THE IMPORTANCE OF TEACHING FUNCTIONAL ANALYSIS IN PRODUCT DESIGN COURSES

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ABSTRACT
The paper describes experiences and reflections, matured at the Faculty of Engineering of University of Calabria (Italy), during the last decade, in the courses of Engineering Design Methods, held at the bachelor degree in management engineering and the master degree in mechanical engineering.
The courses, even addressed to different audiences, contain the functional analysis of an industrial product, that characterize the core of the discipline.
In the paper the product functional analysis is described and the problems of its teaching are reported. The application to a case of study clarify its use and its employment as tool for discovering lacks in device already present on market.

Keywords: Functional analysis, reasoning by function, building of functional net

1 INTRODUCTION

Over the last thirty years the need of teaching "design methods" has become the crucial element in many Industrial Engineering Schools, worldwide. The starting point can be traced back to the pioneering works of Palh & Beitz [1], Ubka [2], where the authors urged the need to educate new generations of technicians to solve engineering problems in systematic or methodical way. Really the need for education can be considered a second task, because the main aim of those works was to recognize the existence of a "scientific" approach to the design problem Ubka & Eder[3]. Nigel Cross [4] went further codifying the design activity as "a way of knowing".
Along this time all aspects of design activity have been investigated and some interesting data structure have been pointed out in order to sustain the reasoning on many tasks and on the organization of the work in every phase of product development.
A set of methodologies have been defined in all design aspects, such as: QFD [5], Axiomatic Design [6], Robust Design [7], Sustainable Design [8].
A set of textbooks have appeared in booksellers to support the education task on product design, such as Ulrich & Eppinger [9], Otto & Wood [10], to cite the few.
Students in engineering schools can now find several courses in these curricula to become true skilled in the "design science". They can find bachelor or master courses on product design, or at least one or more courses on "engineering design methods", "product design and development" and so on.
Even if the methodologies covering embodiment or detail phases are clearly defined, because they derive from the classical asset of engineering studies, such as the analytic study, the major lack is concentrated in the whole treatment of the design: the synthesis study. In this a weak link exists: the product functional analysis (pfa). It consists in the basic study of the problem to be resolved, putting into some relation all the functionalities required to the device that must perform the operations needed to solve the problem.
In every context of design, the initial phase is really crucial to be sure to reach a valid solution at the end of the design process. If it is true that the 80%-90% of the product success is built in this phase, it becomes clear how this is the phase that must be more stressed in every basic course of engineering design, with a deep immersion in the context of product "functionality" [11].
The paper aim consists in putting in evidence how the product functional analysis can guide the designer to investigate if the solution (or the solutions) is strictly related to the customer needs, from which it is derived. Then the importance to teach product functional analysis is emphasized, because it is the compass that must guide each designer to solve an engineering problem. The paper is based on

the experience matured in ten years of teaching “engineering design methods” at the Faculty of Engineering of University of Calabria (Italy).

2 FUNCTIONAL REASONING AND FUNCTIONAL ANALYSIS

During conceptual design the main difficulty is the extraction of a set of functional requirements from the customer needs that have been gathered, by means of questionnaires or interviews, in the initial phase of research for a new product or the revision of earlier versions. Generally students have no idea how this step can be done. They speak and think of elements or parts they have realized and they have consciousness.

The research for functional requirements starts instead from the translation of the component/element properties to their functional characteristics. The use of the couple “active verb + noun” to describe the element functionality is the more difficult moment during the course. Students of engineering courses, at the end for their regular studies, are able generally to analyze wide range of situations and/or element behaviours on the base of theories or application models. In the context of product development they lack of a certain ability to talk and think about functionality. A general complexity emerges when they are invited to describe a functionality in term of “verb + noun”. Even in the past it has been tried and suggested a certain number of codification for the actions that could be present in a device (e.g. in the electro mechanics sector) [12], the approach followed in this course is to freely use a variety of synonymous verbs with which a variety of situations could be precisely described. Also the nouns can be varied using synonymous and also the context could be specified, adding simple propositions.

Functional analysis is pursued decomposing the macro functionality, that characterize the problem to be solved, in sub functionalities, each of these able to put in evidence more precisely contexts and properties that might be present in the final solution. In this functional context the decomposition must be carried out refining the terminology used, trying to enhance property that otherwise could remain hidden or not explicitly stated. Being the linguistic terms that can be employed really numerous, the decomposition can lead to quite different relations. If this generates bewilderment in students, accustomed to use model and theory well codified, this can allow them to solve a problem in original way, trusting on the basic assumption that the decomposition is not unique.

Generally the functional analysis collects a set of low level functionalities, and for an electro mechanic device, these can be linked in a functional net of four levels. Each level for one of the main characteristics present in a device: material, energy, force, signal. The methodology is really general purpose, then a functional net can be associated to the characteristics present in the solution that can be pursued.

Also solutions that will be modelled as a collection of parts, linked by the only contact of force, can be analyzed and studied by means the methodology of product functional analysis.

The procedure of functional decomposition, associated to the functional reasoning, can be followed straightforward from top to bottom: from the main characteristic to each single elementary function, or from bottom to top, like in the reverse engineering approach, trying to collect all the elementary functions till to arrive to the main characteristic.

Neither of these approaches can be followed without re-examination. Students are encouraged to continuously go forward and backwards, reconsidering the validity of the specification done by each “verb + noun” couple. At the end of this process students have a schema on which they can start to embody more than one solution and try to verify the solidity of each architectural solution.

3 PROBLEM COMPREHENSION AND DATA STRUCTURE MANAGEMENT

The main problem in product functional analysis is to collect all the information in synthetic data structures that can be used as starting point for product development. If the functional decomposition schema is sufficiently clear, it could become the basis by which many individual solutions could be generated and/or transformed, as product schema. Else, this phase of early embodiment can suggest the revisions that must be done to the functional analysis, because some functionalities was not well understood, or because links between functionalities was missed.

The strong similarity between product functional analysis and graph theory allows students to use this formalization to collect all the information elaborated till now. Each function becomes a node and a link (of material, energy, force or signal) becomes an arc. So students can draw the graph related to the functional analysis and can build the adjacency matrix that records the relation among functions. Each

solution can be further customized and so from one functional analysis several solutions could be generated, each characterized some typical aspects.
Such data structures (typically matrixes) can be analyzed and a number of checks can be performed to ensure that the functional net is intrinsically valid.
During the course the students have to design an industrial product. They have to choose among many possible solutions and they have to trade off continuously for the definition of product component main characteristics.
The road map of the course involves, in sequence: identification of task, market analysis and customer needs, product functional analysis by means of clustered graph, concept generation (6-3-5 method and brainstorming) and concept selection (screening and scoring), product architecture, customer satisfaction (Kano model), Axiomatic Design, Quality Function Deployment (House of Quality), design for assembly-manufacturing-environment, Robust Design (Taguchi method), detail design.
Many of these methods share the matrix formulation as means to collect and manage project data. Functional analysis, being related to a graph, uses an adjacency matrix to store the relation that exists among functions. These data can be transferred in the “relation matrix” of the House of Quality, after having found the relation between Functional Requirements and Design Parameters, that can be used to verify the “design matrix” of the Axiomatic Design approach [13]. Further the relation among the components can be stored in DSM array [14]. All these relations can be mapped from a formulation to the other and each method can aid the designer to check in every domain if the design he/she is developing is in a right way.

4 STEPS TOWARDS THE PRODUCT FUNCTIONAL ANALYSIS EDUCATION

Students must be guided during the training phase to product functional analysis. First of all a set of examples are shown (typically devices of frequent use) and students are stimulated towards the search for the main functionality that must be expressed by the verb + noun couple in a sort of reverse process, from device to functionality.
Involving students in this search is really intriguing, because the teacher is seen in a strange manner: not a people that shows a new theory or discovery, but someone that ask for the description of the action performed by something that is obvious that do it. So, for example, showing a pen or a pencil, it is sure that the first answer to the question “what does it?” is “it writes”, as the pen could liven up. After some trials, discussing and laughing on some original answers, it emerges that a possible right solution can be “to leave a stroke”. And then, putting a new question: “where?”, it is surprising to discover that a set of possibilities emerge because the context changes the validity of the solution. So several existing devices are recognized to do the main function “to leave a stroke”, if a different context is assigned: on paper, on plastics, on blackboard, on whiteboard, on the wall.
When the main function is found and the context is defined, the second step can start: establish “how” the main function can be pursued. This requires that the most sub functions must be declared and must be linked together, in order to guarantee that the interrelation among several sub functions can, globally, perform the function from which they have been derived.
This process continues till the moment when it does not exist any sub function that require further decomposition.
At this point the designer or the designer team is ready to try to translate the solution from the “functional space” to the “physical space”, where a set of embodiments can be tried, substituting to each sub function a real device or a feature on a part that performs the sub function. Obviously this can be done with sufficient safety if the check on the functional net is positively passed.
During this process two terms have been used that remind to a methodology well used in product development: the Quality Function Deployment, or better its section of House of Quality. This latter put in relation exactly the domains of “what” and “how”. These terms appear also in product functional analysis, but with a slight different meaning. “What” does not represent what the customer requires to the device, but what are the functionalities that the device must have in order to satisfy the customer requirements. The meaning of “How” can be considered quite coincident: it relates to the main characteristics or main parameters that in the embodied device are associated to the functionality and , in both cases, they are quantifying elements that can be measured, with a metric, and compared among different solutions.
Product functional analysis can be considered the intermediary between the customer needs and the embodiment of the solution.

However students need a certain time to realize the difference between the part and the function performed by this. They frequently use a noun alone to represent a function. So a double road is followed to render familiar students about product functional analysis: a so called "straight way" from the functions to the parts; and a "reverse way" form the part to the functions.

5 HOW TO LEARN FROM EXISTING SOLUTIONS: A CASE OF STUDY

In order to expand the product functional analysis, a set of well known non functional solutions are proposed to students, so that the methodology can become a real tool by which it is be possible to discover deficiency in objects. Really useful for the discussion are some examples reported in Donald Norman [15]. But examples abound in our everyday life.
In the course it is proposed to students a "reverse" sequence, that can aid them to recognize what every part or feature really does in the whole product context. Then starting from the parts or features they can recognize which functions are performed by these, and sketch a functional net with the mutual relation among the functions. This is indeed a linguistic exercise because students must translate the nouns, that depict the part or the feature, to the couple "verb + noun", that define the function performed.
As case of study an "eggs container" has been chosen.
Even if it can be considered too simple, this example is a good basis to start with the functional reasoning, and could be useful to verify if the reasoning about the solution can allow students to discover a trap embedded in the solution.
In Figure 1 the example is illustrated, with a set of nouns that depict several features of the parts involved in the object.

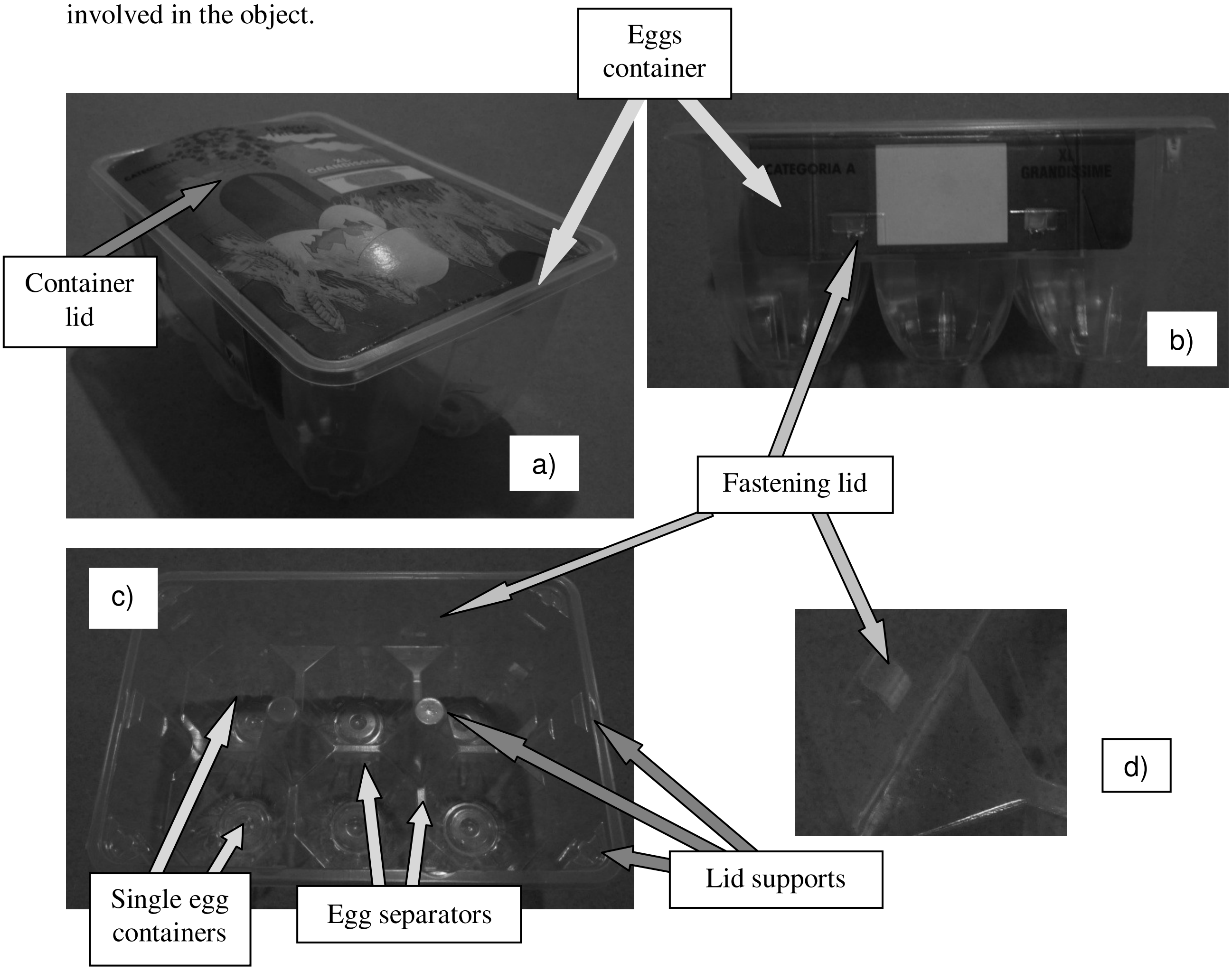

Figure 1. Case of study: eggs container. a) and b) the whole device; c) the container; d) detail of the fastening lid

The container is quite complex, with many more details than those reported in figure, but here only the major features have been highlighted. However, it is important to underline that in many cases a

morphological complex part can contain several features that are mutually linked not by means of force connections but by the material continuity. In any case the relation among the features (and then among the functions) must be represented by a link of force.
The task is now to draw a functional net. The main Functional Requirement can be expressed as "Contain the eggs", and a set of Functional Requirements can be specified in order to perform together this main functionality.
Following the symbology used in Axiomatic Design, they are:
FR1- Contain single eggs
FR2- Separate the eggs;
FR3- Put the lid on container
FR4- Close the container, decomposed: in FR41- Fix the lid and FR42- Sustain the lid;
These can be derived by a set of customer needs, that could be listed as: Transport eggs in safety, Avoid eggs breakage, Easily open the container, Easily extract eggs from the container.
The first step consists in sketching the functional net among all Functional Requirements. The net is reduced to only the adjacency relation among parts that are linked by contact force (being components that explain single functions connected together). In Figure 2 a functional net is reported with the relation among them. Each white arrow defines a connection between two functional requirements that must be associated to a relation between two parts or two features of the same part, if this latter assumes a more complex form.

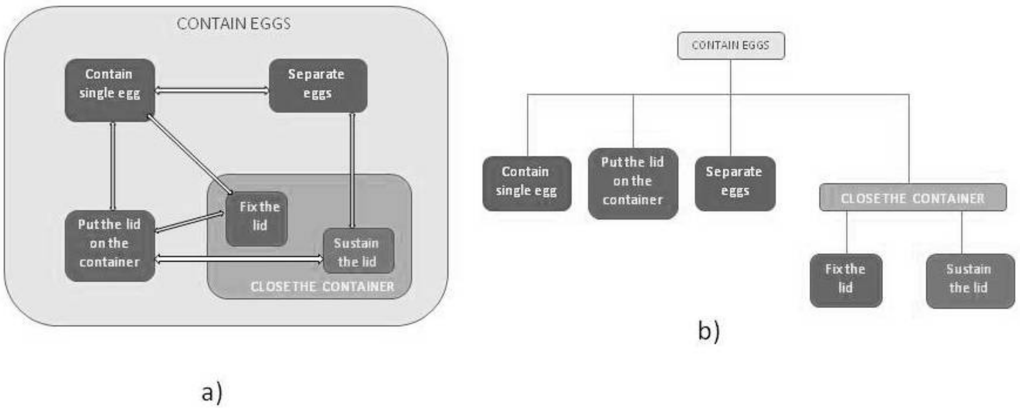

Figure 2. Functional net of the device "eggs container", a) clustered graph, b) tree

It appears at this point that the discussion is over. The solution seems to respect the task required to it. And really it is not so clear the need to have built the functional net. Whereas it is just the functional net with all the Functional Requirements that allows the designer to start again to verify if the solution expressed is really valid. Having in mind the shape of an egg, the designer has to return to the Customer Needs from which he/she started, and verify if all the needs have been satisfied. He/she can recognize that remains to be represented in functional term something associated to the need "Easily extract eggs from the container".

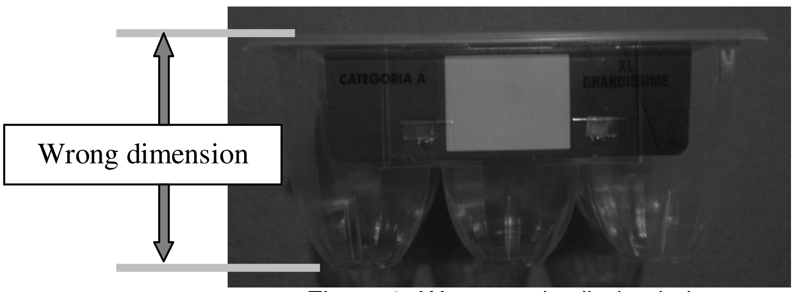

Figure 3. Wrong embodied solution

This need cannot be represented as a further FR in the net of Figure 2, because it is associated to something else: to what must be contained. But this FR must be embodied in the shape that must take

the container. It must house the lower part of the egg, but it must leave free almost one half of the egg to be gathered.
After this reasoning can be concluded that the solution has something wrong: the container is too height to allow someone to leave an egg off from it, by fingers.

6 CONCLUSION

The paper has discussed the importance of the functional analysis teaching in the courses of "product design" held at university level. If such a course is positioned at the end of the curriculum in Faculties of Engineering, it may be used as a course of synthesis among all the topics studied. In any case it is necessary to stress the topic of functional analysis in order to stimulate students to find a strategy in problem solving that allows to verify is the solutions found are really valid.
The example discussed can be a trace how product functional analysis can be taught. The exercise must be repeated many times on several devices before students become autonomous in building a functional net starting from the functional domain. To use only linguistic terms is the major difficulty for people trained to use models and synthesize them in mathematical terms.
Really the process described proceeds formalizing functionalities in matrix form. This kind of data structures (not discussed here), that take form from the graph associated to the functional net, can be mapped in several domains (QFD, Axiomatic Design, DSM) each one characterized by a proper matrix. The students are so able to map information and relations among several methods and they can take under control the whole design process, from concept to detail design.

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