HOLISTIC MODEL FOR COLLABORATIVE INTEGRATED PRODUCT DESIGN

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Abstract
The research aim is to develop a holistic model, combining Pahl and Beitz's systematic design model and Nam Suh's axiomatic design model. Next goal is to build a collaborative integrated product design platform through the corroboration of these two models using an existing DFSS algorithm. In order to sustain the two models integration it were identified some common aspects regarding the first phase from systematic design clarifying the task and customer needs - functional requirements from axiomatic design.

1. INTRODUCTION

Companies' competitiveness and success depends on theirs product's innovation capacities. To support an innovative and creative way of product development it is necessary to have a powerful design process that covers the multitude of the different aspects that arises during this. An important aspect in order to attend these objectives is to choose a collaborative integrated product design [8]. A platform that uses the most advanced management solutions for the product lifecycle - Product Lifecycle Management (PLM) - can materialize this approach. In this context, the presented research's aim is to study the product design models in order to elaborate a holistic model for sustaining a product development platform. In [2] is presented a knowledge synthesis in the field of product design models, methods and tools. Their presentation was made in order to see which are the most suitable to be used regarding the building of a collaborative integrated product development platform. The design process is based on different design models, methods and tools. The research aim is to develop a holistic model, combining Pahl and Beitz's systematic design model and Nam Suh's axiomatic design model. Next goal is to build a collaborative integrated product design platform through the corroboration of these two models using an existing DFSS algorithm. In order to sustain the two models integration it were identified some common aspects regarding the first phase from systematic design - clarifying the task and customer needs - functional requirements from axiomatic design.

2. PARALLELISM BETWEEN SYSTEMATIC DESIGN AND AXIOMATIC DESIGN

2.1 Systematic design

This model [6], based on a sequential decomposition of design process, using phase concept, is presented in figure 1. It is based on a design seen as a hierarchical, sequenced phases, the predominant logic being the convergence.
At the origin of each new technical object, there is a specific problem to solve and a goal to focus on. The first phase is planning and clarifying the task (specification of information in a requirements list): the market, the company, and the economy are taken into account to create and select suitable product ideas. Next, conceptual design phase (specification of principle) has the objective to determine the principle solution. In the embodiment design phase (specification of layout), a working principle is elaborated in the form of preliminary layouts that are then evaluated and rejected and/or combined to produce a definitive

layout. The last phase, detail design (specification of production), is the phase where all production documents are produced.
This model has a coherent structure for the design phases. Based on the authors' experience and consulting the literature were analyzed systematic procedures regarding the ideas generation and solutions finding.
The conditions that have to be satisfied by the users of a systematic model are [6]: define goals, clarify conditions, dispel prejudice, search for *variants*, evaluate, and make decisions. The systematic work is supported by several general methods [4]: analysis, abstraction, synthesis, method of persistent questions, method of negation, method of forward steps, method of backward steps, method of factorization, method of systematic variation, division of labour and collaboration.
The methods regarding solution finding [4] are divided in *conventional methods* like Information gathering, analysis of natural systems, analysis of existing technical systems, analogies, measurements, model tests and *intuitive methods*: brainstorming, method 635, gallery method, Delphi method, synectics, combination of methods and discursive methods: systematic study of physical processes, systematic search with the help of classification schemes, use of design catalogues, methods for combining solutions, systematic combination, combining with the help of mathematical methods, selection and evaluation methods.

The phase clarify the task
To realize a requirements list it is necessary to follow the steps regarding the requirements definition and registering and then to refine and extend them using different methods. According to [4] the methods for refining and extending the requirement suppose the creation of a scenario regarding the product's lifecycle and possible situation where the product can be. This is done by addressing some specific questions and following requirements list where the items from list are checked against the existing task. The requirements can be explicitly and implicitly - the technical requirements are explicitly.
In the refining and extending procedure for requirements it is used a three steps procedure: need's statement, developing the need - client's requirements and refining (by adding details). The results of the third step are added to the requirements list.
Refining is obtained through the answers to the following questions: what are the objectives that the solution has to satisfy, which are the properties that it has to have, what properties it should not have. After this refinement and extending process for a requirements list, the requirements have to be clearly arranged: define the objectives and main characteristics, the division into identifiable subsystems, functions, assemblies or according to check list's headings. A requirements list advances and is developed permanently in the design process. Having a complete, refined, extended requirements list, the next step in the design process is conceptual design phase. The needs are formulated in terms of requirements and not in function or solution idea terms. In [4] is said that is not wrong to use a formulation in functions or solutions terms, it is accepted, because such a formulation encourages a clearly requirements statement and can conduct to the emergence of new ones. Also, the identification of failures can generate requirements that has to be formulated next in a solution neutral way. According to [4], technical systems deal with conversions of energy, matter and information, which must be defined quantitatively, qualitatively and economically and correspondingly, for each task are derived from this conversion the functions that are completed with specifications of the physical quantities.
The functions are usually defined using a verb and a noun and are seen as an abstract formulation of the task, independent of any particular solution. After the overall task is

defined, then it can be specified the overall function.
Because the overall function of a system is usually too complex to allow the identification of a solution principle that alone could fulfil the system purpose, it is necessary to break it down in less complex sub-functions corresponding to subtasks and the relationship between the overall function and the sub-functions implies the existence of constraints. This decomposition must proceed until a solution principle able to perform alone the system task (elementary functions) can be found. The appropriate arrangement of the sub-functions of the overall function is named function structure, which is generally represented by block diagrams. In systematic design, derived from Value Analysis, it is made difference between main and auxiliary functions. *Main functions* are those sub-functions that serve the overall function directly, *auxiliary functions* are those that contribute to it indirectly but they have a complementary aspect and are often determined by the nature of the solutions for the main functions.

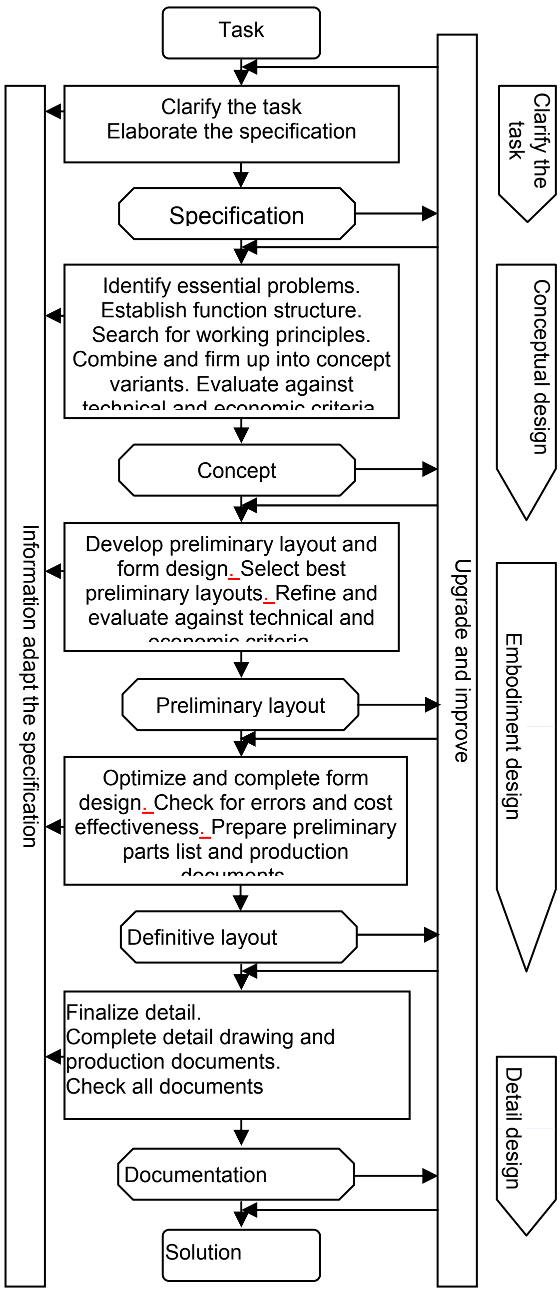

Figure 1. Design process phases [4]

2.2 Axiomatic design

Axiomatic design (AD) deals with principles and methodologies not with algorithms and tools and based on the two axioms, corollaries and theorems are derived. In this way, it is developed a methodology and based on functional analysis and minimization of information content it is realized a robust design.
Axiomatic design has four core concepts: domain, zigzagging and hierarchies, mapping, axiom, detailed in the next paragraphs. The design is interplay between *what* we want to achieve and *how* we choose to satisfy the need. To systematize the thinking process in this interplay, it was created the domain concept, foundation of axiomatic design. The four domains are: Customer Domain, Functional Domain, Physical Domain and Process Domain (fig. 2) and for each domain there are corresponding Customer Needs (CNs), Functional Requirements (FRs), Design Parameters (DPs) and Process Variables (PVs).

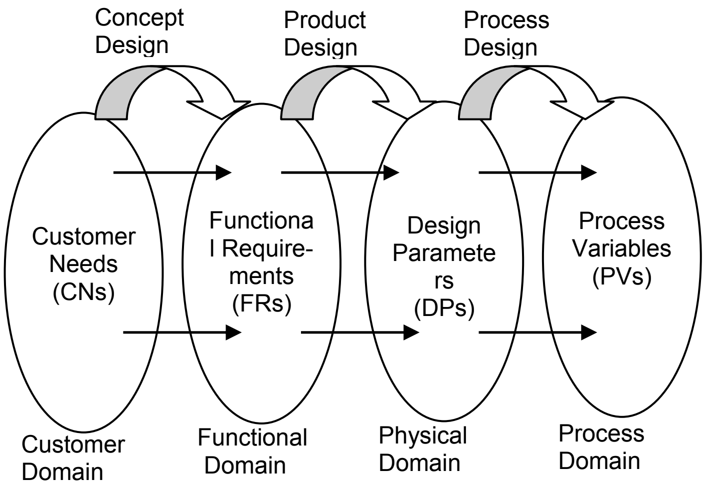

Figure 2. Axiomatic Design Domains

The definitions for Functional Requirements, Constraints, Design Parameters and Process Variables are [6]:
Functional Requirements (FRs) are defined as a minimum set of independent requirements that the design must satisfy and which characterizes completely the functional requirements of the product (system, organization etc.) in Functional Domain. When they are established, they are independent each other.
Constraints represent the bounds on acceptable solutions and differ from requirements in that that they can be related. The design objectives take into account the constraints. The input constraints are mentioned in design specifications and system constraints are imposed by the design of the system in which the design solution must operate.
Design Parameters (DPs) are physical variables in the Physical Domain that characterizes the design and satisfies the Functional Requirements in the Functional Domain.
Process Variables (PVs) are process variables in Process Domain that characterizes the process that can generate the specified DPs in Physical Domain.
The design process starts from a high level of abstractization and from this level, takes place decomposition in levels and sublevels. Realizing decomposition in the domains (functional, physic and process) results a hierarchy for functional requirements, design parameters and process variables in their domains. Decisions taken at higher levels of decomposition will affect the problem at lower levels. To create these hierarchies, we permanently must pass from a domain to another, to realize the decomposition. This

process is named zigzagging between domains (zig from FR to DP and back, zag from DP to FR, figure 3, to decompose further the FR) to make the decomposition.

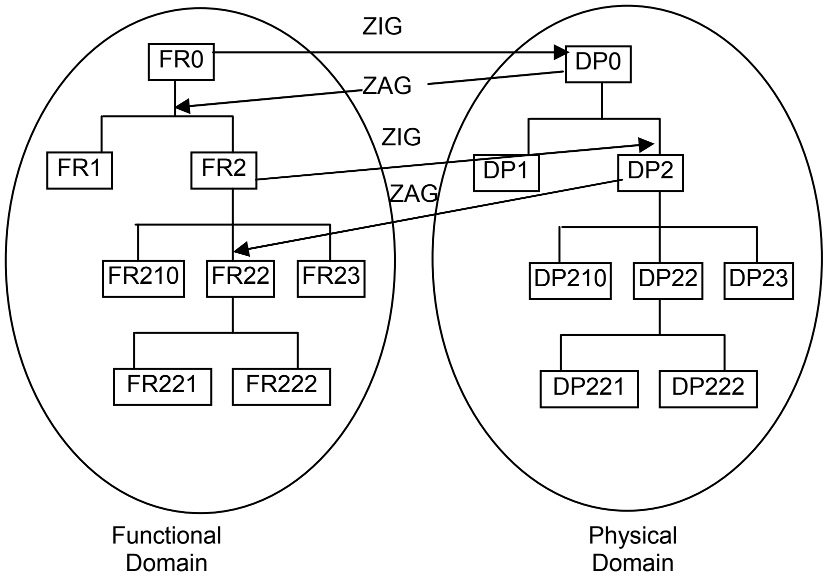

Figure 3. Zigzag between Functional Requirements and Design Parameters [6]

The decomposition does not take place integrally in one domain but in parallel in the both domains.
At a given level of detail in design, functional requirements, which define specific design objectives, are an FR vector in functional domain. In the same way the set of design parameters in physical domain (the how for an FR) are a DP vector. In an acceptable design, DP and FR are related so that a specific DP can be modified to obtain the desired FR without affecting the others FR.
The Independence Axiom - sections of the design should be separable so that changes in one have no (or as little as possible) effect on the other. The relations between the functional requirements FRs and design parameters DPs at a given level of the design hierarchy are captured in the Design Matrix (the [A] matrix in Equation 1) [5]:

$$\begin{pmatrix} FR_1 \\ FR_2 \\ . \\ FR_n \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & ..... & A_{1n} \\ A_{21} & A_{22} & ..... & A_{2n} \\ & & & \\ A_{n1} & A_{n2} & ... & A_{nn} \end{pmatrix} \begin{pmatrix} DP_1 \\ DP_2 \\ . \\ DP_n \end{pmatrix} \qquad (1)$$

Information Axiom refers to minimize the design information content. Among the design solutions that satisfy the first axiom (independence axiom), that which has the best probability of success is the best. That is why, the design, which minimizes the number of functional requirements and constraints, has integrated parts that maintain his functional independence, use standardized parts, uses symmetry as much as possible represents designs with a minimized information content and has a higher probability of success.

The passing from customer domain to functional domain
In AD passing from customer domain to functional domain is a difficult process – the needs are not explicitly defined. If we have an existing product, in AD is said that it is very

difficult to determine FRs and build the design matrix if the original design was a decoupled one

The first step is to analyze the inputs - the client's requirements in order to perform a task clarification. A requirements analysis is used to develop functional and performance requirements; refine and extend them that is, customer requirements are translated into a set of requirements that define what they want and which are the acceptable ranges for this requirements.

A rigorous analyze of this requirements is at the basis of defining the functional requirements and design constraints. The FRs is important to be defined in a solution neutral way. In axiomatic design, the functional requirements are defined like "the minimum set of independent requirements which completely characterizes the design objective corresponding to a specific need" [6].

The functional requirements and the constraints has to be easy to understand, comprehensive, complete, and concise supporting the definition for design equations that unambiguously define the problem that has to be modelled – relations between FRs and DPs and solve them.

In [5] after the FRs definition it follows a conceptualization process, which occurs during the mapping process from functional domain to physical domain. This is requiring a creative work and during the mapping process it has to think to all the different ways to fulfil each of the FRs.

2.3 The common and different elements of the presented models

The common elements between systematic design model and axiomatic design model is that deals with functions, the nature and the definition of functions and also that we have to think in terms of functions and not in terms of solution.

Some of instructions regarding functions generation presented by Pahl and Beitz are useful in axiomatic design to generate the FRs.

In both models, related to the task description and a requirements list for a product regarding its functionality, performances, costs, terms, a useful method to support a requirements list preparation is Quality Function Deployment – it realises the translation for the customer needs in product's requirements.

The differences between the two models, systematic design comparative with the axiomatic design [7]:

- In systematic design does not exist the concept of domains;
- The concepts of hierarchies and zigzagging do not exist. The solution finding process is focused on sub-function identification and finding the solution will generate the possibility to have or not to have a set of the auxiliary functions, working principles that fulfil the sub-functions;
- Functions are classified as main functions which satisfy the main functionality and auxiliary functions that satisfy indirectly the main function and in AD this concepts does not exists;
- There are emphasized operational flows and the possibility to identify minor changes as in AD the aim is to take good creative design decisions;
- The aim is to provide different design variants through the way of functions accomplishment, idea that is consistent with AD where is made a synthesis of the solutions not just a rearrangement of functional requirements;
- In AD, all the FRs are taken into account and has to be satisfied by their corresponding DPs.

In AD it is not necessary to give priorities for FRs. That is because if the design range is clearly defined for all FRs, the design goal is completely specified and any design that satisfy the FRs in the design range satisfies the design goals. When a design cannot be developed so that to satisfy all FRs in specified design range or the design is a coupled one, FRs can be prioritized but this is not in accordance with the independence and information axioms. In AD is said that to determine the design parameters can be found using the methods from systematic design. A way to identify the necessity for a certain DP is to identify the coupled FRs and to try to decouple them by removing the coupled entities [5]. The functional requirements are corresponding to the functions from the functional structure of Pahl and Beitz model, but is not made any difference between main and auxiliary functions.

The two types of models are different in that that in axiomatic design a good design is obtained following and respecting the two axioms as in systematic design the main advantage is that the designers do not have to rely on coming up with a good idea at the right moment. Solutions can be systematically elaborated using the adequate methods and a solution space is created because variants are generated while developing the function structure and when selecting physical effects. The use of a combination of solution-finding methods can be used to extend the solution space.

For less performing designs sometimes is made an optimization - a compromise between the requirements and constraints. In axiomatic design, a design that violates the independence axiom cannot be improved only firs it satisfies this axiom, otherwise the result will be a poor design but optimized.

Both approaches emphasise the fact that design tasks can differ from product to product and the used approaches can differ according to companies specific and the engineering field where they are applied. The abilities required to designer are to be able to realize an abstractization, the ability to have an abstract thinking, a systematic work, a logical, creative thinking, good engineering knowledge and to understand the fundamental principles. These are useful to identify the essential problems, determine the functions structure and apply the rules and principles for embodiment deign.

Creativity and intuition needed in solving of a technical problem can’t be replaced by an approach. They can be supported by TRIZ that can be applied when it appears a technical contradiction and in this way the company’s success through the discovering of innovations or inventions.

2.4 Functional analysis

According to the AFNOR X50-150 standard [1]: "Functional Analysis is an action which consists of searching, set in order, characterization, hierarchy and/or set a value (quantifying) for the functions". Connected to functional analysis it is specified that there are many methods of Functional Analysis (FA) that are more or less adapted to the analysis that we want to realize.

Functional analysis is a method that is included in a total quality strategy because it implies all the departments of a company whether they are functional or operational ones. FA implies the customers satisfaction, a clearly functions identification of the need to satisfy or services to render (need’s functional analysis), analyze how a solution respond to this need (technical functional analysis).

Functional analysis can be seen as a bridge between the needs expressed by the customers and the functions that have to render the products, processes, or organizations. Through these features, FA is essentially a way to conduct to the obtaining of the products’ quality and it can be realized for every specific utilization context of the studied object. Functional analysis has two possibilities to be unfolded: External functional analysis and internal functional analysis.

FA acts on the relation customer-purveyor defining the needs and the exigencies to satisfy. In this stage of need's formalization, the services to accomplish are emphasized, referring to objective data regarding the product's use and the product's design will result from this analyze. The system (product) is considered taking into account its finality, it takes into account all the factors regarding the system and its environment, emphasize the product's quality through its value expression for the customer.
This method has several steps in its application and development: the need's statement and definition; the expected functions definition; the review process of the using environment elements; identification of the relations created by the product between the environment's elements or even between these elements; express the finality of these relations through a phrase that contain the element or the elements tacked into account or a verb that characterizes the action; establishment of a functional diagram block.
Thus, consulting the customer's objective and subjective expectations result what they wants and using the functional analysis, it can be used the qualitative parts of value criterions to complete the functions. Using next the internal functional analysis the product can be structured and organized in a functions ensemble (how). Functional analysis takes into account of customer's needs that are part of the first matrix of the first phase of QFD (Quality Function Deployment). In this phase, QFD dwells on the relation between customer's expected needs and different technical solutions that can conduct to customer's needs satisfaction. In this way the functional analysis will help to the clearly defining of the functional requirements and in this way it can an be used in both approaches.

3 HOLISTIC DESIGN MODEL

A part from Pahl and Beitz design model refers to the structure development of functions. Combining various methods emerged coherent structure for the design phases.

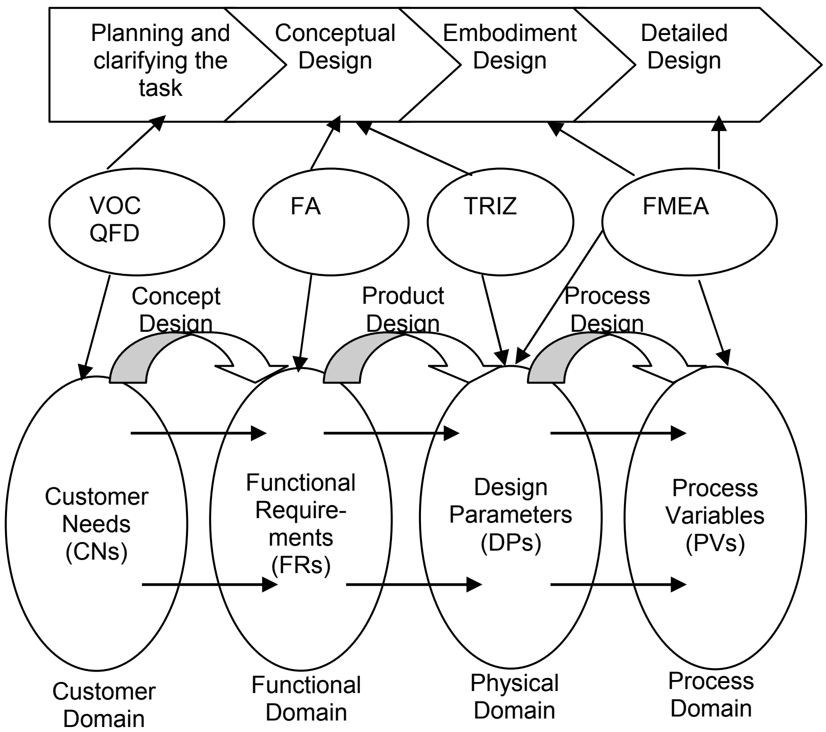

Figure 4. Holistic model

Comparing the two design models, the common elements between systematic design and axiomatic design is that deals with functions, the nature and the definition of functions and also that we have to think in terms of functions and not in terms of solution. Also, the methods used in systematic design are useful to determine the DPs. Axiomatic design is characterized through its generality, it can be applied in all design fields, its rules are the same and the guidelines on how to make axiomatic design are given by the design axioms.

Design methods presented in [4], used separately, are not fully useful only if they are integrated, adapted to the need, in global design and quality approaches. Even their objectives are different; they can be applied to reach a common objective - to improve the design process. In this way, we consider that these design methods are complementary.

Based on this idea it was proposed a holistic design model based on the two design models, different in their concepts but which have also common elements is represented in figure 4. So, various design methods can be used in Axiomatic Design and also in systematic design: VOC (Voice of Customer) for the critical customer requirements gathering, QFD (Quality Function Deployment) for structuring of the customer needs in order to transform them in functional requirements, FA (Functional Analysis) for identifying the functions, TRIZ (Theory of Inventive Problems Solving) for eliminating the physical and technical contradictions, to give an illuminating solution in concept generation and decoupling the design matrix, FMEA (Failure Modes and Effect Analysis), for improving the products reliability, its application being facilitated by the decomposition in physic and process domains, respectively in embodiment design and detailed design.

A holistic design model is proposed. The collaboration between the two design models is realized through the integration of methods and tools used, following a DFSS approach and an algorithm, which offers a coherent structure for the design phases.

The DFSS algorithm that integrates these methods and tools has as aim to develop design entities corresponding to the expressed needs for the entire product's lifecycle at a six sigma quality level [9].The 14 steps are grouped in four phases: I-Identify, C-Characterize, O-Optimize and V-Validate. The phase represents a set of project's design activities and is limited by inputs and outputs.

The identify phase comprise the form team and determine customer expectations steps. The characterize phase comprises the following steps: understand FRs evolution (TRIZ - analyze and derive concepts), select best concept and analyze the functional structure of selected concept. It follows the optimize phase comprises the uncouple or decouple selected concept, simplify using design axiom 2, initiate scorecards and transfer function development, FMEA/PFMEA Asses Risk, DOE transfer function organization, Design for X, Tolerance design steps and finally the validate phase that comprises pilot/prototype design, validate design, launch mass production and celebrate successful completion steps. The above presented algorithm [9] follows an axiomatic design and uses QFD, TRIZ, FMEA. It is important to use also the functional analysis, a common design method for both axiomatic and systematic models. It is contributing to take an account of customer's needs (QFD), to know the functions for each product's using or functioning phase in order to analyze next the failure risks (FMEA).

4 DESIGN PLATFORM

The collaborative integrated design platform comprises the software tools that assist the proposed model. The platform contains two software tools provided by TDC Software (http://www.tdc.fr) and Axiomatic Design Solutions Inc. (http://www.axiomaticdesign.com). The TDC Software Products allows the integration of the functional analysis in collaborative integrated design platform. TDC Need tool helps to classifies, to give value to the generic functional requirements for a specific need and next using an internal functional analysis to find the main functions, the constraint functions with their importance degree. The next step is to use them as entrances in TDC Structure module the result being a more detailed functional structure and next the solutions (ways to provide the functions) list. Acclaro DFSS is an axiomatic design tool that supports a better concept and design process development through its hierarchical decomposition in the four domains: customer needs domains, functional requirements, physical domain and process domain, and modules like those that risk analyses module, cost analyses module, FMEA module.

5 CONCLUSION

A successful design is that one where all the possibilities are taken into account and all the decisions are made on rational basis. An interesting approach in a product development (design process) is to be developed following a systematic design and to be supported by the two axioms from axiomatic design using a holistic model.

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