ANNALS of the ORADEA UNIVERSITY.

Fascicle of Management and Technological Engineering, Volume VI (XVI), 2007

PARALLELISM BETWEEN ALGHORITMIC (SYSTEMATIC) DESIGN AND AXIOMATIC DESIGN

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Keywords: design approaches, algorithmic design, systematic design, axiomatic design

Abstract: Theories of design take an approach, which is either algorithmic (systematic) or axiomatic. Algorithmic approaches define a procedure to be followed during the design process. Axiomatic approaches define general rules that are applicable at each decision-making step in the process irrespective of the procedure used. In this paper, the aim is to realize a parallelism between the two fundamental approaches with further objective to propose a holistic design approach model.

1 Introduction

Engineering design is a creative activity which starting from expressed needs and existent knowledge has as aim to define a material or immaterial object, named also *artefact*, which satisfy these needs and which can be industrial realized [1]. The design is the key factor of new product process development [10].

The most representative approaches of design used now are algorithmic (systematic) design elaborated by Pahl and Beitz [9] and axiomatic design elaborated by Nam Pyo Suh [13].

Generally, the algorithmic approach is founded on the notion that the best way to advancing in design field is to understand the process by following the best design practice. Approaches founded on phase notion are considered algorithmic [6].

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.

In this paper, the aim is to realize a parallelism between the two fundamental approaches with further objective to propose a holistic design approach model.

2 Algorithmic (Systematic) Design

Among design models the most representative is the model of Pahl and Beitz [9]. This model is based on a sequential decomposition of design process, using phase concept (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. Then, requirements and constraints are formed into a requirements list.

Next, *conceptual design* phase (specification of principle): has the objective to determine the principle solution. To do this, the essential problems are abstracted; function structures are established; suitable working principles are sought; a working structure is synthesized; and lastly, solution concepts are evaluated against technical and economic criteria. 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.

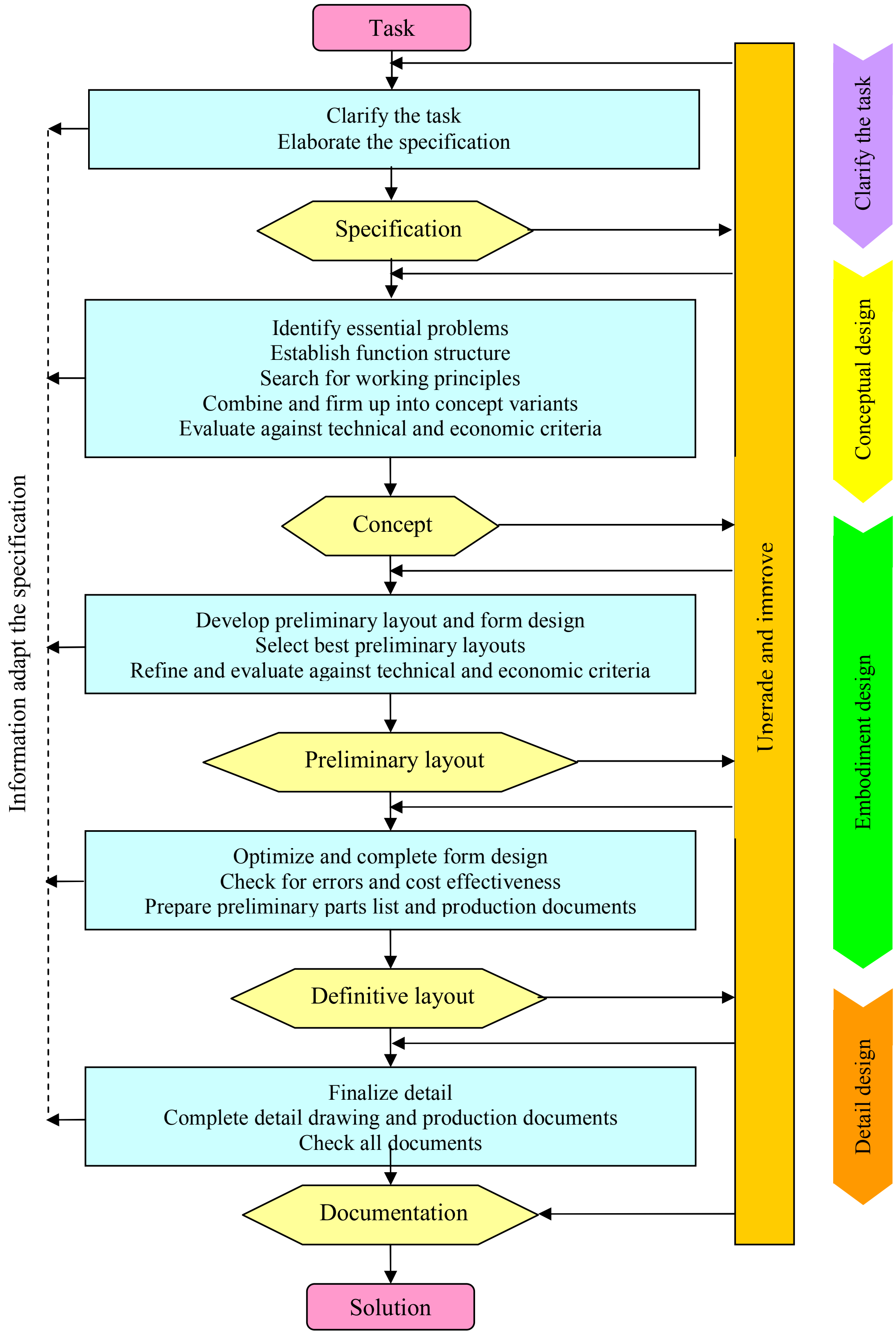

Figure 1. Design Process Phases, after Pahl & Beitz [9]

3 Axiomatic Design

The researches about axiomatic design begun in 1977 initiated by professor Nam P. Suh from MIT (Massachusetts Institute of Technology) and in the next years he analyzed the axiomatic approach application into manufacturing systems.

Axiomatic design has four core concepts: domain, zigzagging and hierarchies, mapping, axiom, detailed in the next paragraphs.

Domain. 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 (figure 2).

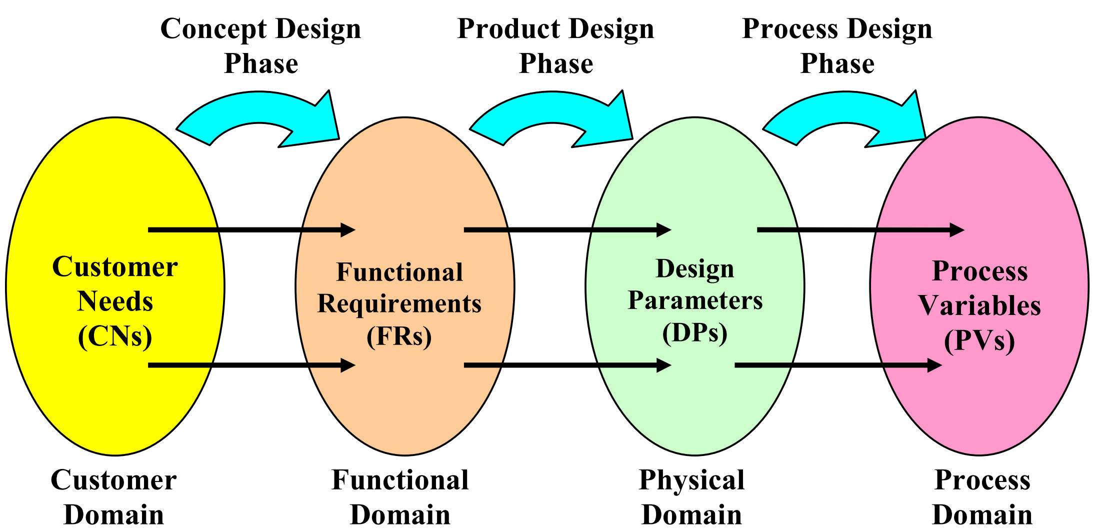

Figure 2. Axiomatic Design Concept, after Nam P. Suh [13]

The passing from left to right through domains represents *what* we want to achieve and the domains from right side represents the design solutions to the question *how* we propose to satisfy the needs from left domain. All the designs can be represented using the four domains this contributing to its generality. The design objectives may be different but the approach used to attend them is the same [13].

The definitions for Functional Requirements, Constraints, Design Parameters and Process Variables are [13]:

- *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.

Hierarchies and zigzagging. The design process starts from a high level of abstractization and from this level takes place decomposition in levels and sublevels. This decomposition is realized in the domains (functional, physic and process) and result a hierarchy for FRs, DPs and PVs in their domains. In Customer Domain, the information is an exception and cannot be rigorously structured [14].

Decisions taken at higher levels of decomposition will affect the problem at lower levels. At a given level of decomposition there exists a set of functional requirements. To make the further decomposition for these functional requirements we have to choose the corresponding design parameters.

If a DP satisfies one FR then we will make the decomposition for this FR further and the process will be repeated. This is applied also to the elements of the Physical Domain and the Process Domain. 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. The decomposition does not take place integrally in one domain but in parallel in the both domains.

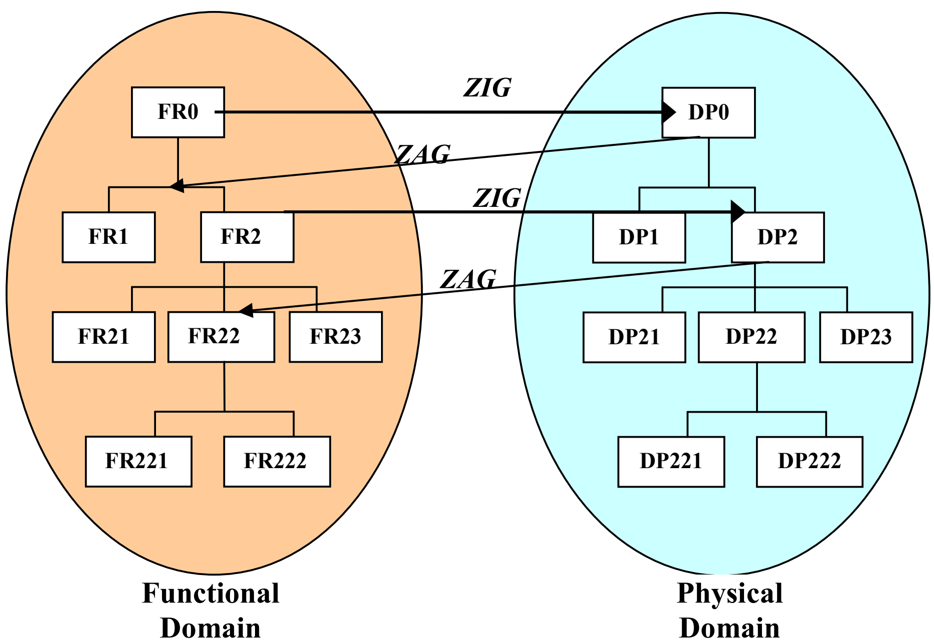

Figure 3. Zigzag between Functional Requirements in Functional Domain and Design Parameters in Physical Domain

Mapping. Solution alternatives are created by mapping the requirements specified in one domain to a set of characteristic parameters in an adjacent domain. The mapping between the customer and functional domains is defined as *Concept Design Phase*; the mapping between functional and physical domains is *Product Design Phase*; the mapping between the physical and process domains corresponds to *Process Design Phase* [5].

Independence Axiom. To materialize what was presented above the mapping process was expressed in terms of characteristic vectors that define the design objectives and the design solutions, put in mathematic expressions. During this mapping process the independence axiom must be satisfied. 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 FRs and DPs at a given level of the design hierarchy are captured in the *Design Matrix* (the [*A*] matrix in Equation 1) [8].

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

The terms of the equation (1) are expressed by the relation (2).

In an *uncoupled design*, the FRs can be independently satisfied by means of their corresponding DPs.

In a *decoupled design* the FRs can be satisfied if the DPs are adjusted and set in a particular sequence.

If the *design* is *coupled* there is no guarantee that the FRs can be satisfied. The same analysis applies to the relationships between DPs and PVs.

$$\begin{aligned} dFR_1 &= \frac{\partial FR_1}{\partial DP_1} dDP_1 + \frac{\partial FR_1}{\partial DP_2} dDP_2 + ... + \frac{\partial FR1}{\partial DP_n} dDP_n \\ dFRn &= \frac{\partial FR_n}{\partial DP_1} dDP_1 + \frac{\partial FR_n}{\partial DP_2} dDP_2 + ... + \frac{\partial FR_n}{\partial DP_n} dDP_n \end{aligned} \qquad (2)$$

In this relation (2) each element $\mathrm{Aij} = \frac{\partial FR_i}{\partial DP_j}$ relates a FR_i to a specific DP_j.

The design matrix can be diagonal, upper or lower triangular, or populated both above and below the diagonal. This is illustrated in Equation 3 through Equation 6. In these equations, an “X” represents a strong relationship between a DP and an FR, and an “O” indicates an insignificant (or no) relationship [8].

A design with a diagonal matrix (Equation 3) is an uncoupled design. A design yielding a triangular matrix (Equation 4 and Equation 5) is known as a decoupled design. Any other matrix (Equation 6) describes a coupled design.

Equation 3 Uncoupled design, diagonal matrix

$$\begin{pmatrix} \mathrm{FR1} \\ \mathrm{FR2} \end{pmatrix} = \begin{pmatrix} \mathrm{X} & \mathrm{O} \\ \mathrm{O} & \mathrm{X} \end{pmatrix} \begin{pmatrix} \mathrm{DP1} \\ \mathrm{DP2} \end{pmatrix} \qquad (3)$$

Equation 4 Decoupled design, lower triangular matrix

$$\begin{pmatrix} FR1 \\ FR2 \end{pmatrix} = \begin{pmatrix} X\ O \\ X\ X \end{pmatrix} \begin{pmatrix} DP1 \\ DP2 \end{pmatrix} \quad (4)$$

Equation 5 Decoupled design, upper triangular matrix

$$\begin{pmatrix} FR1 \\ FR2 \end{pmatrix} = \begin{pmatrix} X\ X \\ O\ X \end{pmatrix} \begin{pmatrix} DP1 \\ DP2 \end{pmatrix} \quad (5)$$

Equation 6 Coupled design

$$\begin{pmatrix} FR1 \\ FR2 \end{pmatrix} = \begin{pmatrix} X\ X \\ X\ X \end{pmatrix} \begin{pmatrix} DP1 \\ DP2 \end{pmatrix} \quad (6)$$

An example of a decoupled design to exemplify those presented above is presented bellow. If we have to design a refrigerator and we have the next decomposition for FRs and DPs:

FR - preserve food - FR1-store chilled food
- FR2-store frozen food

DP - use cold temperature - DP1-Maintain food at 3 C
- DP2-Maintain food at -18 C

The next level of decomposition is presented in figure 4 and it is the design matrix.

	DP 2.1 Vertical Door	**DP2.2** Frost removal Mechanism	**DP2.3** Thermostatically Controlled Temperature	**DP2.4** Circulation Fan
FR2.1 Provide Access to the Food	X	O	O	O
FR2.2 Avoid Frost Buil-Up	X	X	O	O
FR2.3 Control the Temperature	X	X	X	O
FR2.4 Maintain the Uniform Temperature	X	X	X	X

Figure 4. Example of a Design Matrix

The X symbols in matrix correspond to the existence of a relation between a DP and FR, and an O means that there is no relation between FRs and DPs. The DP2.1 vertical door affects all the functional requirements and this is symbolized (an X) in the matrix. If the door is opened FR2.1-Provide access to the food is accomplished but it enhances frost build-up (FR2.2), temperature changes (FR2.3) and the temperature is no more constant (FR2.4). At its turn DP2.2 –Frost removal mechanism that satisfies the FR2.2-Avoid Frost

Build-Up Affects: FR23 Control the Temperature and FR2.4 Maintain the Uniform Temperature. DP2.3 Thermostatically Controlled Temperature satisfies FR2.3 Control the Temperature but affects also FR2.4 Maintain the Uniform Temperature. DP2.4 Circulation Fan satisfies FR2.4 Maintain the Uniform Temperature. DP2.1, DP2.2 and DP2.3 affect more than one FRS, so the design is decoupled (the matrix is populated lower the diagonal). In a coupled design all DPs affects all FRs.

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 which 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 designs, which do not satisfy the first axiom, are coupled and here is impossible to modify a DP without affecting at least two FRs. The design that satisfies the first axiom is named uncoupled or decoupled. The difference between them is that in an uncoupled design DPs are independent and in a decoupled one DP affects at least one FR.

A design specified in terms of DP s has a certain probability to meet specified FR s within given tolerances. A design with high probability to meet FRs within tolerances has also a high probability to satisfy customers and is therefore preferable. Axiom 2 "Minimize information content." is referring to this fundamental connection. Information content is here defined as $\log_2(1/p)$ where p is the probability to meet the requirements. In an uncoupled design smallest sum of information content is equivalent with highest probability to meet all functional requirements within tolerances [12].

At the base of this axiom is the information theory stated by Claude Shannon.

Information theory intuitively starts from the fact that for obtaining information a certain process or event has to take place. The quantity of the information obtained after an event has taken place is all the higher then the likelihood that that event should take place is lower.

If we note with i(p) the quantity of information, I has to be a downward function of p probability of event apparition.

A second restriction imposed by Shannon is that information measure to have an additional character, meaning that, if two events are taking place without any connection between, then the total information obtained has to be equal with the sum of each event's information. As the probability of two separate events is given by the product of probabilities associated with each event separately p12=p1*p2, the easiest function which meets this requirement is logarithmic function [7]. Next, mathematical relations and the explanation are from [13]

Information content I is defined in terms of the probability of satisfying a given FRs. If the probability of success of satisfying a given FR is p, the information I associated with the probability is defended as

$$I = -\log_2 p \quad (7)$$

The information is given in units of bits. The logarithmic function is chosen so that the information content will be additive when there are many functional requirements that must be satisfied at the same time.

In the general case of n FRs for an uncoupled design, I may be expressed as

$$I = \sum_{i=1}^{n} (\log_2 1 / P_i) \tag{8}$$

where P_i is the probability of DPi satisfying FRi.

Since there is n FRs, the total information content is the sum of all these probabilities. The Information Axiom states that the design that has the smallest I is the best design, since it requires the least amount of information to achieve the design goals. When all probabilities are equal to one, the information content is zero, and conversely, the information required is infinite when one or more probabilities are equal to zero. That is, if probability is low, we must supply more information to satisfy the functional requirements.

In the real world, the probability of success is governed by the intersection of the tolerance defined by the designer to satisfy the FRs and the tolerance (or the ability) of the system to produce the part within the specified tolerance.

The probability of success can be computed by specifying the Design Range (dr) for the FR and by determining the System Range (sr) that the proposed design can provide to satisfy the FR.

The vertical axis (the ordinate) is for the probability density and the horizontal axis (the abscissa) is for either FR or DP, depending on the mapping domains involved.

When the mapping is between the functional domain and the physical domain as in product design, the abscissa is for FR, whereas for the mapping between the physical domain and the process domain as in process design, the abscissa is for DP [13]. Figure 5 illustrates Design Range and System Range graphically.

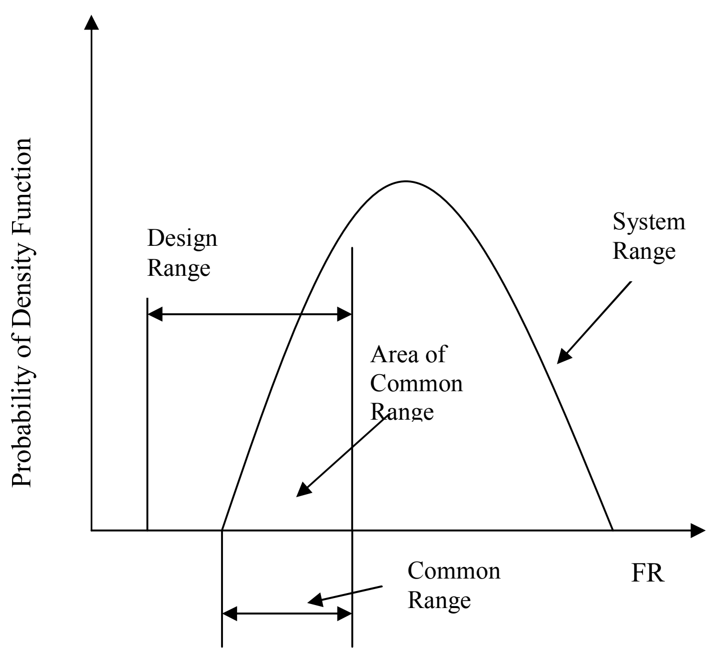

Figure 5. Design Range, System Range and Common Range

The overlap between the design range and system range is called the Common Range (cr), and this is the only region where the functional requirements are satisfied. Consequently, the area under the Common Range divided by the area under the System Range is equal to the design's probability of success of achieving the specified goal. Then, the information content may be expressed as:

$$I = \log_2\left(\frac{A_{sr}}{A_{cr}}\right) \qquad (9)$$

where A_{sr} denotes the area under the System Range and Acr is the area of the Common Range. Furthermore, since A_{sr} = 1.0 in most cases and there are n FRs to satisfy, the information content may be expressed as:

$$I = \sum_{i=1}^{n} \frac{1}{A_{cri}} \qquad (10)$$

When taking into account the uncoupled design the smallest sum of the information content is equal with the higher probability of meeting all the functional requirements within the limits of the tolerances.

Next are presented two examples from [13] - Cutting a Rod to a Length.

Suppose we need to cut Rod A to 1 +/- 0.000001 meter and Rod B to 1 +/- 0.1 meter. Which has higher probability of success? The answer depends on the cutting equipment available for the job! However, most engineers with some practical experience would say that the one that has to be cut within one micron would be more difficult, because the probability of success associated with the smaller tolerance is lower than that associated with the larger tolerance using typical equipment. Therefore, the job with the lower probability of success is more complex than the one with higher probability. Another example is that for Cutting of the Rod with a Hack Saw. We want to cut the rods as specified earlier, but now we know the equipment available for the job. It is an ordinary hack saw available in a machine shop. The system range is shown below (figure 6).

The plot of the system range and the design range shows that in the case of cutting Rod B, the system range is completely inside the design range and therefore, the common range and the system range are the same. Therefore, the probability of success is 1 and the information required to fulfill the functional requirement is zero (equation. 9). On the other hand, Rod A has such a tight tolerance requirement that the common range is almost zero, making the information required approach infinity.

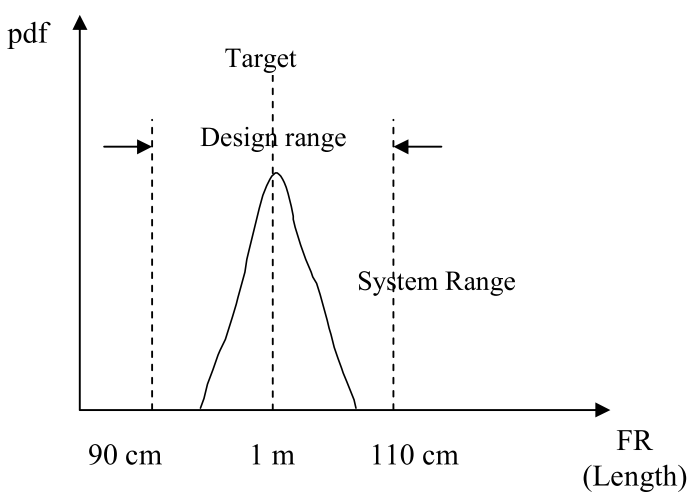

Figure 6. System Range and Design Range

4 Holistic Approach Model of Design

The aim of this paper is to realize a parallelism between the two fundamental approaches with further objective to propose a holistic approach model for design.

A part from Pahl and Beitz approach refers to the structure development of functions. Their objective was to combine various methods in a single one, which can offer a more coherent structure for the design phases. The common elements between systematic approach and axiomatic design approach 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. In [14] are also presented common and different elements of these two approaches.

Some of instructions regarding functions generation presented by Pahl and Beitz are useful in axiomatic design to generate the FRs of lower levels. The idea to start from a rough structure or analyzing known systems to find possible variants to satisfy these functions is useful in AD where the designers have to take into account all alternatively possible variants to satisfy the functions.

The differences between the two approaches are multiple [14]. So, in the systematic design, comparative with the axiomatic design:

- Pahl and Beitz lack a clearly delineated concept of domains. For example, the closest that their theory comes to DPs is the identification of "working principles" and "working structures";
- 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 omit or not 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. In AD, all the FRs are taken into account and has to be satisfied by their corresponding DPs;
- 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.

A holistic approach model for design based on the two approaches, different in their concepts but which have also common elements is represented in figure 7. So various design methods [3] 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.

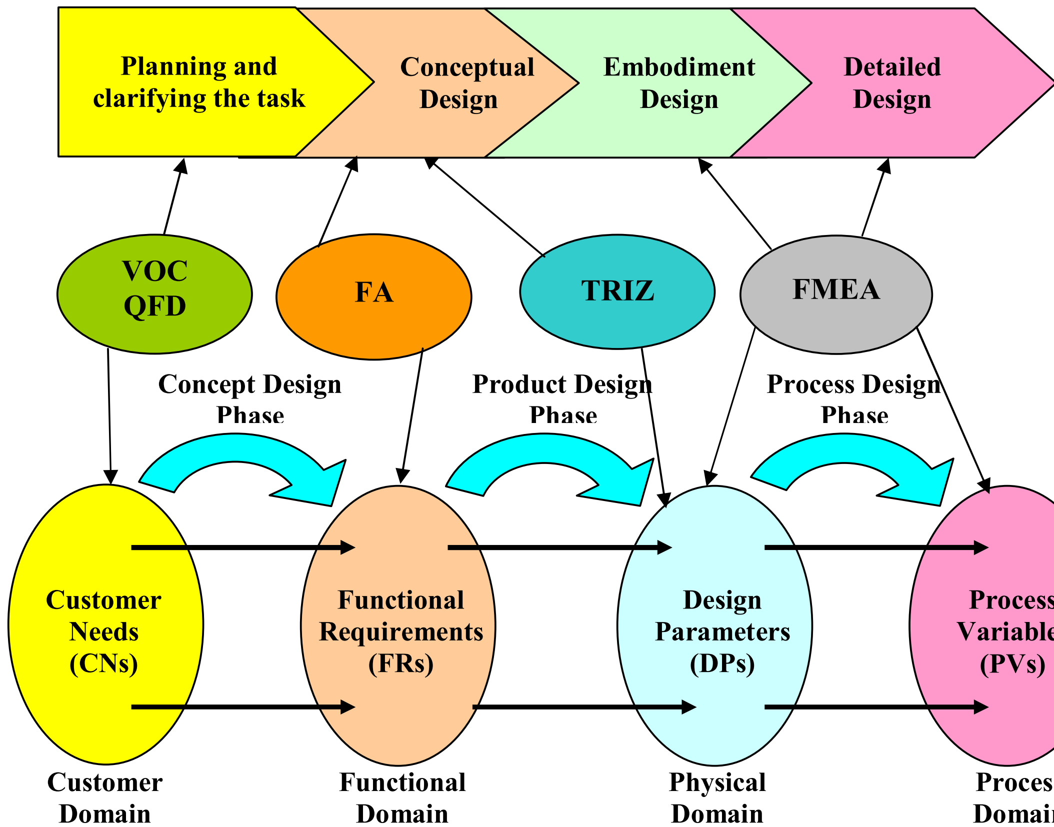

Figure 7. Holistic Approach Model for Design

5 Conclusions

This paper presented the two fundamental design approaches: algorithmic approach (systematic) and axiomatic approach. In algorithmic approach (systematic) is tried to identify or prescribe the design process. Axiomatic design is characterized by 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.

Analyzing the two approaches conduct to identify the places in their development where can be used design methods like: VOC for the critical customer requirements gathering, QFD to analyze the customer's requirements, FA to identify the functions, TRIZ to exceeding the contradictory and without apparent solution situations, FMEA to realize the reliability of product and manufacturing process associated. A holistic approach model for design is proposed.

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