Fuon Theory: Standardizing Functional Units for Product Design

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Abstract

In order for products to be comparable in different Life Cycle Assessments, Functional Units need to be defined. Nevertheless, their definitions tend to be simplified or ambiguous. There is thus a need to standardize these Functional Units, to be properly used for environmental comparison of the environmental performance of products. This paper introduces a systematic approach to define standardized functional units: the concept of fuons. Fuons are defined as *an abstraction of a product, based on its essential function and representing the whole set of products that share the parameters for this function's flows*. The use of fuons, and by these means the correct definition of the Functional Unit, should then help to retrieve a suitable product family for life cycle comparison, hence a set of products *whose LCA shares a common behavior*. This will allow comparing the environmental performance of a new product in development with the products in that family.

Keywords: Life Cycle Assessment, Ecodesign, Functional Unit, Product Development, Product Family, Fuons, Design Domains

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1. Introduction

Life Cycle Assessment (LCA) is considered in most literature as one of the most relevant tools for integrating environmental considerations in design (Jeswiet & Hauschild, 2006; Germani et al., 2004; Nielsen & Wenzel, 2002; Erzner et al., 2001; Gertsakis et al., 1997; amongst others). Including environmental considerations has been given names such as Ecodesign, Design for the Environment, Environmentally Conscious Design, Green Engineering, Sustainable Design, or Design for Sustainability amongst others (Waage, 2007; Howarth & Hadfield, 2006; Karlsson & Luttropp, 2006; McAloone, 2003; Coulter et al, 1995).

LCA consists of a *systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle* (ISO, 2006a). It is considered nowadays as the most widely accepted environmental evaluation tool. Nevertheless, amongst the design community, it is common to find detractors, (Millet et al., 2007; Sousa & Wallace, 2006; Erzner & Birkhofer, 2002, Jönbrink et al., 2000) mainly because:

- Performing an LCA is a time consuming task that is difficult to fit in the product development process.
- A correct LCA requires much information, not generally available in the initial stages. Later on, that information is available, but the results of an LCA are no longer as useful.
- LCA involves complex modeling, which does not necessarily go hand-in-hand with the models used during design.
- LCA is a complex task that generally requires special training.
- There is always some level of uncertainty in the results, although the apparent exactness may be a source of over-confidence.

As time consuming or complex as it may be, it is still considered in most methodologies as the standard to measure the environmental performance (Millet et al., 2007; Collado-Ruiz, 2007; Stevels et al, 1999). Some methodologies even define it as the core of an environmentally conscious product development (Nielsen & Wenzel, 2002; Wenzel et al, 1997). In cases where other alternatives are defended in front of it (Erzner & Birkhofer, 2003; Erzner & Wimmer, 2002; Brezet & van Hemel, 1997), the base methodology still includes in some way principles of LCA (Ostad-Ahmad-Ghorabi et al., 2006; Goedkoop, 2004; Goedkoop, 2001).

Another important trait about LCA is its comparative nature (Ostad-Ahmad-Ghorabi, 2009, Collado-Ruiz, 2007). From two alternatives, the most environmentally friendly alternative can be chosen, as much as a new product can be benchmarked with its predecessors. Nevertheless, when assessing a single product, it is difficult to judge whether a particular impact figure is high or low. ISO 14040 (ISO, 2006a) refers to functional units for this purpose (ISO, 2006b), although the definition allows for high variability between practitioners. The authors (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2008) presented a scaling approach to generate reference environmental impact ranges for LCA results of new products.

Initiatives to reduce the negative traits of LCA must be established. This paper aims to increase the robustness of proposing reference ranges, by gaining insight in the definition of standard functional units.

In order to allow a systematization of the definition of FUs, the product will be described in a new way. A theoretical concept will be developed inductively, based on common product descriptions used successfully in engineering design. After this, tests will be carried out to ensure the validity of the initial concept.

The current paper presents the theoretical phase of this research, in which the problem has been coherently defined and the theoretical groundings are set. A new concept is brought up to solve the problem, and it is exemplified for a set of 52 products. A workshop was conducted to test the applicability of the concept.

2. Domains in Engineering Design

In the development of a new product, many different groups of people get involved in the modeling. It is common to have different representations depending on the purpose, some of them even coexisting (Ostad-Ahmad-Ghorabi et al., 2008; Dankwort et al., 2004; Roche, 2004; Kobayashi, 2003).

Pahl & Beitz (1996) speak about function structure and construction structure, developed in different times, the second taking the first as its origin. Suh (1998) presents 2 domains, Functional Requirements or FR, and Design Parameters or DP. Gero (1990) explains de development of a product as the transition from a functional domain F to a description D, which is divided in behavior B and structure S. In all the previous, a particularly important transition is marked between the functional aspects of the product and its physical performance. A product will therefore be potentially described in these two manners independently.

In Value Engineering (VE) there is also a strong distinction between the functional and the physical domains (Miles, 1989). Value is defined as the ratio between the functionality in the first, and the costs in the second (Mudge, 1989; Miles, 1989), and it can be evaluated for functions or for components, i.e., for each one of the domains. Thus, they can be related but they are not intrinsically linked.

Furthermore, even though most times they are not established as an independent domain, all cited literature points out the different nature of the problem statement, i.e., the customer's or user's needs. Integrally, the previous theories can be seen as a distinction between the needs that establish the design, the functional domain and the physical domain. The first two can only be developed in the designer's head, and have an abstract nature. The third can be interpreted from physical elements, and can therefore be observed, measured and specifically defined (Hubka, 1984). The technology under which they are presented can vary from simple pencil sketches to very complex computer databases or structures.

The needs to be covered tend to be structured in a contract or a product design specification (PDS). These documents are a restatement of the design problem in terms of parameters that can be measured and have target values (Ullman, 1997). Generally, their definition tends to be very specific and as measurable as possible, so that there are no misunderstandings in the development team. Functions tend to be structured mostly in diagrams, and sometimes in lists (Hirtz et al., 2002; Pahl & Beitz, 1996; Bytheway, 1992; Mudge, 1989). The type of diagrams will depend on the type of relationship that is to be studied more thoroughly. Finally, physical components are represented in many sorts of ways. CAD systems or drawings define the physical properties, and they are interpreted in virtual and physical prototypes and simulations.

In LCA, the two domains are also present. The inventory data that is handled during most of the process is of the physical nature, since the environmental evaluation must be performed from this point of view. Nevertheless, since a product is being analyzed, the functional domain is needed, and the term of Functional Unit (FU) is defined in the goal and scope. Based on ISO 14044 (ISO, 2006b), a functional unit is defined as the quantified performance of a product system for use as a reference unit.

These FUs, however, tend to be defined in a simplified or insufficient way (Hirtz et al., 2002; Stone & Wood, 2000). Only the main functionality tends to be stated, with parameters that are not necessarily representative of all the effects (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2008). It would be the case of defining a car by the amount of kilometers driven, regardless of speed or comfort constraints. Furthermore, verbalization of the FU is possible in very different ways, so the final result depends on who is carrying out the LCA.

Lagersted (2000) presents the concept of Functional Profile for LCA, by which an additional set of characteristics are considered. In the domain of Functional Analysis, efforts from Stone and Wood (2000) are further completed in Hirtz et al. (2002) to generate a standard functional basis that will uniform functional descriptions. Experience shows that this has not yet transcended to LCA practice, and FUs still tend to be more vague than what would be necessary to treat LCA scaling in a systematic way.

3. LCP-families and LCA scalability

It is common in the design process to try to infer environmental behavior from analyzing previous cases. Benchmarking is also often performed in such a way. Nevertheless, the two compared products tend to differ in some aspects. On other cases, behavior must be estimated from products that are not equivalent. While an environmental expert can perform rough estimations, it is generally not possible to infer directly, and some error is accepted.

Nevertheless, environmental performance can be scaled on a number of parameters. The environmental impact, for a similar technology, tends to follow patterns than can be modeled. For this reason, the authors of the present paper developed previously the concept of product families for life cycle comparison (Life-cycle Comparison Product Families or LCP-families) (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2009; Ostad-Ahmad-Ghorabi et al., 2009). LCP-families are defined as *a set of products whose LCA shares a common behavior, and can therefore be compared in some practical way*. By grouping products in such a sort of family, it is possible to estimate a target environmental impact. If the new product has a lower impact, an improvement will have been made.

With an LCP-family in place, it is possible to find parameters to allow its scaling. The FU provides a useful source for this matter. Nevertheless, as was stated in the introduction, this matter constitutes a source of difficulty for most practitioners, since a complex modeling of the functional structure is a highly abstract and time-consuming task. Furthermore, FU’s will be disperse and therefore provide no uniformity.

For that matter, it is necessary to come up with a concept that:

- Is easily developed – the product can be modeled in an easy way, without investing time in detailing functions or other abstract terms.
- Gives a uniform answer – different practitioners should get to a unanimous result, so that scalability does not depend on judgment or expression.
- Gives representative answer for the LCP-family, allowing scaling of LCA results.

All methods that analyze or structure the mentioned domains under-perform in one or more of the previous requirements, as seen in Table 1.

	Is easily developed	Gives a uniform answer	Gives a representative answer
Requirements (PDS)	👎	👍 / 👎	👍
Functions (FA)	👎	👎	👍
Functional unit (LCA)	👍	👎	👍
Inventory (LCA)	👎	👍	👎

Table 1.- Performance of tools to analyze the different domains in design

An FU can be developed in few minutes, although – like other functional modeling such as Functional Analysis (FA) – practitioners will be likely to come up with different formulations. On the other hand, developing PDS gives a more uniform answer, but takes much more time.

It is important to mention that the scalability has to be performed in a functional domain. That is why, in conventional LCA’s, the FU is used to compare equivalent products, or in some sense to scale the life cycle to units that are comparable. That is also why inventory data cannot be used for this purpose. The reason for this is fundamentally ethical, since what is being stated is that it will only be fair to compare products that perform a similar function. This makes much sense when stated in this way, although it would not be so clear for specificities on FU’s. For example, from a certain point of view, i.e. urban transport, it would seem reasonable to compare a kilometer ridden with a bicycle and a kilometer ridden with an automobile. Nevertheless, if users are asked, the reasons to select one or the other depend on a set of additional factors that were not introduced into the model. For example, if it is a product for older people and the trajectory has steep paths, only a motorized bicycle should be entitled to comparison.

Since previously conceived descriptions in different domains fail to meet the requirements for scaling LCA, it is important to come up with some solution to avoid their problems, to systematize the process of obtaining the scaling parameters.

One initial step for this is to develop an understanding of the FU in a parameterized way. Collado-Ruiz and Ostad-Ahmad-Ghorabi (2009) developed a redefinition of functional units into a reduced set of parameters (FU Parameters or FUp’s) that can be used to scale the product. These parameters represent the main functions and the possible secondary functions. Many of them will be physical magnitudes like kilometers transported or bits of information contained, although most probably not all of them. Others will be dichotomies or subjective scales, like how important handling or aesthetics are. It is important to make the division into two sorts of FUp's, as shown in Table 2.

Type of FUp	Description	Examples	Representation
Physical unit	They are modeled in the form of a physical magnitude that represents the main functions of the product, and thus have values to scale with.	Contained volume, lifted weight, transmitted power, etc.	FUp^{p}_{i}
Functional constraint	They constitute a constraint to design, or an additional function or performance specification that the product must fulfill. Their nature can be dichotomic (true/false), or of any other which explains the phenomenon.	Protection from corroding environment, Ease of access, Transparency, Type of source energy used, etc.	FUp^{c}_{n}

Table 2.- Types of FUp's

Functional constraints are very general in nature, and several types can be identified:

- Additional magnitudes. They have physical units, but represent a different sort of magnitude to that of the main function or functions. They imply restrictions in the technology or physical implementations that the product can have. Any sort of physical magnitude, if not part of the FUp^{p}'s, can be an example of this.
- Scalable subjective constraints. They can take a value out of a subjective scale – such as 1 to 9, for example, which can be particularly useful in qualitative evaluations (Saaty, 1980). Examples of this are hygienic or ergonomic constraints.
- Classifications or selections from a set of options, with a limited subset of answers. Examples of this are types of energy used or produced.
- Requirements as dichotomies. They set a constraint for something that has to be accomplished in the design, and are modeled as a Boolean variable (true/false). One of the most important problems of these variables will be that, if false, are difficult to be detected. Examples of this are requirements for transparency or corrosion resistance.

The structure of *FU* is then as follows:

$$FU = \{ FUp^{p}_{i},\ FUp^{c1}_{j}, FUp^{c2}_{k} \} \quad (1)$$

With i,j,k as the number of FUp's necessary to meet all physical FUp's and constraints.

The strategy to systematize the process is to develop a set of concepts or a classification, by which the FU or equivalent shall be defined in a single way. Even in a functional domain, there is a set of requirements that this classification must fulfill:

- They should constitute an idealization of the product – it should not include every detail in the product.
- They should be comprehensive – it should include every possible product.
- They should be as general as possible – no artificial barriers should be introduced in the LCP-family.
- There should be a limited number of them – to ease the process.
- They should be combinable – and addition of several of them should be able to define an LCP-family.
- They should be independent in abstract terms – each concept should be understood as an entity, and not conflict with any other.
- They do not have to necessarily be independent in physical terms – they are combinable, and implementations are bound to spawn from more than one concept.
- They should have a direct link with the functional unit, and just by this means to the product's inventory.

4. Fuon theory: linking the domains

A systematic approach will be developed to derive the LCP-family by means of correctly defining the FU. In order to do so, products' functions need to be described in a standardized way. Where function may be something abstract, the FU is the quantification of the function.

There are many approaches and possibilities to define and to set up a FU for a product, but none of them standardized enough. The fact of having various definitions of functional units for a product may even lead to randomly proposed LCP-families. The question that arises here is: is it possible to functionally describe and define the various products out in the market and any new product which will be developed by a limited set of FUp's?

To seek answer to this question, the authors of this paper have been inspired by a theory in psychology called Recognition-by-Components (RBC), first proposed by Biedermann (1987). The assumption in this theory is that a modest set of generalized components, called geometric icons or geons, can be derived from contrasts of two-dimensional images. The arrangement of geons is used to represent a particular three-dimensional object. Examples of geons are blocks, cylinders, cones or wedges. The discussed theory provides even more (Biederman, 1987):

1. The number of available geons is limited to 36, from which all objects which need to be recognized by human can be constituted. In (Biedermann, 1987) an amount of 3000 basic-level object categories are identified, where each category contains about 10 types of objects, leading to an amount of 30000 objects which need to be recognized by human.

2. Another important consequence of the theory is a property of the geons: they are invariant over viewing position and image quality and therefore,

3. allow robust object perception.

In a similar manner to RBC theory, the question arose whether elements could be defined to describe the FU of all products which are under use by human. Is it possible to have a limited set of icons, hereon called *functional* icons or *fuons* which analogously have the following properties?

1. It is a limited set of fuons which help to establish the FUs for all products,

2. to provide a systematic approach for defining the parameters included in a FU, regardless who is defining the FU. In fact, the same FU should be achieved for the same product, regardless who, where and when the FU is defined, and therefore,

3. allow reliable functional product modeling for scaling purposes.

For the previously stated purpose, the concept of fuons is defined as *an abstraction of a product, based on its essential function; it represents the whole set of products that share the parameters for its functions' flows*. Although the definition concentrates on the main functions, secondary functions are also considered in additional variables (FUp^p's and FUp^c's) with enough level of detail for LCP-families and LCA scaling (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2009). One advantage of fuons is that it makes the development and the usage independent. An expert in the field can develop the fuon by performing market studies, consulting PDS's and sectorial studies, and/or consulting other experts. Once it is developed, LCA practitioners can make use of it to establish standardized and uniform FU's for their products. As these concepts will be more general and related to the main function, the selection between one and another shall be clearer. The FU will be derived from the fuon, taking the form shown in Equation 1. The user, e.g. the engineering designer, will select the fuon and automatically be faced by a standard list of FUp's developed by whoever developed the fuon. Therefore, for the same fuon, always the same parameters will be selected, and it can be made sure that no FUp^p is left undefined. All FUp^c's defined will be considered restrictions as to the products that can fall under the same family, and the ones that are not defined will be considered irrelevant for the study. In that way, the LCP-family can be more easily developed, as seen in Figure 1.

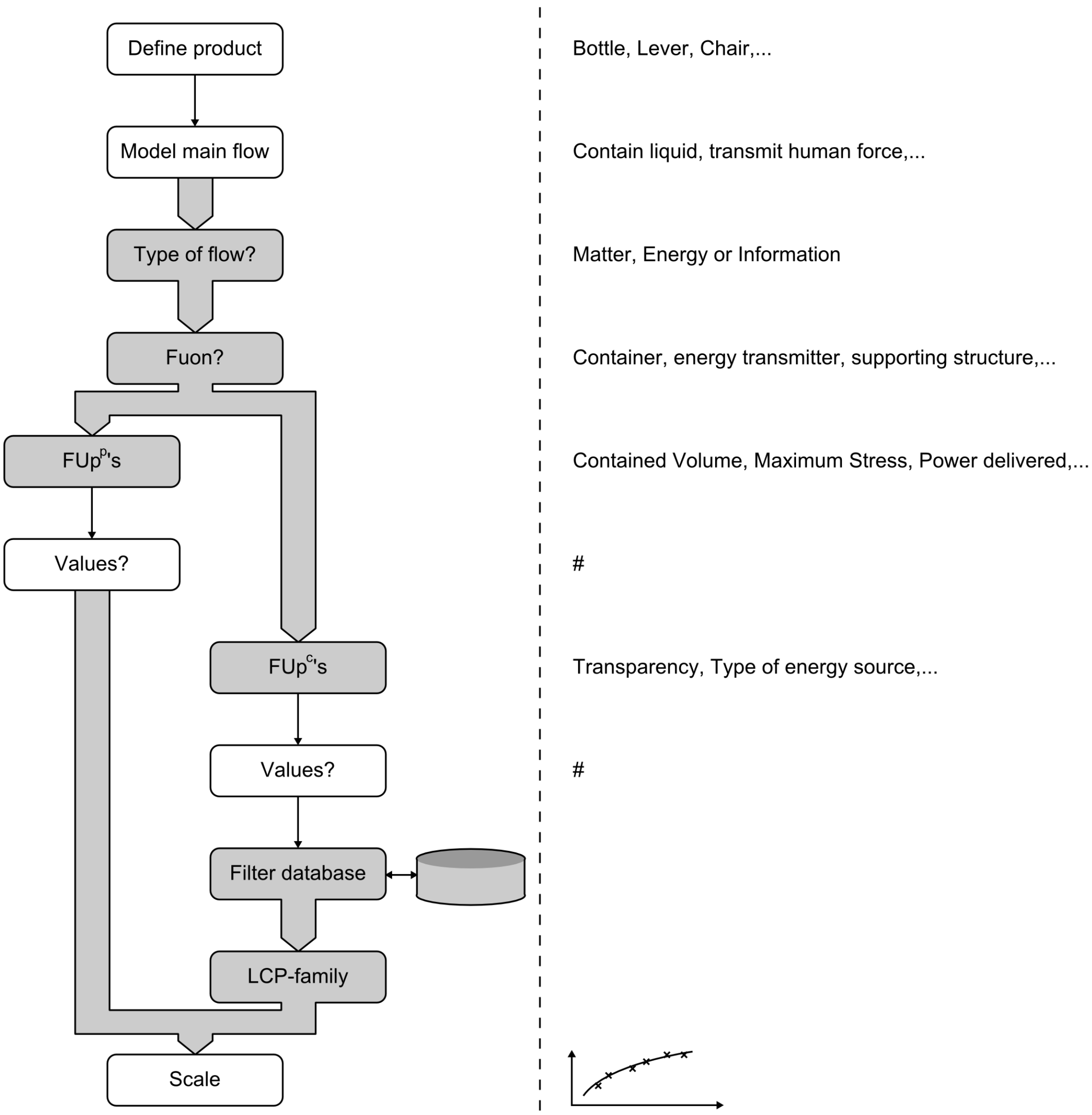


Figure 1.- Flow diagram of how to use Fuons for developing LCP-families and scaling LCA-results

A presumed advantage of this approach is that a different person will select the same fuons, and therefore phrase an identical FU. This assumption will be tested in the workshop presented further on in this paper.

In order to completely exploit the benefits of fuons, products have to be modeled at complete assembly level. Nevertheless, it is not possible to neglect that some users might be suppliers of only components within a product. For these suppliers, each component can also be modeled by fuons. This will however entail that part of the solution principles (part of the so-called “how”) have been determined, thus partly limiting their application.

For example, a car manufacturer might regard its products’ fuon as *a provider of movement* or *transportation*, although an engine manufacturer might regard its component’s fuon as *a provider of power*. Figure 2 faces the previously mentioned physical and functional domains, building the links between fuons and the different already existing concepts.

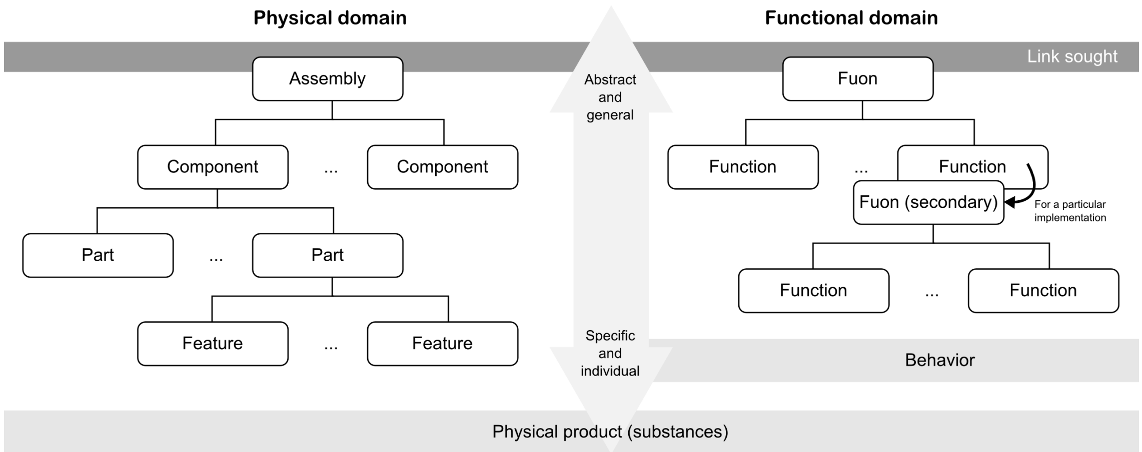


Figure 2.- Physical domain versus functional domain

Contrarily, the structure of the physical domain is intrinsically hierarchic: an assembly can be parsed into its components and components on the other hand can be parsed into different parts. Parts are built out of specific shapes or features that define them completely. Behavior is a direct consequence of these features.

There is however some analogy between the domains, in the sense that higher levels of abstraction come with lesser levels of detail. Naming an assembly (the same car, for example) is more general than specifying particular features from it, like describing the material that the capacitors from an electric engine are made of. To state the second, many decisions have been already taken about the car (i.e., that it is electric), and thus it has been strongly specified. Fuons work in the same way, since the fuon would be valid for the car (or for any transportation device), but if specific functions (or secondary fuons for the components) are specified, some decisions will also have been already taken. Fuons have a link to the highest level of abstraction of the implementation (the car), that can be conveniently used for LCA scaling: acceptable environmental impact ranges for cars can be inferred from other cars or transportation devices, and improvement ideas could spawn from them.

5. First steps: The birth of a Fuon

To test the application of fuon, two of them are developed by the authors to be used for testing during a workshop by a set of 10 practitioners, for a group of 52 containers, understood as “any object that contains matter”. The examples were the result of a brainstorm on products that could follow this definition. The exact products and variations are shown in Table 3.

Type of product	Number of products	Variations	Times *Container* fuon was selected	Times *Logistics* fuon was selected	Times any other geon was selected
Glass bottle (single use)	4	1l, 0.5l, 0.33l and 0.2l	8 / 8	0 / 8	0 / 8
Glass bottle (multiple use)	4	1l, 0.5l, 0.33l and 0.2l	8 / 8	3 / 8	1 / 8
PET bottle (single use)	2	1.5l, 0.5l	3 / 3	0 / 3	0 / 3
PET bottle (multiple use)	5	1.5l, 1.5l thin, 1.5l slim, 1.25l, 0.5l	6 / 6	2 / 6	0 / 6
PP bottle (single use)	2	1.5l and 1l	4 / 4	2 / 4	0 / 4
Drinking can	3	Al, PP+Al, Steel	16 / 17	2 / 17	2 / 17
Food can	2	0.5l and 0.6l	6 / 6	0 / 6	1 / 6
Paper sleeve	1	-	6 / 7	0 / 7	1 / 7
Paper bag	2	With or without handles	14 / 16	3 / 16	6 / 16
Cardboard box	3	Small (0.5l), medium (0.7l) and big (1.5l)	7 / 7	1 / 7	1 / 7
Pizza box	1	-	9 / 9	5 / 9	3 / 9
Tupperware	6	0.1l, 0.25l, 0.4l, 0.8l, 1l and 2l	10 / 10	1 / 10	1 / 10
Closable bottle with ceramic cap	1	-	5 / 5	1 / 5	0 / 5
Plastic bag	2	PP and PE	12 / 13	5 / 13	4 / 13
Tight-closing bag	1	-	7 / 7	0 / 7	2 / 7
Freight container	4	TEU and FEU, Europe and Global	8 / 8	6 / 8	2 / 8
Envelope Letter	6	A4, C5 and C6/5, Europe and Global	3 / 9	4 / 9	2 / 9
Trash can	3	For mixed waste, for biowaste and for plastic waste	5 / 7	1 / 7	2 / 7

Table 3. - Products under study for the development of the container fuon

Since the common characteristic from the product is the fact that they contain matter, their fuon will be called *container*. They are described as *an element that encloses partly or totally other physical elements, protecting them or isolating them from the external environment*. Its only apparent existing flow is matter. This matter – whatever is introduced in the container – is stored in the container until it is required by the user, who then extracts it.

Since most of the products do not apparently have more than one main flow, it is possible to describe it by means of one fuon. It is then necessary to define a standard unit for this parameter. Mainly, containers are defined by the quantity of matter they contain. A closer look reveals that the limiting factor tends to be the *volume contained* (V), being the mass adaptive to the physical characteristics.

Nevertheless, some products will be under stricter mechanical specifications than others, as can be seen in the variation of their PDS. Therefore, there is a need for additional variables to be defined as FUp^p. In a first approach the maximum stress requirement (σ) for the product was chosen to form the second FUp^p.

To test these FUp^p's, environmental and functional information about the 52 products was modeled. Their life cycle inventory was developed and assessed by using cumulative energy demand (in MJ). The previously mentioned FUp's were also defined accordingly. A regression model was built with the environmental impact as dependent variable and the FUp^p's as independent variables. Stress requirement did not prove useful as a scaling parameter. Instead, the weight supported, hence the weight contained in the container, and the number of storages, were taken into account. This deductive approach was then statistically verified, and finally the three variables *volume contained*, *weight supported* and *number of storages* proved suitable for scaling among the investigated products.

Since FUp^p's do not define the product completely – other characteristics must be specified for products to comply with the needs of the user, i.e. to provide with secondary functions – the PDS document must be scanned to detect additional requirements, that will take the form of FUp^c's. A brainstorm was performed to add any additional requirements (Hubka, 1984). Figure 3 shows the final concept of the container fuon.

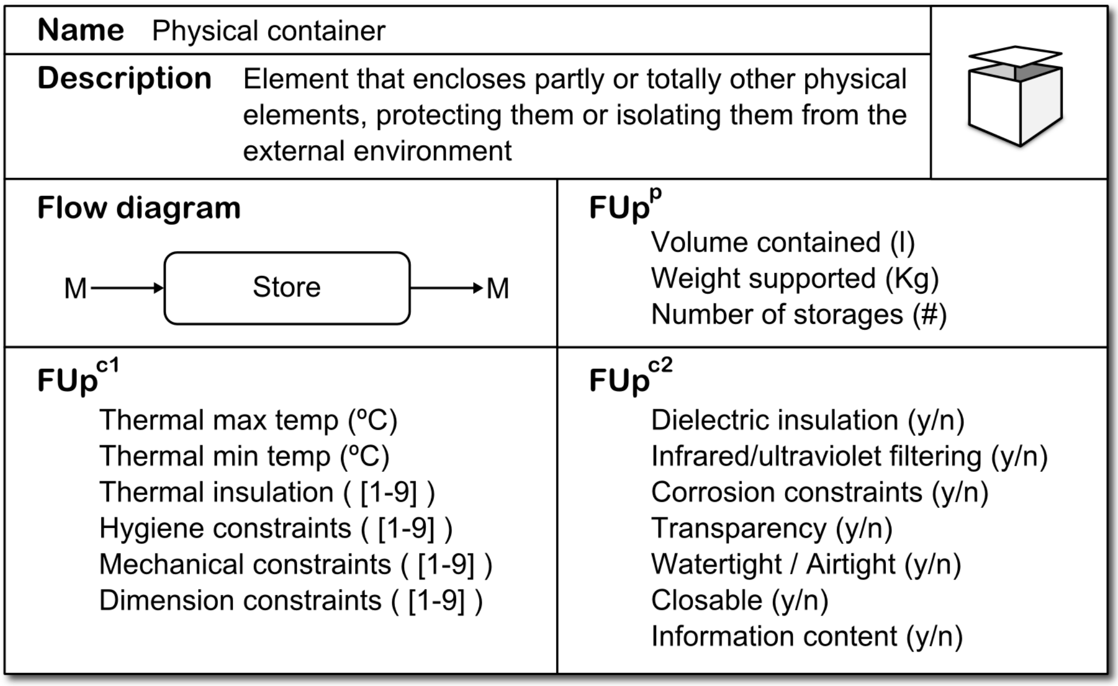


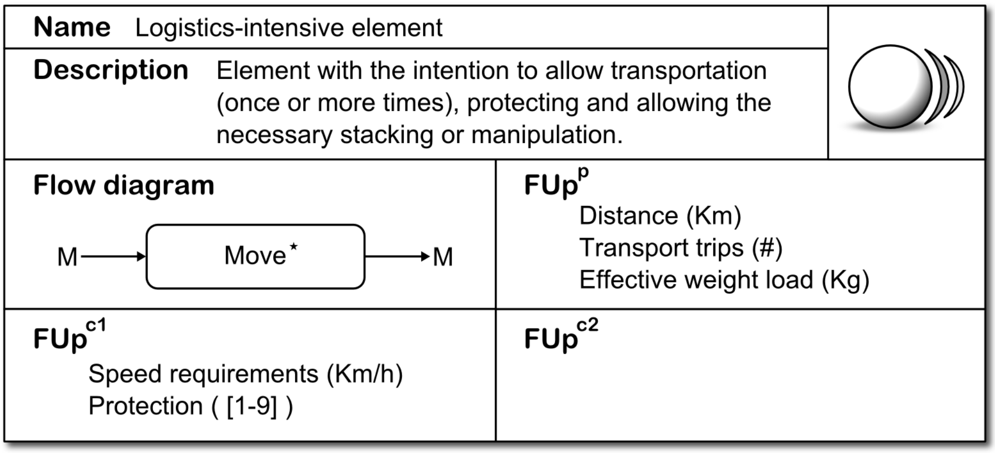
Figure 3.- Final concept of the fuon physical container

Some of the products, e.g. some of the glass bottles or the freight containers, will be used more than once in their life cycle. Some others, such as the envelopes, might be single use, but they will be transported over more or less long distances. The fuon container with its defined FUp's is not able to cover the need for more or less transportation, which for some of the products constitutes the main reasons of their existence. Hence logistics must also be considered for some of them. The effects of logistics will be covered by an additional fuon.

Since the characteristic of the fuon is to move matter from one point to the other from a service point of view, the fuon will be named *logistics-intensive element,* further named as *logistics.* It is described as *an element with the intention to allow transportation, protecting and allowing the necessary stacking or manipulation*. The only existing flow is matter. This matter is moved from one point to the other. It is a function for the provider/company, not for the product. In other words, it is not the product providing the possibility to move, but the product needs to be moved from one point to the other to fulfill its function.

The parameters which are decided to describe the fact of transportation are the *distance* (in Km) to be covered, the *effective weight load* (in Kg) to be transported and the *number of trips*. By using these three parameters as FUp^{p}'s, not only products being moved can be modeled, but also logistics as a service.

The final concept of the fuon logistics-intensive element is shown in Figure 4.



* This is a function for the company, not for the product. It is performed by another product or element, but it is included in the life cycle. Although the philosophy does not totally fit a functional approach (the function is not performed by the product), it is common practice to proceed in this way in LCA.

Figure 4.- Final concept of the fuon logistics-intensive element

All products covered by the logistics fuon (33 cases) were assessed with both fuons, as well as with the logistics fuon only. In both cases, a convenient linear regression model could be developed out of the FUp^p's. Furthermore, the container fuon was tested with those products that were not part of the logistics fuon (19 cases), giving also an acceptable model. The model was also tested filtering through the FUp^c's, i.e. varying the secondary functions that the product performs, or how it performs them. For each developed scenario, at least one of the FUp^p's turned out to be relevant for the elaboration of a model. In most cases, most of the FUp^p's took part. Therefore, for all the studied combinations, it was possible to generate a model that was representative enough of the environmental impact, with a reliability of 80%.

6. Workshop and results

In order to test the correct performance of fuons, a workshop was conducted with 10 students, selected among different technical disciplines (process engineering, industrial engineering, mechanical engineering and industrial design mainly) and with different levels of knowledge about LCA. After a brief introduction about LCA and FUs, they were asked to come up with the FU of a set of 15 products each from the list of products mentioned before. On a second round, they were introduced to the concept of fuons presented in this paper, and asked to model the same list of products through them. They were handed a list of fuons, including those two generated in section 0 and the names of some other tentative ones such as force transmitter, information storage or supporting surface. From this list, they were asked to select as many as they considered adequate. Their answers are shown in Table 3. The last three last columns present the ratio between how many times a particular fuon was selected and the number of times any of the products was assessed.

If the participants selected any of the two fuons of section 5, they were given Figure 3 and/or Figure 4, and they were asked to select the most relevant FUp's and to rephrase the FU accordingly. This information was not available for the other rarely selected fuons, and the participants had to continue the process without it. However, all participants were given the chance to add new parameters if they considered it relevant.

For the analysis of the workshop results, all FU's developed in the first round were analyzed and keywords were extracted with their specific phrasing. Words with a same root (e.g. Resist and Resistant) were considered as the same concept as long as their meaning in the sentence was the same. For the initial FU's, a reduced list of keywords was developed by the use of synonyms, and both of them were analyzed. In the case of the FU's developed from the fuons, FUp's and new keywords were documented. FU's both with and without the new keywords were assessed. For each product, the average keywords used and the amount of keywords that more than 50% of the participants use were measured. The ratio between both is considered a percentage of commonality between FU's, as stated in Equation 2.

$$Commonality_{FU} = \frac{Nr. of\ keywords\ stated\ by\ more\ than\ 50\%\ of\ the\ participants}{Average\ keywords\ used\ to\ define\ the\ product} \quad (2)$$

Participants were asked to select the relevant FUp's, and they were processed in the same way as above. Additionally, commonality in the selection of fuons was assessed with a stricter threshold, as presented in Equation 3.

$$Commonality_{Fuons} = \frac{Nr. of\ fuons\ selected\ by\ more\ than\ 90\%\ of\ the\ participants}{Average\ fuons\ used\ to\ define\ the\ product} \quad (3)$$

Individual products were analyzed, averaging 47% of commonality on their FU's (37% without synonyms), which shows the rather high level of disagreement. Furthermore, only 4 products showed a commonality rate higher than 50%. Categories of products (e.g. all bottles or all boxes) for which the keywords should be similar were also analyzed. The new average for the groups was of a meager 31% (18% without synonyms), showing once again the lack of homogeneity in the answers.

Comparing this to the FU's generated by the fuons, the results are considerably higher. If only the FUp's are considered, the commonality averages over 70% (75% for groups). Extending the keywords to those added during the formulation of the FU slightly reduces these figures, to 68% and 71% respectively. Additionally, fuons were intended to be used completely, and not to have their FUp^{P}'s selected, so fuon commonality (with a much stricter threshold of 90%) was also assessed, giving an average of 70% for individual products. This would mean that 70% of the selected fuons (and thus, of the FUp^{p}'s) are agreed by at least 90% of the participants.

In general, it was observed that in 92% of the cases, there was an increase in the percentage of commonality when using fuons, as compared to when not using them (97% compared to FU's without using synonyms). In most cases where commonality decreased, the cause of this was a more detailed or relevant FU (higher amount of keywords, excluding keywords that are not measurable or that do not represent performance …).

Similar studies were developed with all the products that had been defined by the authors as "containers" or "container and logistics". Commonality is obviously much higher when using fuons, with a value of 71%, compared to an 8% (0% without synonyms) when comparing FU's. This shows that through fuons it is possible to have a common understanding of all the exposed products, and therefore to compare them.

Nevertheless, there is still room for improvement of the fuons and their description. Some of the cases provided important information for enhancing the FUp's of the fuon. In 35 cases out of the 150 available ones, participants considered they need additional keywords and terms to detail and to phrase the FU, additional to those given through the selected fuon.

In 10 out of 35 cases, the term "protection" was used to underline the fact that the stored materials need to be protected from the external environment. All 10 cases include at least the fuon physical container. Some of FUp's contained in this fuon already cover the issue of "protection", e.g. infrared/ultraviolet filtering (protection from a spectrum of light waves), watertight/airtight (protection from water/air), hygiene constraints (protection from bacteria), etc. Some keywords dealt with protection from mechanical exposure, external impacts and/or forces. To deal with this property, "mechanical constraints" is added as an additional FUp^{c1} to the fuon physical container. The fuon logistics-intensive element, which was used in 1 case, contains the parameter "protection" as a FUp^{c1}; it covers protection issues for a safe transport of the product.

The keyword "transport" is used in 10 out of the 35 cases. It covers the fact that the products need a lot of transportation along their life cycle, hence are logistics-intensive. The fuon logistics-intensive element covers transport parameters, and it had been chosen in 5 out of 10 cases. But only in 1 case the related parameters were further used and quantified. A more detailed description of the fuon logistics-intensive might ease the understanding of its concept as well as its proper use.

In 4 cases the fact that the product needs to be "chilled easily" was mentioned. This is the case for the analyzed cans. The fuon physical container includes the parameter thermal insulation with a scale from 1-9 which was meant to cover this fact, as for example a bad thermal insulation means a good heat transfer and the property that a product can be chilled easily is a consequence of its good heat transfer.

Also in 4 cases the term “storing” was mentioned. In 1 case this term was synonymously used for containing matter, in 3 cases the term described the ability to store and stack the product itself, e.g. to stack for transport or the ability to store in the refrigerator. The stacking requirement could also be covered by the introduced parameter “mechanical constraints”; a product being stackable induces a higher mechanical exposure which can be quantified in a 1-9 scale. The ability of the product to fit into predefined or standardized dimensions (e.g. refrigerator) will be covered by an additional FUp^{c1} for the fuon physical container. It will be named “dimensions constraints” scalable from 1-9; 9 means that standardized and/or limited dimensions are given and need to be complied with and 1 that dimensions can be chosen freely.

The participants were asked to assess the process of phrasing an FU by means of fuons. In a scale of 1-4 (total disagreement-total agreement) the following three core questions were assessed:

1. Was it easy to choose the appropriate fuon and the related parameters for the product? (average assessed value 3.2)
2. Do you consider the use of fuons being intuitive? (average assessed value 3.2)
3. Did the use of fuons ease the formulation of the functional unit of the product? (average assessed value 3.1)

On top of that, direct feedback of participants was that the phrasing of functional units (without the use of fuons) was a difficult task, even for those who had an LCA background. However, the use of fuons gave a feeling of robustness as to phrasing a comprehensive enough formulation of the FU, which could later be used for scaling purposes.

7. Conclusions and outlook

The present paper opens a new area in which to develop the understanding of the assessment of products, and more particularly their environmental assessment. Analogously to RBC theory, the authors present a concept that can explain the functional behavior of products and link it to FUs in a way to allow LCA scaling.

To elaborate this concept, a set of requirements was defined taking as origin the needs of LCA-scalability. With them and practicality in mind, the concept was derived inductively. Two fuons were developed, providing insight in the behavior of big collectives of products when scaling or concluding out of a limited set of parameters. These parameters constitute a standardized FU of the product, and can therefore be used to compare different products and estimate the impact of non-existent products with current technology. A systematic framework for the definition of fuons is to be developed from this point.

To check these assumptions and gain insight in the performance and applicability of fuons, a workshop was conducted in which FU's were stated both with and without the help of fuons. Since participants had different levels of experience with FU's, it was possible to get a notion of the learning curve for both cases. Phrasing the FU's was perceived as a difficult task, and the use of fuons was seen as facilitating and guiding. Uniformity in the answers increased by using them, although not to values of 100%, mainly due to the fact that using fuons also has a learning curve. It is important to properly document the current and future fuons, so that their selection and proper use is simpler. It is proposed to come up with a simple question based on the definition of each one of them, to assist in this selection process.

Out of the results of the workshop, the three conditions shown in Table 1 can be assessed for product modeling by means of fuons. *Ease of development* can be justified by the fact that all participants were able to develop the FU's in approximately the same time than without that assistance, with a very positive feedback concerning the avoidance of difficulties. Furthermore, the results show an increase in *uniformity*, particularly if only the parameters in the fuon are selected. Finally, the results are *representative for scaling* of LCA because of being in the functional domain, and especially for being defined by a set of scaling parameters that have been tested before during the development of the fuon.

A first step in developing this new research area is the development of a systematic procedure for the development of fuons. To do this, combination of fuons must be further studied, as well as the way in which different parameters interact. The development of each fuon is a time and information-intensive process requiring market studies, PDS and product studies consultation, and expert knowledge, which nevertheless eases future work when applied.

The map of fuons should also be expanded to allow the analysis of different products. Additional fuons should be generated, e.g. like *information storage*, *energy generator* or *energy transformer*. For each one, a list of the FUp's will be generated. It should be comprehensive enough to phrase all the FU's, for those products described by the fuon. Furthermore, this process can be automatized using collaborative platforms that would allow LCA users to include information about their impact results and functional characteristics.

Once a robust set of fuons is developed, another potential field of development is to include the concept of fuons into current LCA and CAD systems, to allow comparisons, estimations and scaling of environmental performance, as well as automatic recommendations for designers.

Furthermore, the concept establishes a link between the disciplines of design theory and LCA, easing the application of either of them. It can help to include environmental assessment into early design stages, which is up to now one of the biggest challenges in ecodesign.

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