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A NEW LIFE CYCLE MODEL FOR THE CONCEPTUAL DESIGN PROCESS

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Abstract

Life cycle considerations and design options are hardly quantitatively taken into consideration during the conceptual design phase. In order to provide the type of information required to make decisions based on scientific arguments, a general life cycle model is gradually introduced through out in this research. This presentation tries to give an overall picture of our model. Some other articles have developed the proposals made in this article more thoroughly [Coatanéa et al., 2004]. At first the general problematic is introduced. The three main issues which guide this research are respectively: the desire to reduce the ambiguity at the modelling level, the importance of unifying and minimizing the way of describing a design concept and finally the importance of providing repeatability and measurability. The key idea of this research consists of using dimensional analysis. At first, our research method consists of showing that on the mathematical point of view dimensional analysis can help in attaining the ideal topological space called Metric space as described in the general design theory (GDT) [Yoshikawa, 1981]. We show how the basic semantic of functions and attributes can be described in agreement with this theory. In the third section, we present the general structure of our design model. In this structure we have decided to use existing tools but we have improved those tools by the introduction of two fundamental proposals: design is seen as a "Russian dolls" system of thermodynamic structures called Open systems [Glansdorff et al., 1971] and classification is systematically used in order to progress in direction of the topological space called metric space. The progressive transformation of the semantic description is briefly explained using the example of a pressure regulator. A more precise description is available in [Coatanéa et al., 2004]. The fourth section is devoted to the analysis of the system of based and derived quantities necessary to build a consistent framework. In the fifth section, some other aspects related to the progressive modelling of the pressure regulator are studied through the viewpoint of the developed framework.

1 Introduction

This research tries to avoid the trial and error process which remains a usual way to solve design problems. Some other methodologies have already been developed to provide help during the early phase of the design process. A major contribution is the framework developed by Ulrich and Eppinger [Ulrich et al., 2000]. Unfortunately, this framework leads inevitably for the designer to make subjective choices at some stages. In our point of view this aspect is a failure; it gives a reason to consider design not mature enough to be called a real science. Similar observations have been made by several other researchers. One way used to improve this issue consists of using a mathematical formulation of the design process. One branch of design theory called axiomatic design provides this type of formulation. We state in this paper that an axiomatic vision of design could be applied successfully at the early stage of the design process. The basic aim of this paper is to present the general framework developed in this research. The theoretical base of the methodology is constituted by the general design theory, and other scientific components are added gradually through out the paper.

The research method used consists of showing at first that Dimensional analysis theory could be embedded in the mathematical theory of design called General Design Theory (GDT). In order to achieve this intuition we have used the branch of mathematics called topology.

The great interest of this approach is to transform an initial multi-metric design problem into single-metric one.

The need for a formalized representation of design activity has already been explained above. It is an issue of great importance for a number of reasons:

The first reason is the need to reduce ambiguity at the modelling level.

In this paper, we try to answer to this question by using a descriptive model of design in order to clarify and define how design is carried out. The descriptive model used in this research is based on the GDT. In few words, in GDT, a design process is regarded as a mapping from the function space to the attribute space, both of which are defined over the entity concept set. The theory introduces at first the design in the hypothetical case of an ideal knowledge where everything is known perfectly. In the real situation, design is not a simple mapping process but rather a step by step process of refinement during which the designers seek the solutions that satisfy the constraints. Basically it means that design in the real knowledge could be regarded as an evolving process where a finite number of attributes called metamodel are used to describe artefacts in the physical world.

The second reason is that of uniqueness. The greater the number of terms in the vocabulary and the fuzzier the design procedure is, the higher is the numbers of ways to describe or model a design concept,

This issue is addressed in our framework in two ways. First, we use the central concepts of function and attribute. In the following section these concepts are defined in an explicit manner.

Secondly, the framework developed in this research is considered to fit with the specific axiomatic viewpoint of design activity called GDT. This axiomatic theory states that design model can be described using the mathematical formalism of the topology. In simple words, the branch of mathematics called topology embraces the concept of classification.

This concept of classification is of central interest in our research and will be extensively used.

The third reason is the desire of creating early and repeatable physical models of a product, decomposing design problems into realizable sub-problems and synthesizing designs with computable formulations.
This issue is related to the necessity of providing measurability for the attributes used in the physical description of the artefacts. In this research this issue is addressed in several manners. At first, the consistency of the SI system of units is discussed from the viewpoint of design and three new quantities are proposed. Then the quantities are analyzed using the properties of comparability, addition operation and the concept of bigger or smaller. Finally the new system of quantity is introduced in the dimensional analysis theory and applied to a practical example.

Research methodology:
To summarise the content of this paper, it could be said that it's main purpose consists of showing that a design problem could be transformed and analysed using a unique metric under certain conditions. Those conditions are briefly described in this article from the view point of an old methodology called dimensional analysis [Barenblatt, 1979]. It is proved at first in the article that this methodology is perfectly consistent with the general design theory (GDT). Using GDT as the core theory the research method consists of showing at first that the concept of classification is compulsory in an axiomatic approach of design. Then it becomes possible to demonstrate that classification is a topological structure which can be useful in order to progress in direction of a metric space structure. The design model presented in this research (figure 5) is defined in order to present design as a succession of classifications. Functions, flows and attributes are classified in this research using an existing taxonomy [Hirtz et al., 2002] and a proposal for the classification of attributes (table 1). The topological decomposition axis represents another type of classification (figure 5).
The second step of the research methodology consists of showing that dimensional analysis is perfectly consistent with the GDT. We show that some conditions should be followed when applying dimensional analysis in order to obtain the topological structure called Metric space.

The paper is organized in three sections, the first describes the basic semantic used in this research in order to describe later the classifications attached to this semantic. The second section presents the general structure of the multi-level model developed in this research and the third one introduces some other aspects of the developed methodology using the practical case of a pressure regulator.

2 The basic semantic: Concept of function and entity concept

In GDT, the concept of function is defined as following "When an entity is exposed to a circumstance, a peculiar behaviour manifests correspondent to the circumstance. This behaviour is called as *visible function*. Different behaviours are observed for different circumstances. The total of these behaviours is called as *latent function*. Both are called *function* inclusively." [Yoshikawa, 1981]
In most of the design theories [Pahl & Beitz, 1988, Suh, 1990], functions have been studied by focusing on two essential aspects: *What an object is for?* and *What an object is and what an object does?*
Those approaches are focusing on the designers' or users' intentions, and certain kinds of attributes or behaviours of artefacts. This duality of functions makes the analysis difficult.
Very different events can be resulted from the very same behaviour of an object. The definition of function is not clear. It is hard to build rigorous principles based on that type of fuzzy definition.

According to Kikuchi and Nagasaka [Kikuchi & Nagasaka, 2003], it is suitable to shift the formulation of functions from "What is D's function?" to "How does it function?" As a result, the function is not anymore something intrinsic to a machine. In order to achieve this goal Kikuchi and Nagasaka proposed to refer to the formal theory of natural language semantics developed by Barwise and Perry [Barwise & Perry, 1999] and called Situation Semantics. This theory claims that: "If considering a function of an artefact or machine *D*, we consider also two kinds of situations. One is the situation *u* that a person is designing *D*, and the other is the situation *s* of its outer system. The intention of the person is embedded in *u*, and the attributes or behaviours of *D* are accounted in *s*. *u* and *s* are not unique even if considering the same event."

According to this definition, a function could be defined as a pair of the inner and outer situation and it represents the possible states of the artefacts. This viewpoint is presented in the following Figure.

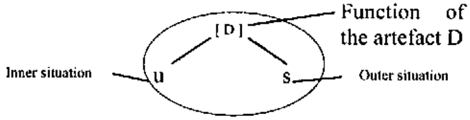

Figure 1: The function structure

In GDT Yoshikawa calls the design result an entity, and mentions that concepts about entities are necessary items for design. These items, entities and concepts, are introduced formally in the following definitions.

Definition 1 The *entity set (S')* is a set, which includes all entities in it as elements. By all entities, we mean entities, which existed in the past, are existing presently and will exist in future.

Definition 4 *Concept of entity (S)* is a concept, which one has formed according to the actual experience of an entity. In this concept, any attributes or functions are not abstracted of the entity. The entity is totally a concept for one.

Definition 5 *Abstract concept (T)* is derived by the classification of concepts of entity according to the meaning or the value of entity. As a result of classification, we get classes, each of which includes entities carrying the common meaning or value; and correspond to a peculiar abstract concept.

In order to discuss design, Yoshikawa introduces the notion of attribute and function. In GDT, a design specification is formulated as a set of function concepts, and a design solution is described by a set of attribute concepts (Interested readers can refer to Yoshikawa [Yoshikawa, 1981] and Tomiyama and Yoshikawa [Tomiyama & Yoshikawa, 1987]). He also introduces axioms which are basic conditions about the relationship and properties of entities, entity concepts, and abstract concepts.

Axiom 1 (Axiom of Recognition) Any entity can be recognized or described by the attributes.

Axiom 2 (Axiom of Correspondence) The entity set *S'* and the set of concept of entity (ideal) *S* have one-to-one correspondence.

Axiom 3 (Axiom of Operation) The set of abstract concept is a topology of the set of entity concept.

The mathematical concept of topology is extensively used in this theory. We need to define it according to Nicolas Bourbaki [Bourbaki, 1989].

Definition A *topological structure* (or *topology*) on a set X is a set $O \in P(X)$ having the following properties:

(1) $\emptyset \in O$ and $X \in O$,

(2) for any $U, V \in O$, $U \cap V \in O$,

(3) for any set I and $U_i \in O\ (i \in I)$, $\bigcup_{i \in I} U_i \in O$.

A *topological space* is a pair $X = <X, O>$ of a set X and a topology O on X. An element of O is called an *open* set of O, and the complement of an open set is called a *closed* set. We say a subset of X is *clopen* if it is open and closed.

It is explicitly written in the theory, that the axiom of Correspondence is valid only for the ideal knowledge. Furthermore, Yoshikawa deduces in his Theorem 13 that: "design is possible in the real knowledge if and only if we can make a direct connection between the specification and the attribute without intervention of entity concepts". Then, we cannot formulate abstract concepts as sets of entity concepts in the real knowledge; hence it follows that, not only the axiom of Correspondence, the axiom of Operation does not work in the real knowledge. There is a similar problem about the axiom of Recognition. In the real knowledge, we can treat only a finite numbers of attributes about entities, but it is clear that we cannot always specify an entity with any finite collection of attribute concepts. The axiom of Recognition holds only in the ideal knowledge.

Tomiyama and Yoshikawa argue two kinds of description methods of entity concepts. One is called *extensional*, and the other is called *intentional*. The difference of them can be regarded as the difference of the formulations of the relationship between *entity concept (S)* and *abstract concept (T)*. In the extensional description we have first the entity concept and the abstract concept is a result of this entity concept. In the intentional description it is the opposite. Both methods have advantages and disadvantages.

In their formulation Kikuchi and Nagasaka consider that the paradox is overcame by using the intentional description. This proposal needs to be investigated more thoroughly in a future paper.

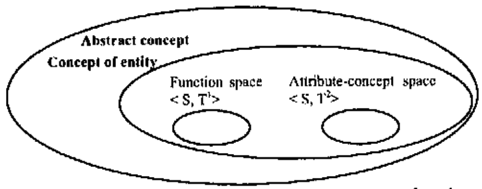

Figure 2: Topological structure of the abstract concept and entity concept

<u>Separation and recognition ability of the topologies:</u>

There exists a hierarchy of separation/recognition ability of the topological spaces (S, T) as defined in the axiom 4 of GDT:

T_0: For each pair $a \neq b$ in S, there is $U \in T$ such that $a \in U$ and $b \notin U$ or vive versa.

T_1: For each pair $a \neq b$ in S, there is $U, V \in T$ such that $a \in U$ and $b \notin U$ and $b \in V$ and $a \notin V$.

T_2: (Hausdorff) similar to T_1 but $U \cap V = \emptyset$.

T_3: T_3 is a generalization of T_2 where A is a set instead of a single entity.

T_4: Satisfies T_1 and for every pair of disjoint closed sets A, B $\in \overline{S}$ there exists a pair of disjoint open sets U, V $\in T$ such that A $\subset$ U and B $\subset$ V.

T_5: Satisfies T_1 and for every pair of closed sets A, B $\subset \overline{S}$ with $\overline{A} \cap B = A \cap \overline{B} = \emptyset$, there exists a pair of disjoint open sets U, V $\in T$ such that A $\subset$ U and B $\subset$ V.

Metric space: There exists a metric on the space

It can be shown that: *Metric space* $\Rightarrow T_5 \Rightarrow T_4 \Rightarrow T_3 \Rightarrow T_2 \Rightarrow T_1 \Rightarrow T_0$ and that none of these implications are reversible. Therefore, the type of separation defines an order on topological spaces.

The metric space has interesting features and it could be useful to analyze a design problem using that type of topological space. The key idea at this stage consists of introducing Dimensional analysis to transform the initial problem in a pseudo metric space (metrizable space).

At this stage it becomes essential to discuss the necessary conditions for creating a metrizable space. In this article, we will not analyze in detail those conditions but briefly it could be demonstrated that classification provides a certain type of topological space called uniform space.

Kakuda et al. have demonstrated that any topological space **X** =<X,O> generates a classification cla(X). Conversely, any classification A induces a topological space called a classification space. Consequently A as the structure: A=<tok(A), typ(A)>

with tok(A) which is the set of concepts to test and typ(A) which is the functional topology in the function space or the attribute-concept topology in the attribute space.

That type of space has many good features of the metric spaces and it is explained in [Kakuda et al., 2001] that:

<u>Theorem 4.6:</u> A uniform space is metrizable iff it is Hausdorff and has a countable fundamental system of entourages.

The consequences of such theorem could be summarized as followed:

- The taxonomy selected should be Hausdorff,
- Secondly, we have to define a system of fundamental quantities which satisfies the requirement to be a fundamental system of entourage.

As a conclusion of this brief analyse it could be noticed that the next steps of our framework are organized as a consequence of this short study. Classification will be systematically used in this research, an enhanced fundamental system of unit will be introduced and finally dimensional analysis theory will be used to transform the initial space into a metric space.

3 The general conceptual model

The general model presented in the figure 6 is divided in three main steps. This model is introduced in order to create a consistent model which uses extensively classification and has a countable fundamental system of entourages. The steps are:

The multilevel/multidisciplinary design model

The first level of concretisation progressively describes and refines the raw semantic description of the future product. This analysis is done using three successive levels of details called respectively the ecosystem level, the product level and the modules level (figure 6). The taxonomy developed by Hirtz [Hirtz et al., 2002] is used here to analyse the functions and the flows. At each stage a graphical tool derived from the Pahl and Beitz tool [Pahl & Beitz,

1988] is used in order to describe functions and flows. This basic graphical tool is enhanced in two aspects in order to represent the environmental burden of the design process and to provide a clear vocabulary to describe the functions and flows.
To achieve the first goal each box is considered as an open thermodynamic system far from the equilibrium [Glansdorff & Prigonine, 1971]. This graphical tool is presented in the following figure.

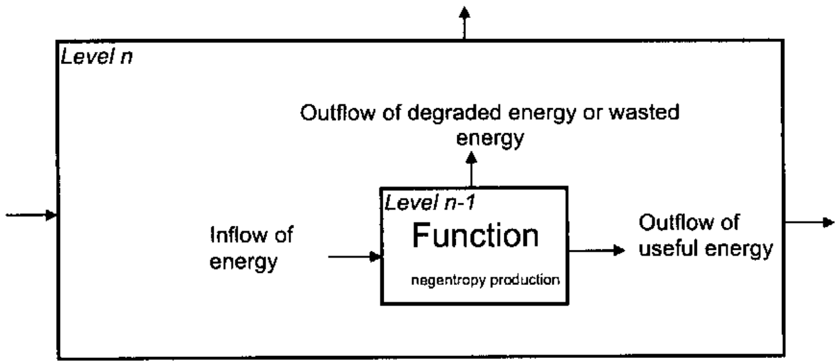

Figure 3: Topological structure of the abstract concept and entity concept

According to the theory developed by Glansdorff and Prigonine [Glansdorff et al., 1971] and used by Ramade [Ramade, 1993], each black box needs to export its entropy in the upper level in order to "survive". We could note that entropy in this framework is considered as the unique quantity expressing the environmental burden. This characteristic provides simplicity and measurability. The traditional weakness of the Life Cycle Assessment (LCA) methodologies [PréConsultant, 1999] due to the fact that life cycle indicators are not measurable is overcome here. It could be argued that this simple measure does not provide similar degree of precision than LCA. It could be answered that during the conceptual design stage the amount of information available is so small that no LCA could be performed.
In the example of the pressure regulator [Bhashkar et al., 1990] this phase leads in defining a group of dimensionless indicators. Those indicators describe three aspects of the artefacts:

- The physical behaviour of the pressure regulator,
- The environmental impact of the pressure regulator during each phase of its life cycle,
- The economical impact of each phase of the life cycle.

At this stage it could be noted that the connection between the different phases of the life cycle during the design process is ensured via the flow of information cascading hierarchically from the use phase to the other phases. This process is visualized in the life cycle space of the figures 4 and 6.
In other words, the multilevel/multidisciplinary design model is obtained by analysing successively the phases of the future product life cycle according to the following figure.

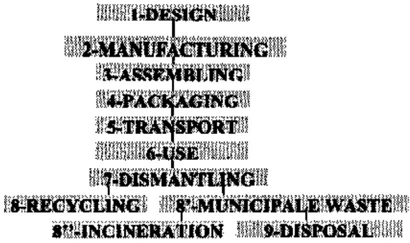

Figure 4: The life cycle

The feature based modelling

The three families of indicators resulting from the previous stage are classified using the proposed taxonomy of the table 1 and computed during the feature based modelling.

Table 1: Classification of the attributes

Classes	Families	Type and based quantities
Physical attributes		
	Macro geometrical attributes Micro geometrical attributes Material attributes	Discrete ($M^i.T^j.L^k.K^l$) or Synthetic ($In^m.L^k$)
Environmental impact attributes		
	Design impact	Discrete ($M^i.T^j.L^k.K^l$)
	Manufacturing impact	
	Assembling impact	
	Packaging impact	
	Transport impact	
	Use impact	
	Dismantling impact	
	Recycling impact	
	Disposal impact	
Economical attributes		
	Design cost	Discrete ($E^n.M^i.T^j.L^k.K^l$)
	Manufacturing cost	
	Assembling cost	
	Packaging cost	
	Transport cost	
	Use cost	
	Dismantling cost	
	Recycling cost	
	Disposal cost	

As an example, the literature case of a pressure regulator [Bashkar et al., 1990] is used in order to present this modelling; it becomes possible using a draft representation [Coatanéa et al.,2004] to design a 3D artefact (figure 5).

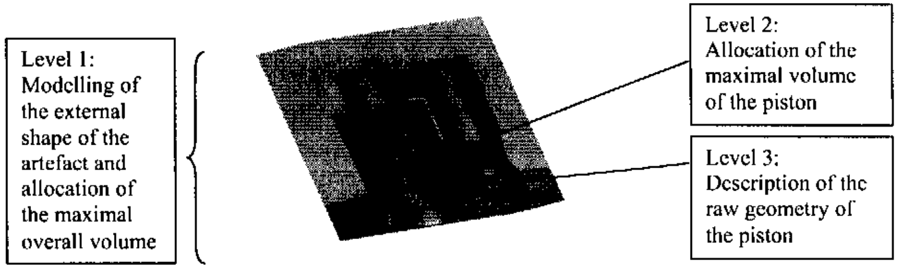

Figure 5: Level 1-2-3 of a 3D pressure regulator concept

In order to provide comparability among the developed artefacts, the 3D draft should follow a basic rule. This rule consists simply of allocating a fix overall volume for the level 1 of the 3D artefacts of the pressure regulator. This process is visualized in the figure 5 and 6. All the other parameters could vary.

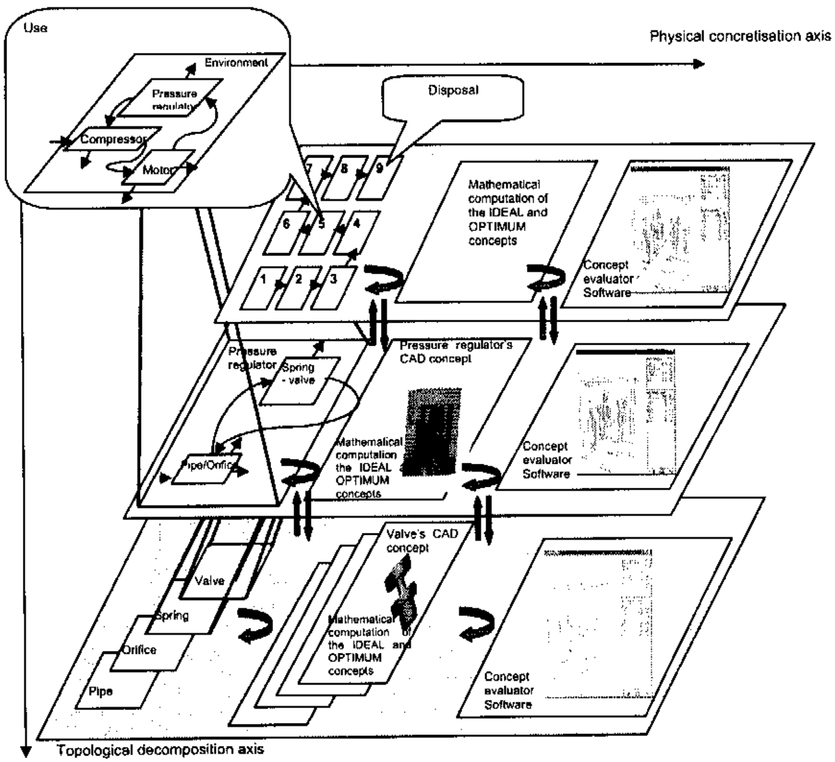

Figure 6: The new conceptual design model

The concept evaluation and selection

Using dimensional analysis dimensionless indicators explaining the behaviour of the artefacts are defined. The general structure of the indicators could be described as follows:

a) $\pi_{1\,use}$ are the dimensionless indicators obtained during the analysis of the use phase,
b) $\pi_{1\,life\ cycle}$ are the dimensionless indicators obtained during the analysis of the other phases of the life cycle.

According to the Vashy-Buckingham theorem [Barenblatt, 1979, Sonin, 2001], the indicators could be presented as follows:

$f_{use}(\Pi_{1use}, \Pi_{2use}, \Pi_{nuse}) = 0$ **Equation 1**

$f_{life-cycle}(\Pi_{1life-cycle}, \Pi_{2life-cycle}, \Pi_{nlife-cycle}) = 0$ **Equation 2**

The analysis of the relation within the dimensionless parameters, between the dimensionless parameters and between the ensembles is made using the Bashkar and Nigam methodology [Bashkar et al., 1990]. This methodology gives qualitative information about the form of the mathematical functions described in Equation 1 and 2. Interested readers could refer to the article for detailed explanation. This analysis leads to define a qualitative model in the sense of the qualitative physics [Forbus, 1984].

Those dimensionless indicators are obtained using a system of base quantities. This system uses 9 base quantities below presented. This system has been enhanced by the introduction of two fundamental quantities: **the information quantity** (needed to connect the steps of the life cycle) and **the monetary quantity** (required to take into account the economical aspects).

Mass (M), Length (L), Time (T), Temperature (K), Courant (I), Number of elementary particles (mole), Light intensity (Li), Information (In), Monetary (€)

The Table 1 makes a summary of this classification. Using this type of classification it becomes possible to store the knowledge about the attributes.

Experimental design, model choice, model fitting:

We will not describe in detail here the algorithm used in this research. In simple words the general scheme consists of creating a numerical model called metamodel. This metamodel follows the general procedure described by the survey of Simpson [Simpson & al., 2001]. At first step, the experimental design is done through the collection of numerical data related to the table 1. Those data provide the experimental values needed for the computation of the indicators.

Afterwards, the evaluation of the Equations 1 and 2 consists of selecting a model to express the relations between the dimensionless indicators and then to adjust this model to the experimental values by selecting a fitting model. In our case we have selected respectively a polynomial model and a least square regression according to the critical review from Simpson.

Computation of the optimum and Ideal:

The principal idea at this stage consists of screening the entire solution space in a graphical manner. The solution space is organised by layers and group of layers. Each layer combines the dimensionless indicators by pair. The grouping procedure is described in the following example of the pressure regulator. First of all the concepts of Ideal and Optimum are computed in agreement with the general optimisation method reviewed by Colette and Siarry [Colette & Siarry, 2002]. The computation of the Optimum is done by using the Lagrange multipliers method [Bertzekas, 1982]. At the moment we perform the algorithm for the evaluation and selection of the concepts using the software called CES4 from Granta Design

[CES4, 1999]. We plan in the near future to use the prototype software developed during this research http://pddi.free.fr/.

The new unit system and its implications

In the actual SI system two major aspects of the design activity have not been taken into account. First design could be defined as the science of analysing, selecting and producing *information*. Secondly, *economical aspects* in terms of evaluation of the value of goods or services in human activities are of major importance. If considering the SI system composed of 6 base quantities -length, time, mass, temperature, current, number of elementary particles, and luminous intensity- and one derived unit -force- none of the base or derived physical quantities have the adequate properties to express the two artificial phenomena described above. If considering *Environmental consideration*, the life cycle of a product can be viewed as a process of organization with a decrease in entropy all over the life cycle and a corresponding increase of entropy through dissipation of energy into the environment [Wall, 1977, Ramade, 1993]. The process is driven by transformation of high quality energy to low-quality heat and waste flows. Our proposal is to use entropy as a new derived quantity to express the environmental consideration phenomenon involved in human activity. On the theoretical point of view as pointed out by Barenblatt, Sonin and Lavau [Barenblatt, 1979, Sonin, 2001, Lavau, 1997], the definition of the unit system is a matter of choice. It means that we are allowed on the theoretical point of view to use this quantity as a derived quantity to take into account the environmental aspects.

4 Discussion and conclusion

Only a small part of our theoretical and practical framework had been presented in this paper. The main difficulty for us was to present a very large field of investigation in few pages. We are conscious that it could be difficult for a reader to understand plainly the all framework analysing solely this article. Interested readers could find extra information in the other articles from Coatanéa et al. [Coatanéa et al., 2004]. The main objective here was to present a general picture of the developed framework.

The model proposed in this article provides quantitative help to designers. It enables design teams to investigate different design options and to reach quickly optimal solutions from a large number of available technologies and their combinations. The framework is constructed using an axiomatic approach. The connection of this axiomatic approach to dimensional analysis seems to be a promising field of investigation because of the interesting fundamental properties of the metric spaces. The introduction of new base quantities enlarges the field of design investigation.

The information analyse is a central aspect of our model. The concept of synthetic information roughly presented in table 1 needs to be more thoroughly investigated in order to take into account the sense and value attached to the information cascading all over the life cycle. It is a difficult aspect which has been shadowed in the Shannon and Weaver theory of information [Shannon et al., 1949]. This paper is summarizing the first year work of Eric Coatanéa's doctoral research.

Contribution of the research:

This work tries to unify GDT and Dimensional Analysis. Our desire is to show that dimensional analysis could become a central methodology in design. The dimensional analysis has been enhanced during this research by the introduction of two base quantities

(e.g. information and monetary quantity) in order to deal with design complexity. We have also introduced a derived quantity in the quantity system called entropy to take into account the environmental aspects. This final contribution has been to present a complete design framework able to integrate those initial ideas in a consistent model.
The main parts of this framework have already been tested successfully by practical examples. We have shown specifically that the methodology provides a qualitative simulation of the whole concept or parts of the concept (e.g. simulation of pressure regulator concepts) [Coatanéa et al., 2004].

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