INTERNATIONAL DESIGN CONFERENCE - DESIGN 2004
Dubrovnik, May 18 - 21, 2004.

DESIGN 2004

DESIGN BY FUNCTION: A METHODOLOGY TO SUPPORT DESIGNER CREATIVITY

F. Giampà, M. Muzzupappa and S. Rizzuti

Keywords: functional approach, conceptual design, creative design

1. Introduction

The Conceptual Design refers to the creative phase of the design process which, according to authoritative approaches in literature [Pahl 1996, Ulrich 2001, Hubka 1992], is placed between the product planning phase and the embodiment design phase. In other words, it includes all logical processes which, as from the task clarification phase, lead the designer or the project team, to formulate hypothesis, and search for solutions, thus defining the product architecture during the ideation phase. Therefore, the primary task of the conceptual design phase is to satisfy the functional requirements.

However, it is important to consider the fact that, satisfying the functional requirements, the designer must take decisions which significantly condition all aspects of a product and, in particular, its cost is determined by the correctness of the operated choices.

Nevertheless, this phase, unlike all other phases that compose the design process, is also the one which is less supported by dedicated tools. This could be explained considering that:

- it is intrinsically difficult to support this phase without inevitably risking to set a limit to the designer's creativeness;
- many studies [Wang 2002] have been dedicated to conceptual design, but few of these have been transformed in effective software tools.

So designers who are not supported by suitable tools, rarely follow a systematic approach and simply prefer using their intuition and experience.

Considering the fact that the definition of a suitable methodology is the first step to develop a software tool to support conceptual design, in this paper we present a new methodology able to support the designer during the conceptual design phase allowing him/her to speed things up to generate new concepts.

This methodology has been characterized by an approach to conceptual design which aims at combining the characteristics of approaches that historically have received greater favours: the functional approach and the knowledge based approach [Wang 2002]. In previous publications [Bruno 2003], systematic aspect of methodology have been illustrated. Whereas, in the present paper, we mean to discuss the more properly functional aspects of methodology and the related knowledge base which notably increases the potentialities of the CACD (Computer Aided Conceptual Design) software that has been developed to support the methodology.

Thanks to this tool, the designer is led to approach the conceptual design from a point of view which is not purely geometric, but based on functional aspects which are implicit in the product requirements. This way, it is possible to elevate the level of abstraction to which the designer operates. Consequently, the designer's mind can be more creative and therefore can better lead one's imagination to generate innovative solutions, although always in the respect of the functional requirements.

2. The function and its representation

Conceptual design seeks to generate product concepts which satisfy desired functions. Researchers have attributed different meanings to the term "function" but many of them agree in classifying such notion into two categories [Deng 2002]:

- Purpose function: the description of the designer's intention or the purpose of a design. It is thus abstract and subjective.
- Action function: an abstraction of how one wishes the product to function and at the same time it individualizes the more convenient working.

In fact, Chittaro & Kumar [Chittaro 1998] and Winsor & MacCallun [Winsor 1994] assert expressly that the function could be intended either like "purpose function" or like "operational". Chakrabarti [Chakrabarti 1998] proposes two views of function: the one at the level of abstraction of the working of device and the one at a higher level of abstraction which represents the design intents. Chandrasekaran and Josephson [Chandrasekaran 2000] propose an environment-centric viewpoint of function (function as effect) and a device-centric viewpoint (function as role). Although Hubka and Eder [Hubka 2001] suggest eight kinds of function, among these there are a "purpose function" and a "working function"

These two types of function are related to the different levels of development (abstraction) of a design. On higher levels of abstraction, the designer operates with purpose functions because they are the only ones which may represent, in this phase of development, the design intents. In fact, the first selections of concepts are generally a set of purpose functions. Obviously, the designer still ignores how these functions will be carried out. During the conceptual design phase, the purpose function will be gradually replaced by any sub-functions, at lower levels of abstraction, which are connected to specific physical working. Then, the designer attends, often in an unaware way, to the gradual transformation of the purpose functions in action functions.

However, it is necessary to point out that there is not a definite borderline between purpose function and action function. Infact, while an action function refers only to the more efficient working that the designer has considered for a product, a purpose function could implicate information that refers to specific actions, not expressly mentioned.

2.1 Semantic and syntactic representation of functions

The representation of a function has been always characterized by some ambiguity. In every case, it is commonly approved that this representation can be semantic, syntactic, or both.

Semantically, the representation of a function is a description of the characteristics of the object, which reflects the user's understanding and perception. Syntactically, the representation of a function aims at describing the ways in which the object may be represented in a software where it can be defined and manipulated by a designer in a specific design situation [Deng 2002].

Chakrabarti and Blessing [Chakrabarti 1996] have studied different approaches used to represent a function. Among these, the most common are:

- verb-noun pairs;
- input-output flow transformation.

The authors of this classification, on the basis of what they asserted previously, affirm that the representation by means of the verb-noun pairs is a syntactic representation while the other one is a semantic representation.

In a more recent article [Chakrabarti 2001], Chakrabarti, clarifies that the function could be expressed by means of a representation in natural language (that is a better clarification of the representation by the verb-noun pairs) or by means of a mathematical representation of input-output transformation. Both the proposal representations are syntactic representations.

The representation of a function by phrases in natural language is one of the methods which is frequently used by designers and researchers: thanks to the expressiveness and the generality of the natural language, it could be employed both for the purpose functions and for action functions. However, due to the subjective and abstract nature of the purpose function, this can be expressed, in a complete way, only by phrases in natural language. On the other hand, an action function can be expressed in many different ways: it is possible to employ input and output state variables; or it can use a state table specifying the parameters in input and in output of a transformation (Schmekel, [Schmekel 1989]) or it can also use a matrix, charts or sketches (Chiou & Kota, [Chiou 1999]), etc. Furthermore, according to Chakrabarti & Blight [Chakrabarti 2001], an action function can be represented by a mathematical form of input-output transformation, such as formulas and equations.
Regardless of the type of representation selected by the designer, the syntactic representation of an action function must however express its semantics, namely the input-output flow transformation [Deng 2002]. Thus, if the natural language (syntactic representation) is used, the semantics of an action function could be represented by a phrase that describes the flow in input (or the initial state) and by an other phrase that describes the flow in output (or the final state). Or, in alternative, it is possible to use a single phrase selecting a verb in a suitable way, in order to suggest the difference between input and output; for example, the phrase "amplify the force" is a syntactic representation that describes its semantics because it recalls the difference between a force in input and a force in output.

3. The proposed methodology

This methodology, combining and revisiting the classic approaches to the systematic design [Pahl 1996, Ulrich 2001, Hubka 1992, Andreasen 1980, VDI-GKE 1987, Hubka 1988, Roth 1979], allows the designer to develop his/her ideas, assembling existing components and trying several alternatives in order to generate and evaluate different product solutions.
Even in this methodology, purpose functions and action functions are employed. In fact, by operating in keeping with this methodology, which is supported by a CACD tool (whose definition is in progress), the designer begins the conceptual design phase establishing the overall function that the product must perform. The overall function is exactly the purpose function which subsequently will be rendered explicit in more sub-functions. The designer works the whole time in a so called "*design space*", a 3D environment where he/she can visualize the project development, from his/her initial thoughts to the final lay-out of the product. In the design space, the overall function is represented by a kind of black box (named functional block) connected by four different kinds of links (energy, force, material and signal) with the external environment. Developing the overall function in more sub-functions, the initial block decomposes into more functional blocks which are linked to one another and to the external environment by the same types of links.
During the conceptual design phase, each functional block develops its meaning according to the current level of detail in the design process. In fact, if in the initial phase of the study, the functional block can represent a non specified apparatus or a device that respects the functional requirements, in the last definition phase, each functional block takes a defined shape and geometry, and represents a defined single component or group that carries on a request action function. In the design space, both functional blocks and real components, connected by links, form a so called "*functional net*".
This sequence, in concordance with the top-down approach, can easily be reversed and a bottom-up sequence can be followed. Both approaches are attractive, since new ideas can arise in unforeseen ways, and the designer must have the possibility of reappraising all that has already been developed and make changes in the most flexible way [Bruno 2003].
With the proposed methodology, the representation of purpose functions and action functions is both syntactic and semantics. In fact, the functional net is certainly a semantics representation; moreover, the CACD software, that supports the methodology, provides a particular way of representing functions: by moving the pointer of the mouse on a functional block, a call-out makes its function explicit through a phrase in natural language, that is a syntactic representation; in accordance with Deng [Deng 2002], this phrase is structured so that it also represents the semantic of the function.

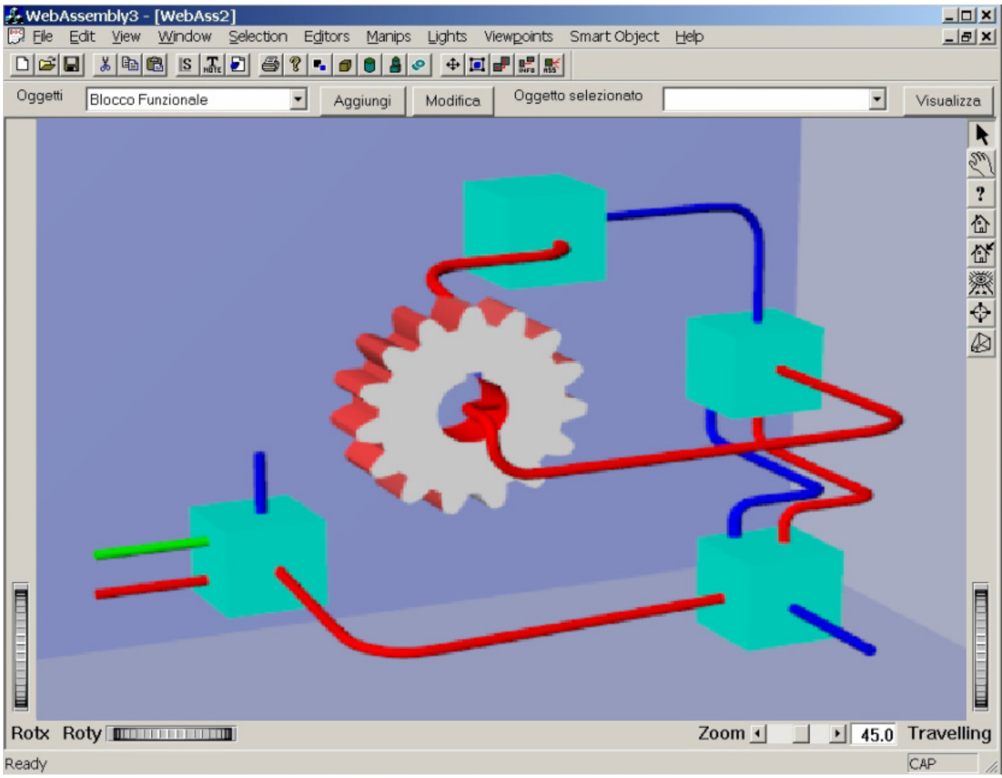


Figure 1. Example of functional net

4. The classification of functions

In the 3D design space, the designer builds a functional net in order to investigate the space of possible solutions on different levels of abstraction; moreover, he/she can verify the compatibility of links among the functional blocks and/or the real component of the net. In particular, in the CACD tool it is possible to employ, as real components, standard mechanical and electro-mechanical parts.

In order to improve the effectiveness of the proposed methodology and to increase the potentiality of the tool, rather than develop the library of components, the interest has been focused on the function, classifying every component in relation to the performed function. The main idea at the basis of this classification is that of supporting the conceptual design phase by supplying the designer with a set of functions which he/she may put together (just like several letters in the alphabet) in order to define more concepts for a determined product. Therefore, the designer has helped to define a layout based exclusively on the functions which the product must perform.

Moreover, this classification, at the lower level of abstraction, allows the designer to easily associate a component to every function.

The classification was done starting from the “International Classification for Standards” and with the aid of the Internet site www.tremnet.com. The “International Classification for Standards” (ICS) is a system made by the ISO (International Organization for Standardization) by which a hierarchical classification, structured on three levels, of all existing standard components has been provided.

For example, among fields classified by the ICS, the field N°21, named “mechanical systems and components for general use” is reported.

Further information has been taken from the site http://www.tremnet.com of the TGR Europe (Thomas Global Register) that includes a guide of services and products, classified by means of 10500 categories, with 210,000 manufacturing and distributors of 17 European countries.

Table 1. an example of components classified by the ICS

MECHANICAL SYSTEMS AND COMPONENTS FOR GENERAL USE			
Fasteners and Screw threads	bolt, screws, studs	Shafts and couplings	Shafts
	nuts		couplings
	washer		Keys and keyways, splines
	Pins, nails		Ball joints and articulated joints
	Rings, bushes, sleeves, collars		Torque limiter
Bearings	Thrust bearings		wheels
	Radial ball bearing		Anti-unlock systems
	Angular contact ball bearings	Seals, glands	Dynamic glands
	Needle bearings		Static glands
	Roller bearings	Dampers	Shock-absorber
	Self aligning bearings		Vibration damper
	Accessories for bearings	Springs	Laminated springs
	Bearing brass		Torsion springs
Positioning elements	Taper pins		Helical springs
	Rafters	Gears	Cylindrical gears
	Nogs		Conical gears
Articulated joints	Hinges		Racks
	Eyelets	Flexible driver and Transmission	Belt drives and their components
	Linear guides		Chain drives and their components
	Rotational guides		Rope drives and their components
Journal elements	Catchs		Rotary-reciprocating mechanisms
	Seatings	Lubrification systems	Lubrificators
	Wedges		Oiler

4.1 The Macro-functions and the elementary functions

Starting from above mentioned catalogues, a complete list of mechanical and electro-mechanical components commonly employed in the industrial products, has been generated. Each of these components has been successively associated to the possible elementary functions that it could perform in an assembly; finally, all elementary functions have been grouped into nine macro-functions: *to block - to place - to contain - to convey - to dissipate - to furnish - to transform - to transmit - to employ*.

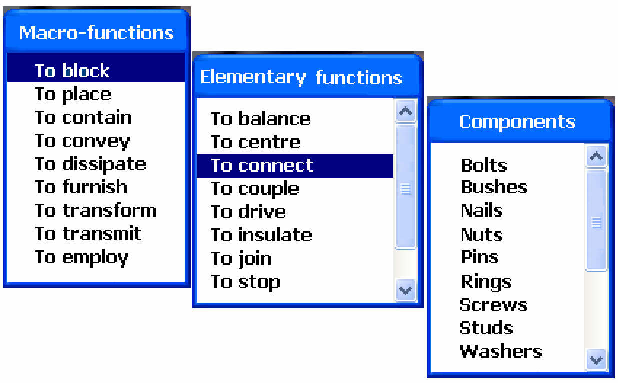


Figure 2. Example of the consultation of the knowledge base

These macro-functions, as well as simplifying the use of the knowledge base, when connected to the link (energy, force, material or signal), represent the purpose functions expressed by the verb-noun pairs (i.e. to block a force, to transform mechanical energy, …).
Thus, they represent the designer's starting point for conceptual design phase. Infact, operating according to the proposed methodology, the user, during the definition of a product layout, could be helped to select the right component by the knowledge base. To consult the knowledge base, the user starts from the macro-function that the searched component performs in the assembly. Then, detailing a macro-function in more elementary functions, he/she is led to individualize the component within a list of proposed components, as shown in figure 2.
Back in 1979, Koller [Koller 1979] has proposed a knowledge base related to functions. Besides, the Koller knowledge base does not have any link to real components. In addition, it is less detailed with respect to our knowledge base.
In order to represent the various elementary functions by functional blocks, the most generic functional block, represented in figure 3, as been detailed into the nine cases related to macro-functions.

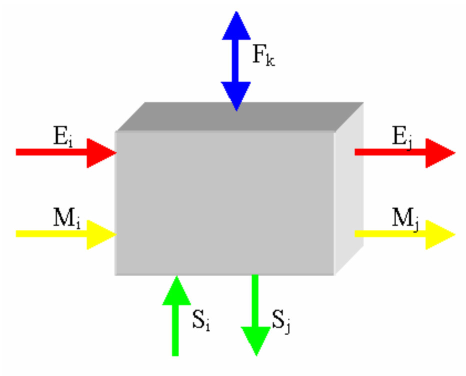
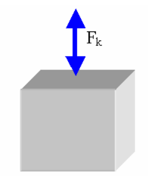
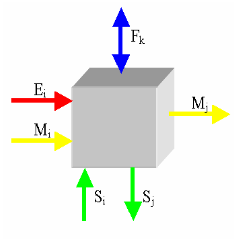
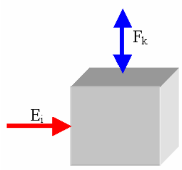
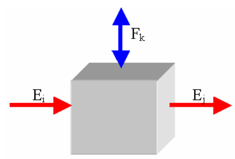
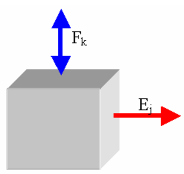
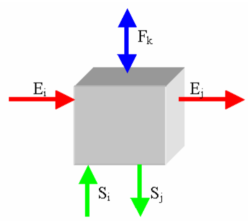
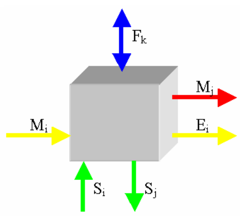


Figure 3. The most generic functional block

The table 2 groups functional blocks related to macro-functions and accordingly to the different elementary functions. It is important to remark that each link could be multiple, while for some blocks, some links could also be absent.

Table 2. The functional blocks related to the macro-functions

<table>
<tr>
<td>TO BLOCK
TO PLACE
</td>
<td>TO CONTAIN
TO CONVEY

With Ei, Si, Sj optionals</td>
<td>TO DISSIPATE
</td>
<td>TO TRANSMIT
TO EMPLOY
</td>
</tr>
<tr>
<td colspan="4">TO FURNISH / TO TRANSFORM
  
With Si ed Sj optionals</td>
</tr>
</table>

Altogether, over 40 elementary functions, that practically cover all the activities of the standard components employable in the realization of the industrial products, have been catalogued. All elementary functions are however represented by the functional blocks related at nine macro-function in which they are grouped. From this, it is possible to point out that the blocks in table 2 are the elements which, when properly combined, allow the designer to make the functional net that represents a particular product concept, just as one combines the letters of the alphabet.
All the retrieved information has been organized in order to constitute a knowledge base easily employable by the designer; one has made a table, organized in macro-functions and then in elementary functions, that reports for each of them:

- the ways in which an action could be performed;
- the components that perform the specified function;
- the specific functional block, with the related links, which represents that function;
- the list of compatible components which can eventually be connected.

This knowledge base, that will be implemented in the CACD software, frees the designer from geometric modelling, by focusing his attention on a more original re-combination of existing components, in order to obtain innovative product concepts through an exploration of unusual and original connections.

5. Conclusions

In the present paper one has presented a methodology for conceptual design of industrial product through which one aims at supporting the designer in the generation and development of new concepts.
One has proposed a “functional modelling” of product concept, which may be seen as a process which allows one to reach functional architecture of products not yet defined in detail.
One has created a knowledge base including a great variety of mechanical components; and for each one of these, one has individuated the fulfilled elementary function, which may not be combined with other ones to give life to different functional architectures.
The focus point of the present study is the definition of an alphabet though which one may form complex functional structures, starting with just a few functions, but aiming at the definition of various innovative concepts for a specific product.

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Sergio Rizzuti, Professor
Dept. of Mechanical Engineering
University of Calabria
Ponte Pietro Bucci 44/C
87030 Rende (CS), ITALY
Telephone: 39-0984-494601, Telefax: 39-0984-494673
E-mail: rizzuti@unical.it