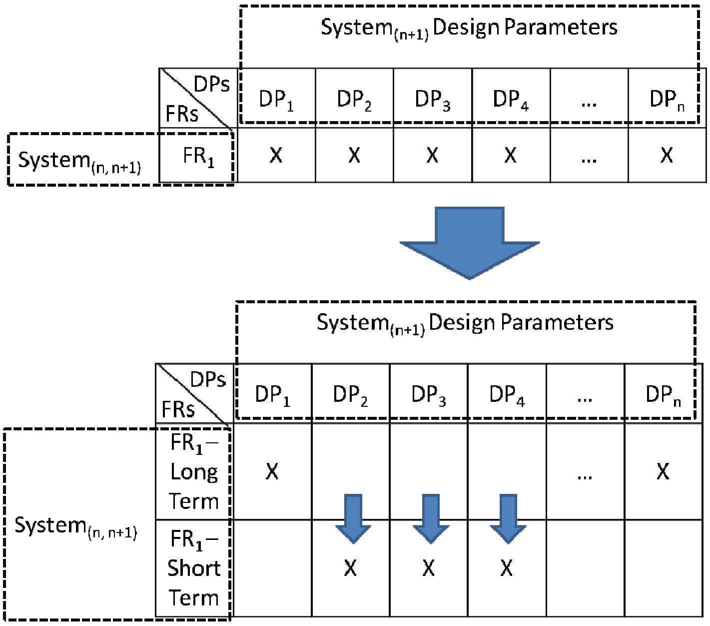


**Figure 7. Design Matrix modified by overdesign detection.**

## 4 CASE STUDY: IMPROVEMENT OF REFRIGERATOR AND KITCHEN CABINET SYSTEM

The proposed approach has been applied to a specific functional system composed of a refrigerator and a kitchen cabinet (RKC). The structure of a conventional refrigerator and kitchen cabinet is shown in Figure 8. The Design Matrix of the refrigerator and of the whole RKC Functional System are summarized in Figure 9. The refrigerator Design Matrix results in a partial selection of optimal sustainable solutions for the RKC system. Instead the RKC Design Matrix permits the designer to identify more possible design solutions to reduce the use of materials and energy connected with the oversize and the redundancy of one or more technical characteristics of the Functional System.

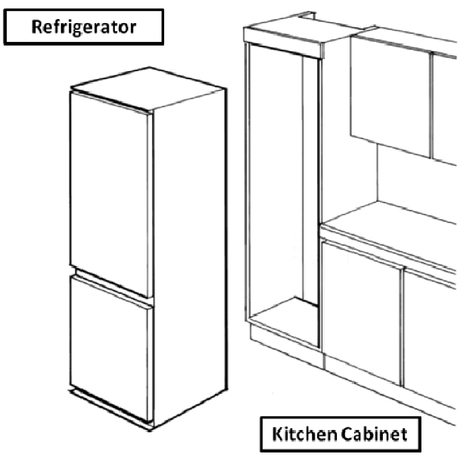


**Figure 8. Structure of conventional refrigerator and kitchen cabinet.**

| | Refrigerator | | | | | Kitchen Cabinet | | Interface |
|---|---|---|---|---|---|---|---|---|
| DPs / FRs | DP1 External refrigerator dimensions | DP2 Refrigerator structural layer | DP3 Internal layer | DP4 Insulating layer | DP5 Compressor and cooling circuit | DP6 Cabinet dimension | DP7 Cabinet cover | DP8 Interface dimension |
| FR1-Weight support | | x | x | x | | x | | |
| FR2-Have a pleasant appearance | | x | x | x | | x | x | x |
| FR3-Keep food cold | x | | | x | x | | | x |
| FR4-Keep food in a clean and hygienic environment | | | x | | | | | |
| FR5-Minimize energy consumption | x | | x | x | x | x | | x |
| FR6-Optimize refrigerator capacity | x | | x | | x | x | | |

**Figure 9. Design Matrix of refrigerator and of the refrigerator and of the whole RKC Functional System.**

For Example we can consider only FR5, FR6 and their related DPs. The reduced Design Matrix obtained is shown in Figure 10. This matrix can be improved using the first axiom of AD. In particular, an innovative concept is developed through the analysis of the matrix and the FR/DP correlations. The progressive consumption of food and the frequency of its supply rate suggests that the real needed capacity for the refrigerator (in terms of liters) is variable. Then it is possible to divide FR6 into two sub-functional requirements: FR6.1 - Full Load refrigerator capacity, and FR6.2 - Partial Load refrigerator capacity. These two FR6.i divided FR6 in a long terms characteristics (FR6.1) and short term characteristic (FR6.2).

Similarly, FR5 is divided in a short term (FR5.1) and a long term requirement (FR5.2). This knowledge helps in the identification of a more sustainable architecture for the RKC system. This new system architecture is shown in Figure 11 and consists of a decoupling of FRs in the short term and the external dimension of the refrigerator. These results can be obtained through the use of a unique structure for the refrigerator and cabinet and by the introduction of a movement degree of freedom on the insulation layer.

The Design Matrix of modified RKC Functional System is shown in Figure 12. The modified RKC System has a better efficiency at various loads.

| FRs \ DPs | DP1 External refrigerator dimensions | DP3 Internal refrigerator dimensions | DP6 Kitchen cabinet dimension |
|---|---|---|---|
| FR5.1-Minimize full load energy consumption | X | X | X |
| FR5.2-Minimize partial load energy consumption | X | X | X |
| FR6.1-Optimize full load refrigerator capacity | X | X | X |
| FR6.2-Optimize partial load refrigerator capacity | X | X | X |

**Figure 10. Design Matrix of Functional System RKC considering short terms and long terms FRs.**

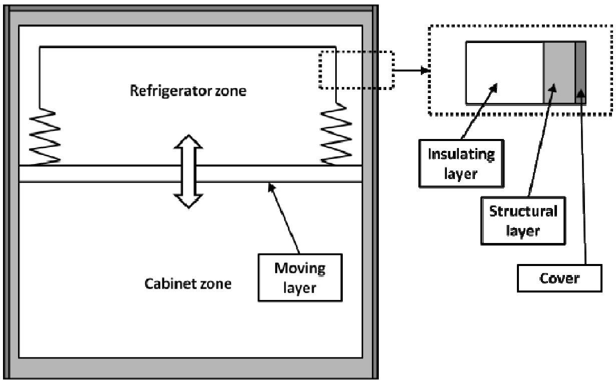


**Figure 11. Innovative architecture of RKC Functional System obtained using first axiom of AD.**

| FRs \ DPs | DP1 External refrigerator dimensions | DP3 Internal refrigerator dimensions | DP6 Kitchen cabinet dimension |
|---|---|---|---|
| FR5.1-Minimize full load energy consumption | | | X |
| FR5.2-Minimize partial load energy consumption | X | X | |
| FR6.1-Optimize full load refrigerator capacity | | | X |
| FR6.2-Optimize partial load refrigerator capacity | X | X | |

**Figure 12. Design Matrix of modified RKC Functional System.**

## 5 CONCLUSION

This Functional System Approach to the eco-design of new product drives the designer towards more eco-sustainability solutions. In particular, this approach helps the existing environmental management of products in a broader vision that takes into account a more integrated system. This is possible through the approach of a Functional System and permits the creation of a more integrated and holistic analysis of eco-sustainable products. Therefore this approach goes beyond the second critical issue through the introduction of a database based on $C^2$FRs. It shares the eco-design experience among different industrial sectors and different types of industries (large companies and SMEs). The reason is that $C^2$FRs have general characteristics based on the customers and not on the specific technicality of each industrial sector. Therefore $C^2$FRs result in a very user friendly indicator for the management of the Smart Eco-design Platform, as the users query the database for the functional requirement of the product. Therefore they obtain all of the information about materials, best practices, guidelines, and experiences that can help to design an eco-sustainable product depending on different contexts.

This paper shows how Axiomatic Design can be used as the core of the Smart Eco-design Platform for the detection of potential areas of improvement and for the introduction of innovative solution in particular regard to the sustainability of products.

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