TOOLS FOR INNOVATION AND CONCEPTUAL DESIGN

A Dissertation

by

SRINAND SREEDHARAN KARUPPOOR

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2003

Major Subject: Mechanical Engineering

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ABSTRACT

Tools for Innovation and Conceptual Design. (August 2003)
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The ability to design is the distinguishing characteristic of an engineer. Recent research has increased our understanding of both the engineering design process and effective means for teaching that process to neophyte design engineers. In that spirit, a design methodology was developed at the Institute for Innovation and Design in Engineering (IIDE), Texas A&M University. At the core of this approach is a design philosophy based on the cognitive skills of Abstraction, Critical Parameter Identification, and Questioning. This philosophy along with the design process is taught in the senior undergraduate design and graduate design courses. The goal of the methodology is not only to teach the design process to novice designers but also to instill in them the design philosophy that would enable them to perform design effectively and innovatively in any area of specialty.

In this dissertation the design philosophy along with its role in the design methodology is explained. The Need Analysis and the Conceptual Design stages of the IIDE methodology are elaborated. The weaknesses in these stages are identified and addressed, by developing and incorporating design methods and techniques that fit the spirit and framework of the IIDE design methodology. The Object Function Method was developed to address certain aspects at the Need Analysis stage. There was need for an effective concept searching method within the Concept Design stage of the IIDE design methodology. This is addressed by the development of new search techniques and methods for effective concept discovery during concept searching. The usage and application of these methods and techniques is explained in detail along with examples.

Additionally, this dissertation contains the results of a study conducted with two groups of senior design students, those who have been through the process and those who have not, to evaluate the effectiveness of applying the IIDE design philosophy and performing the Need Analysis and Conceptual Design stages for the given design challenge. The goal of the study was to investigate the relationship, if any, between the degree to which these aspects of the design methodology were followed and the quality of the resulting design solutions produced.

DEDICATION

Om Ganeshaaya Namah
Om SriRaghavendraaya Namah

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I would like to express my deep and sincere appreciation to my advisors Dr. Burger and Dr. Chona. It was Dr. Burger's passion for design and design methodology that led me to this wonderful world of research. I have always admired his breadth of knowledge and enthusiasm. Dr. Chona's insights and attention to detail are admirable qualities I wish to emulate. I am really thankful to both of them for providing the freedom in conducting research and providing me the various opportunities to participate in learning and teaching design. I am extremely grateful to them for their guidance and assistance in all matters, and for their infinite wisdom and patience. I am indeed fortunate to have two such advisors like Drs. Burger and Chona.

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I would like to express my heartfelt gratitude towards my parents who supported and encouraged me throughout my career. To Krithika, my wife, my heartfelt thanks for her support, encouragement and patience.

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1 INTRODUCTION

Design is the culmination of knowledge in engineering sciences. It is a process of devising a system, component or process to meet desired needs. During this process, the designer utilizes the knowledge from basic sciences, mathematics and engineering sciences, along with creativity, to convert resources to optimally meet the stated objective. Traditionally, the acts of designing of artifacts or devices and their creation were not separated. But now in modern industrial societies, with increasing economic costs and complexity, the designing of devices and their manufacture are usually separated. The process of making something only starts after the process of designing it is complete. Over the past three decades research has been pursued in understanding the design process and the ability to design. This ability to design, that is, to innovatively utilize knowledge to produce products that meet required goals, is the hallmark of a good engineer.

There are several reasons why there is a need to understand and improve the design process. One of them is the increasing complexity of modern designs. The advent of new materials and devices, the rapidly increasing knowledge base available for engineers to exploit, and the ever accelerating pace of new product creation presents daunting challenges to designers. To cope with these demands, a systematic approach is needed. Also, the complexity of the tasks and the shortened time to market often necessitate that a team of designers work on a problem. To help coordinate the team, it is necessary to have a clear, organized approach to design, so that specialists' contributions are made at the right point in the process.

This dissertation follows the style and format of Journal of Mechanical Design.

Additionally, increased complexity has increased the costs associated with design work. Typically many products are designed for mass manufacture, and the costs of setting up the manufacturing plants, buying materials, and so on, are so high that the designer cannot afford to make mistakes. By employing a systematic design process, a designer can avoid many of those risks.

These concerns have led to the development of new design methods, procedures, techniques, aids, and computing 'tools' for designing. They deal with several kinds of activities that designers may use at different stages of the overall design process. These methods can be rational procedures that formalize conventional design practice, or may be adaptations of methods from unrelated domains such as operations research, decision theory, etc. The new design methods generally have two features in common [1]. They formalize certain procedures of design and they externalize design thinking. Formalization attempts to avoid the occurrence of oversights during the execution of a design. At the same time formalizing tends to widen the approach and the search for appropriate solutions. Externalizing involves getting the thoughts and the thinking process out of the designer's mind by organizing them onto paper in the form of charts and diagrams. The externalizing of design thinking is a significant aid when dealing with complex problems, especially when the problem solving involves number of persons working in teams. It also helps to free the mind to pursue creative thinking.

In general, an engineering design process starts with the identification of a need. It then assists a designer to generate solutions to that need, to develop and give form to systems or components, and concludes with satisfactory qualification and testing of a prototype. This whole process involves organizing and managing resources and people. Critical factors such as cost, safety, reliability, aesthetics, ethics, and social impact are also considered during the design process.

Some of the primary contributors to research in the engineering design process are:

- Pahl and Beitz [2] – definition of the design process and development of the systematic approach based on Theory of Technical Systems,
- Hubka and Eder [3] – the development of Technical Systems,
- Ertas and Jones [4] - engineering design process,
- Dym and Little [5]– contributions to product design,
- Ulrich and Eppinger [6] – contributions to product design and development,
- Magrab [7], Matousek [8], Hyman [9] and Ullman [10].

Other contributors whose work has targeted certain areas of the design process and design methods are:

- Cross [1] – work on design methods,
- Glegg [11-13] – overall approach to design,
- French [14]– conceptual design,
- Pugh [15] – on total design and concept selection,
- Suh [16] – principles of design.

The above research has shown that engineering design is a process that can be developed and imparted to engineers. These research findings have increased our understanding of the design process as well as effective means for teaching that process. In that spirit, a design methodology [17, 18] was developed at the Institute for Innovation and Design in Engineering (IIDE), Texas A&M University. This methodology adapts, incorporates, and integrates methods and techniques from many of the above sources to form a cohesive approach to the design process. Parts of this methodology are explained in subsequent sections of this dissertation. The core of this approach is a design philosophy based on Abstraction, Critical Parameter Identification, and Questioning. This philosophy, along with the design process itself is taught in the senior under-graduate and graduate design courses. The students understand and experience the design philosophy and apply the design process to real world design challenges provided by industrial partners. The goal of the methodology is not only to teach the design process to the students but also to instill in them a design philosophy that would enable them to perform design effectively and innovatively in any area of specialty.

The work in this dissertation pertains to certain stages in the design process within the domain of the IIDE design methodology. It aims to improve some of the weaknesses in this methodology, primarily those in the area of the Need Analysis and Conceptual Design stages of the design process. This is achieved by developing and incorporating enhanced design methods and techniques within the overall spirit and framework of the IIDE design methodology. Also, this dissertation presents the results from a study conducted to evaluate the effectiveness of the engineering design methodology currently taught to senior undergraduate students as a part of their required curriculum in mechanical engineering at Texas A&M University.

The organization of this dissertation is as follows:

- The IIDE design methodology along with the design philosophy is explained in Section 2.
- The Need Analysis stage of the design methodology along with the activities and the outputs in that stage is explained in Section 3.
- Section 4 describes the Object Function Method and applies it to the Need Analysis stage. The usage and the issues that are addressed by this method in the Need Analysis stage are explained with examples.
- Section 5 describes the Conceptual Design stage including the Concept-Configuration model and the looping process.
- The need for an effective concept searching method within the Concept-Configuration model, and the development of new techniques and methods for effective concept discovery during concept searching within the Concept-Configuration model is explained in Section 6.

- Section 7 contains the details and the results of a study conducted on two groups of senior design students to evaluate the effectiveness of applying the IIDE design philosophy and performing the Need Analysis and Conceptual Design stages for the given design challenge. The goal of the study was to investigate the relationship, if any between how well these aspects of the design methodology were followed, and the quality of the resulting design solutions produced.
- Finally, Section 8 summarizes the dissertation with some pertinent conclusions.

2 IIDE DESIGN METHODOLOGY

The design methodology described below was developed at the Institute for Innovation and Design in Engineering (IIDE), Texas A&M University. The goal was to better understand the overall design process and to develop effective means for imparting that knowledge to novice engineers. This methodology incorporates and integrates methods and techniques from a variety of sources to provide a cohesive approach to the design process. The core of this approach is a design philosophy based on the conscious and effective application of the cognitive skills of Abstraction, Critical Parameter Identification, and Questioning at all levels and through all stages of the design process.

Research shows that certain differences exist between experienced and novice designers [1, 11, 19]. When experienced designers are given a problem, they first identify and then attack the core issues. This enables them to come up with innovative solutions quickly. The desire to impart similar capabilities to novice designers motivated the search for identifying and developing the necessary skills. Subsequent research led to the focus on the three fundamental skills of Abstraction, Critical Parameter Identification, and Questioning. These three cognitive skills form the core of the IIDE design methodology. They permeate through all stages of the design process, making the IIDE methodology unique from other design methodologies. These cognitive skills, along with the design methods embodied within the overall framework enable novice designers to perform design tasks effectively, efficiently, and innovatively.

2.1 DESIGN PHILOSOPHY

The design philosophy described in this dissertation is the essence of the IIDE design process. It emphasizes certain analytical skills that are applied throughout the design process at various stages. These skills are: the ability to think on an abstract level; the ability to identify critical parameters; and the ability to question. These form the core of the methodology, and when applied simultaneously, enable the designer to be effective, efficient, and innovative. Each of these skills is described further, and illustrated through examples and discussion, in the following sections.

2.1.1 Abstraction

Abstraction is the process by which a perceived need is progressively transformed from a colloquially expressed statement into a functionally precise definition, using technically fundamental terms. This is key to identifying the core or the essence of the challenge at hand by increasing the insight that the designer has into the task that is to be performed. This has been identified as one of the key skills required of a designer and primarily has been adapted from Pahl and Beitz [2]. The Information Axiom, as stated by Suh [16], to 'Minimize the information content of the design' indirectly pertains to the abstraction process.

To understand the abstraction process, let us consider the task of designing a transportation canal to facilitate the movement of ships across a landmass. A need statement that describes the given task is, "Connect two bodies of water with no gradient." The Suez Canal that connects the Red Sea to the Mediterranean Sea at sea level is a good example of a solution that satisfies the above need statement. Now, taking a closer look at the statement raises the question, "Is no gradient a real constraint?" Many canals with gradients exist and locks are used to raise and lower ships during their passage through the canal. For the Panama Canal, the French tried to connect the Atlantic and Pacific Oceans following the same approach as they had taken to the Suez Canal, i.e., a canal without gradients. Their failure can be at least partially ascribed to this unnecessarily restrictive need statement. The Americans successfully built the present Panama Canal by incorporating locks that raise and lower the waterway in the canal by 85 feet during a single passage. So, "no gradient" placed an artificially restrictive and unnecessary constraint on the design task.

We can now question the earlier need statement and reword it as, "Connect two bodies of water." We then move to a deeper level and ask the question, "Is the real need to connect two bodies of water?" The answer is, "No!" The ***real*** need is to, "Move ships across a landmass." This rephrasing of the need opens up the solution space to include the possibility exploited at Ronquiéres, in Belgium, where ships are transported in water-filled railway containers across a mile-long stretch with a 220 feet change in elevation. This example illustrates the importance of abstraction in increasing the insight that the designer has into the problem and simultaneously expanding the solution space that can be explored.

A general methodology for achieving the required level of abstraction for a given problem statement can be summarized as:

- Eliminate solution-specific details;
- Define the problem in solution-neutral terms;
- Convert quantitative information into qualitative information;
- Question and eliminate perceived and fictitious constraints;
- Increase the technical conciseness of the statement by
    - defining the various terms used in the need statement; and
    - looking for scientific principles that are relevant to the particular solution.

By asking and answering certain questions, the designer can judge and evaluate the effectiveness of abstraction. Is the abstraction technically precise? Is the abstraction simultaneously more general yet less vague? Does the abstraction capture the real need? Is it solution independent? Are all the possible solutions included by the need statement? Are extreme cases also included in the solution space? Answering "yes" to all of the above questions can be used to evaluate whether abstraction has been achieved to the required degree. The ultimate goal of abstraction is to simultaneously increase the insight into the problem and expand the solution domain, thus encouraging innovative and non-traditional solutions.

Another example is provided to further illustrate the process of abstraction. The task is to design the brakes of a car. Figure 1 shows the evolution of the need statement from a colloquially expressed form to a technically precise, but more abstract, form. The solution-specific details are eliminated and the terms are made qualitative. Through abstraction, the final need statement is simultaneously technically precise, solution independent, general but not vague, and allows a larger number and a greater variety of possible solutions.

Task: To Design the Brakes of a Car

Need Statements:

- To stop a car
- To reduce the speed of a car from 60 mph to 0 mph in less than 200 feet
- To decelerate a car at a controlled rate
- To dissipate the kinetic energy of a car at the required rate
- To transform the translational kinetic energy of a car at the highest acceptable rate

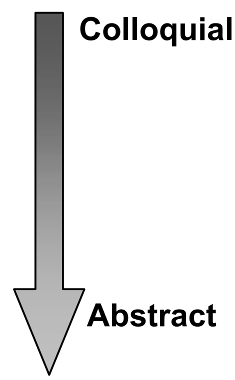

Figure 1: The Role of Abstraction in the Development of the Need Statement for the Design of the Brakes of a Car

2.1.2 Critical Parameter Identification

Critical Parameter Identification is the systematic process by which a designer identifies the crucial "make-or-break" issues in an identified need. These issues can be physical, natural, chemical, or mathematical concepts that are relevant to the need. The Critical

Parameter Identification and Abstraction processes go hand-in-hand, along with questioning. This issue has been dealt with by Glegg [11-13,] Cross [1] and others [19] from the standpoint of how experienced designers attack a problem and quickly reach and address the core issue in the problem. This characteristic of a good designer is, in essence, the rapid and skillful identification of critical parameters.

To understand how to identify critical parameters, let us consider the previous example on designing the brakes of a car. Figure 2 shows the evolution of the need and the associated critical parameter at each stage of abstraction. Initially, the need satisfied by the brakes is to reduce the speed of a car from 60 mph to 0 mph in less than 200 feet. The critical parameter here would be the "stopping distance." However, when the need is expressed in more abstract terms, we recognize that the brakes decelerate the car at a controlled rate. The critical parameter in this stage is the "deceleration" of the car. On further abstraction, and considering both disc and drum brake solutions, the need statement is, "To dissipate the kinetic energy of the car." At this stage, we can recognize that "dissipation" is unnecessarily restrictive. It is only one of the means of reducing the kinetic energy of the car. This realization results in a new statement, "To transform the translational kinetic energy of the car at the highest acceptable rate". Since only the forward motion of the car is to be affected, the term "translational" better defines the part of the kinetic energy that must be transformed. The critical parameter associated with this new statement is the "energy transformation rate." By identifying the critical parameter, the required information for meeting the need can be identified. Hence, the "energy transformation rate" allows the designer to identify the total energy of the car and establish rate limitations. By performing the energy transformation at a controlled rate, factors like the dynamics of the vehicle, the safety of the passengers, and the road conditions can all be taken into account, as they should be.

Evolution of the Need	Evolution of the Critical Parameter
• To reduce the speed of a car from 60 mph to 0 mph in less than 200 feet	Stopping distance
• To decelerate a car at a controlled rate	Deceleration
• To dissipate the kinetic energy of a car at the required rate	Energy dissipation rate
• To transform the translational kinetic energy of a car at the highest acceptable rate	Energy transformation rate

Figure 2: Evolution of the Critical Parameter for the Brakes of a Car

The actions involved in identifying the critical parameters for the design are:

- Identify the primary functions and primary constraints in the need. For example, "transform the translational kinetic energy" would be the primary function and "highest acceptable rate" would be the primary constraint.
- Identify the defining parameters for both the primary function and the primary constraint. For example, transforming kinetic energy and the transformation rate.
- Develop (constitutive) relationships between variables that define the function(s) – these could be equations or rule of thumb relations.
- Identify the consequences of a failure to perform the primary function. This would constitute a critical failure mode, which points to a critical parameter with respect to that function.
- Look for interfaces between a function and the environment. Look for extremes in the influence of the performance of the function on the environment and vice versa.
- Introduce quantification of the functions and constraints to establish the operating envelope or range.

Critical parameters generally come from two sources: Limiting conditions and gradients that address the rate of change of a variable. The limiting conditions at interfaces between the functional requirements of the design and the environment often determine the critical parameter. For instance, in the car brake example, the road conditions of the tire-road interface provide the limitations on the rate at which the energy transformation can be achieved. The science of engineering is mostly about (three dimensional) fields. The goal of nature is to minimize the gradients or slopes of these fields. Consequently, critical parameters often involve spatial or temporal gradients or slopes. From the above example, the "energy transformation rate" is an example of a gradient-based critical parameter. The magnitude or difficulty of the design task is often set by the rate requirements on the design. The goal of the designer is then to minimize these rates of change while meeting the specified need.

2.1.3 Questioning

This is one of the key skills required of a designer and goes hand-in-hand with abstraction and critical parameter identification. For instance, in the previous example of the design of a canal, questioning the constraint of "no gradient" helps establish whether this is a real or a perceived constraint, or one that is being artificially imposed. Similarly, in the example of the brakes of a car, questioning the need for "dissipation of kinetic energy" identified that this action was really a combination of "transformation of the kinetic energy" coupled with "do not store the transformed energy." This led to the recognition that "transformation of energy" was the true need, and that too only of the translational component. The possibility of storing the transformed energy thus became an option that would not otherwise have been considered. This illustrates how the process of questioning is a subtle, yet powerful tool, in helping define the true need and opening up the solution space for further exploration.

The effective designer, by questioning needs and assumptions, makes a conscious effort to be innovative and to not get fixated on certain ideas. Figure 3 shows the various questions that should be asked in relation to the need. These consist of the five "W" s (Why? What? …) and the "H" (How?) along with the opposite questions of the five "W-not's" and one "H-not." The designer can use these questions to fully explore the task and gain insight into the true need. The arrangement shown is intended to convey that the questions of What? When? Where? Who? and Why? enable effective gathering of information. The question of How? encompasses all the other questions and is, in a sense, the means through which the answers to the W's can be implemented.

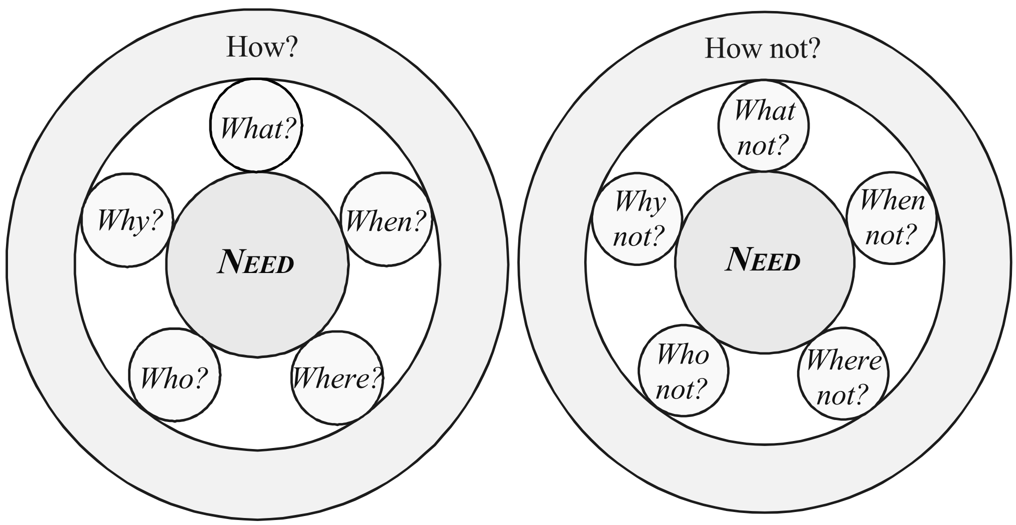

Figure 3: Schematic of the Questions – Five "W"s and One "H" Along With the "-nots"

One of the primary functions of Questioning is to direct the designer's thoughts into new domains and thus avoid fixation on existing solutions. The application of heuristic thinking in the thought process enables the designer to be innovative and to consider issues that have not been thought of before. These heuristics are: consider contradiction, i.e., instead of making a system simper make it complex; take things to an extreme, e.g., maximizing, minimizing, using multiple objects instead of a single one, trying radical arrangements, and so on; view adversity as an advantage, i.e., convert the undesired problem into a desired solution or eliminate the undesired feature.

The process of questioning, along with the use of heuristics, is a powerful tool that helps the designer in gathering information and considering problems in new and different perspectives. This can provoke the designer to think in ways that he/she has not done before, thus enabling the designer to be innovative.

2.2 THE IIDE DESIGN PROCESS

The IIDE engineering design process, shown in Figure 4, is a sequence of design activities, broadly divided into four stages. Considerable attention and emphasis is placed on the Design Methodologies and the strategies associated with each of the four stages and on the philosophical basis for the methodologies that are to be employed in achieving the desired goals of each stage. The overarching purpose is to enhance the efficiency and effectiveness of the execution of the activities within each stage, while maximizing the potential for innovation. The strategies of abstraction, critical parameter identification, and questioning are the key elements that are emphasized. These activities form the essence of the design process.

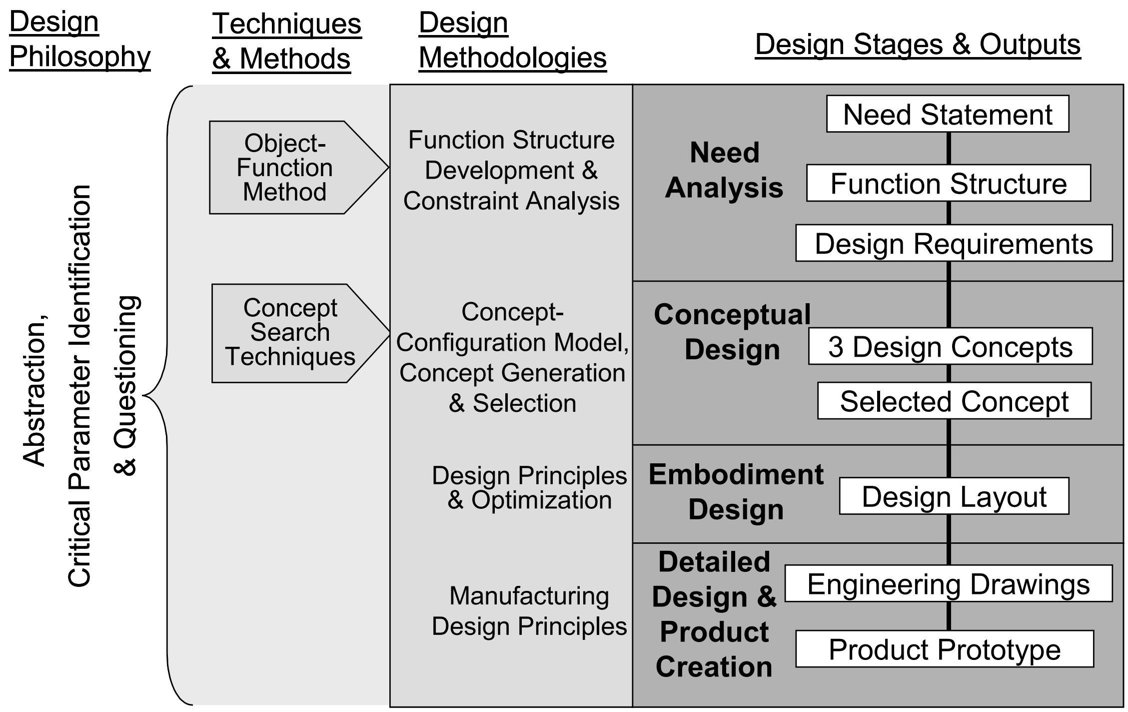

Figure 4: Overview of the IIDE Design Process

The design process can be organized into four major stages, namely need analysis, conceptual design, embodiment design, and detail design. This organization of the design process into four stages has been adapted from Pahl and Beitz [2]. The right hand side of Figure 4 shows the four stages and the outputs from each of these stages. The methodologies followed in performing the activities associated with the various stages are listed alongside each stage. For example, the outputs in the Need Analysis Stage are the Need Statement, Function Structure and Design Requirements. The methodologies used in this stage are Function Structure Development and Constraint Analysis. The methodologies in each of the stages provide the framework within which to perform the activities and provide a basis for evaluating the design by the quality of the outputs generated from these activities. The design methodologies that are associated with each of the stages are based on a combination of work done by other researchers and work done by researchers at IIDE, but the end product has been tailored to fit the spirit, requirements, and framework of the IIDE design methodology. For example, the approach to function structure development is based on the work done by Pahl and Beitz [2], the concept-configuration model expands on the work done by Jansson [20, 21], and the concept selection process is adapted from the work of Pugh [15]. The organization of different design methodologies into a unified framework, the well-defined outputs at each of the design stages, and the incorporation of the design philosophy throughout makes the IIDE design methodology unique. This is due to the efforts and key contributions of researchers at IIDE. The Techniques and Methods shown alongside their respective design methodologies represent one of the contributions from the work undertaken for this dissertation. The layout also indicates how these techniques and methods are applied in the overall design process. The Object Function Method is used in the Need Analysis Stage and Concept Search Techniques are used in the Conceptual Design Stage. The design stages are briefly described in the following paragraphs. Since, the methods developed largely pertain to the Need Analysis and Concept Design stages, these are discussed in detail in subsequent sections of this dissertation. However, for completeness, all four design stages are briefly described below.

2.2.1 Need Analysis

In this stage of a design activity, the designer strives to extract the core of the problem from colloquially expressed statements from various people like the customer, the manufacturing team, and marketing. By performing Abstraction and Critical Parameter Identification, the problem is “distilled” into a need statement that captures, in technically precise yet abstract terms, the fundamental issues in the design challenge. The designer identifies the various functional requirements (FRs) that have to be met to satisfy the need. In addition to the FRs, the designer identifies various constraint requirements (CRs) and non-functional requirements (NFRs) that have been imposed on the design. (Examples of NFRs would be the size, the weight, the cost, the environmental conditions and/or the operating conditions within which the design has to be realized). Based on this information, a function structure is developed which identifies the various solution-independent functions and sub-functions that are to be performed by the design. In this context, the function structure is a list of all the functions that ***any*** design must perform to achieve the need. Based on the FRs and NFRs, the designer creates a list of design requirements. In short, the need analysis results in a thorough understanding of the design requirements and the outputs from this stage dictate the rest of the design process.

Care must be taken at this stage to maintain independence of the FRs, as coupled FRs invariably result in poor designs and significantly increase the product development time and cost [2,16]. Also, the solution space needs to be kept as large as possible so as not to preclude any solutions through misperceptions, unwarranted assumptions, or unnecessary constraints. From an innovation perspective, the need analysis stage lays the foundations for the design and determines the envelope for innovation.

2.2.2 Conceptual Design

This design stage involves searching for the scientific principles and technologies that can potentially be exploited to satisfy the design need. The chosen principles and technologies are then abstracted into potential conceptual solutions for the need. Each generated concept is developed into a reasonably configurable solution and is evaluated with regard to how well it satisfies the requirements for the design. The concepts are either developed into viable solutions or discarded by using the Concept-Configuration Model. Typically, in this stage, three or more conceptually different competitive solutions are developed. Each of these has been cycled through the concept-configuration looping process to a point where an objective evaluation of the proposed concept is possible. The output of the conceptual design stage is a viable conceptual design that is selected by the designer based on a thorough evaluation using both the functional and non-functional requirements of the design. The conceptual design stage is critically important because it establishes the overall form of all the downstream parts of the design process. It is very difficult, if not impossible, to correct the shortcomings of a conceptual design in the embodiment and detailed design stages. Therefore, the success of the design process hinges on the outcome of this stage. The methodology of the concept-configuration looping process and the principles behind it are explained in Section 5 which deals with the Conceptual Design stage.

2.2.3 Embodiment Design

In this stage, form and shape are given to the selected conceptual design. The designer develops the concepts into a feasible assembly or layout that depicts the relative positions of various components, their sizes, shapes and interrelationships. Certain design principles are considered while giving shape to the concept, namely:

- Separate functions (Avoid coupling);
- Provide direct and short transmission paths;
- Constrain to required degree (Don’t over-constrain);
- Minimize gradients /Match impedances (Let Form Follow Function);
- Provide functional symmetry / Balance forces and moments internally;
- Design for self-help;
- Design to fail-safe.

During this stage, the design layout is optimized by balancing the demands of functionality, safety, assemblability and manufacturability. If the design is highly coupled, this is the stage where the designer has to resolve the conflicts between functional requirements, since these inevitably lead to compromises in the performance of the final product. The above principles can also be used to evaluate an existing design and suggest improvements to a design.

2.2.4 Detailed Design

In this stage, part drawings are prepared from the layout or assembly drawings, and material and manufacturing processes are specified. In this stage, the designer performs detailed analyses of the design via computer simulation and/or prototype testing. The results assess the performance of the design and evaluate how well it meets the original requirements. The designer, in conjunction with the manufacturing facility and utilizing manufacturing design principles, develops detailed drawings of the design. At this stage, the design is in its final stages and fundamental improvements to the functionality of the design are very difficult and expensive to achieve.

2.3 DISCUSSION

One of the unique aspects of the IIDE design methodology is that it is based on the three cognitive strategies of an underlying design philosophy: Abstraction, Critical Parameter Identification and Questioning. This design philosophy along with the design methodology enables a novice designer to be effective and innovative in the design process. The goal is to inculcate, in a novice designer, effective ways to think about and to approach the design task, rather than solving the problem. The Object Function Method and the Concept Searching Techniques that have been developed as a part of the research described and documented in this dissertation are key enhancements that are consistent with the spirit, goals, and framework of the IIDE design methodology.

3 THE NEED ANALYSIS STAGE

Prior to starting a design, the designer has to clarify and identify the objectives of the design challenge. The objectives of the various design tasks and sub-tasks are gathered from a variety of sources, including customers and the marketing department. These sources usually define their needs, likes and dislikes in non-technical and general terms. It is up to the designer to reformulate these requirements into design objectives and to filter out the perceived needs from the real needs. The tendency of a novice designer is to start thinking of solutions based on his/her perceptions of these "problems" before gaining an understanding of the scope and magnitude of the design task at hand. This tendency, together with a lack of proper definition of the task, often leads to wastage of efforts because the designer is busy solving the wrong problem. The effort put into proper identification and understanding of the design task is worthwhile, not only because it clarifies the design needs, but also facilitates the efficient development of innovative and effective solutions.

The primary goal of the need analysis stage is to identify the ***real*** need. The secondary goal is to identify those design tasks that absolutely must be performed by any solution to the need. By using the design philosophy of Abstraction, Critical Parameter Identification and Questioning, the designer gains a deeper and fundamental understanding of the problem domain. Further questioning of the apparent needs and constraints leads to an understanding of the permissible solution space. A major goal for the designer is to minimize the constraints that shrink the boundaries of the permissible solution space. These goals are best achieved by not thinking about solutions at this stage, thereby increasing the probability that the need will be expressed in a form that includes all possible solutions. In this manner the designer facilitates innovation and divergent thinking. By performing these activities at this early stage of the design activity, the designer is able to establish the scope of the design task, understand its difficulty and identify the critical issues. Furthermore, this methodology enables the designer to identify the informational needs, i.e., to identify the required and available information, establish the required and available resources, break design tasks into smaller subtasks, establish the interfaces between tasks, provide team organization, and identify the scope for innovation. This is a key stage as it lays the foundation for all future stages in the design process. The designer's skill in executing the Need Analysis stage determines, to a large extent, the level of innovation and the breadth of the possible solution space for the overall design task.

3.1 ACTIVITIES OF THE NEED ANALYSIS STAGE

The activities in the need analysis stage are shown in Figure 5 and are explained in the following sections. The outputs for the design activities in this stage are: need statement; function structure with its functional requirements; their associated design parameters and constraints; and the design requirements. The last two outputs will be used later to evaluate the conceptual solutions developed.

3.1.1 Recognition of the Need

In this first activity of the Need Analysis stage, the focus of the designer is to determine if there is an actual need to be met. This is done by subjecting the statements and the perceived design tasks provided by the customer to Abstraction, Critical Parameter Identification and Questioning. Basically this activity interrogates and validates the 'need' for a design task. Frequently, the need as stated by the customer, does not represent the true design challenge that needs to be addressed. It may be perceived as such by the customer, but is too vague to serve as the centerpiece for a design activity.

3.1.2 Gathering of Information

Once the designer is satisfied that a valid need exists, the next step is to gather information about the needed device or system through a coherent process of questioning that clarifies the design task. A good format for the questions is to divide them into six categories: the five 'W' s and the 'How.' Samples of typical questions from each of these categories are:

- What is the purpose of the device/system?
- Why is it needed?
- When is it needed?
- Where is it to be used?
- Who will use it?
- How will it be used?

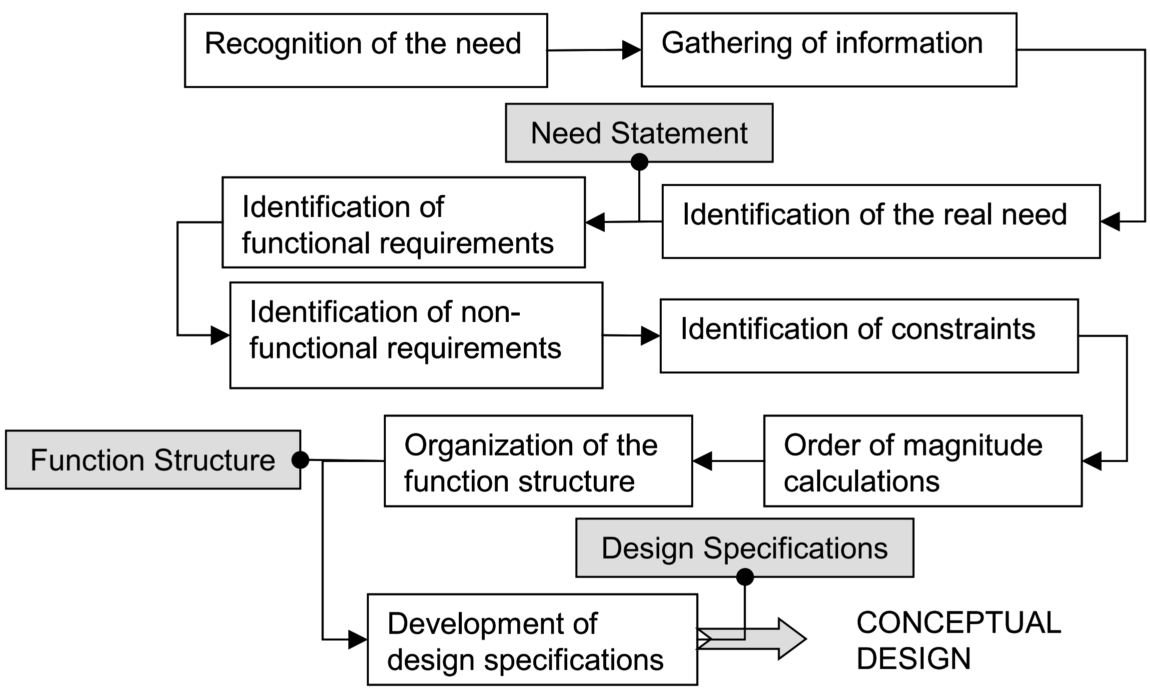

Figure 5: Activities and Outputs in the Need Analysis Stage

Additionally, the "W-not's" and the H-not" should also be asked as explained in the previous section. The information gathered and the answers obtained to questions like the ones above will help the designer to understand the design task, to identify critical parameters and to perform the abstraction process effectively. This information gathering activity is performed consistently throughout the need analysis stage as necessity, clarity and precision improve.

3.1.3 Identification of the Real Need

In this activity the single most important need that defines the fundamental design task is identified. The designer uses Abstraction, Critical Parameter Identification, and Questioning, to identify the cause and effect of the problem and to diagnose the task in a form that can be used to obtain the information that will set both the magnitude and the scope of the design task. By doing this, the designer guides himself or herself to address the cause of the problem instead of solving the symptoms. For example, in the case of the canal example, the designers at Ronquiéres in Belgium realized that the true need was to transport ships across the landmass. It was not necessary to build a canal. Essentially, the latter definition of the need would allow consideration of only one possible solution set.

Typically, the problem statements given by customers tend to be configurational. They identify the required end product rather than emphasize the need, which is the function that the product has to perform. "Design a shaft," "Design a bridge," "Design a counter-flow heat exchanger" are some typical statements. These immediately evoke existing configurations that were the consequences of particular design solutions for a more fundamental need. They tend to fixate the designer onto similar solutions, thus inhibiting innovation. To suppress this tendency, the designer has to abstract the perceived statement of the need and determine the underlying need, the one unwittingly expressed but not always recognized by the customer, who often adopts an analog to an existing device or solution in order to express his/her need. For example, the request for a shaft expresses a need to "transmit torque" or better still to "transmit power." In the latter case, a possible solution set could include a copper wire to transmit power from a primary source such as an engine, to a motor. By redefining the need, other solution sets are included within the solution domain. Thus, proper definition of the need invariably leads to a larger solution space for the design task.

Starting with the information gathered from the customer, and by performing Abstraction and Critical Parameter Identification, the problem is "distilled" into a *need statement* that captures, in technically precise yet abstract terms, the fundamental issue in the design challenge. This statement identifies in qualitative terms the primary design purpose and the critical constraint within which the objective must be satisfied. Through the need statement, the designer defines 'what must be done' by the artifact and not 'how it should be done.' The need statement defines 'what the design has to perform' not 'what the designer has to perform.' An important characteristic of the need statement is that it is solution independent. For example, the task to 'Design a labyrinth seal' can be restated as 'Seal against leakage around a shaft without contact.'

The need statement consists of a primary function and a primary constraint. The primary function is identified by the Abstraction process and the primary constraint is identified by Critical Parameter Identification. From the previous example, 'seal against leakage around a shaft,' would constitute the primary function and the primary constraint would be to do it 'without contact.' Also, in the example of the design of the brakes for a car, the final need statement was, 'To transform the translational kinetic energy of a car at the highest acceptable rate.' The primary function is, 'To transform the translational kinetic energy of the car,' the primary constraint is, 'at the highest acceptable rate.' The first part of the statement is concerned with "what needs to be done to what." It defines the primary functional requirement of the need, which is typically stated as a noun and verb pair. The second part of the statement identifies the critical parameter that constrains the breadth of the conceptual domain from which solution sets can be drawn. It usually is the requirement that ultimately sets the magnitude of the design task. With a fully developed need statement, the designer has identified the information or knowledge that must be obtained before any conceptual solution set can be embodied. Based on this knowledge the designer can proceed with obtaining information and defining the order of magnitude and scope of the design task. Thus, a designer has identified a qualitative characterization of the design task. In the case of the car brake example, there are two orders of magnitude that need to be identified, the kinetic energy to be transformed and the acceptable deceleration rate.

In this case neither quantity is easy to obtain. The total amount of energy that needs to be transformed depends on the initial velocity of the car and the mass of the car, which can be easily agreed upon between the designer and customer. These may be considered as policy decisions. The highest acceptable rate of energy transformation, on the other hand is not really an independent policy decision. The designer has to identify and establish the limits. The limits may be dictated by the physical ability of the drivers and passengers to withstand the maximum deceleration. The road tire interface, a somewhat indeterminate condition, also influences the limit. If the driver is to maintain control of the car, the overall dynamics and suspension of the car may set an upper limit on the maximum and average deceleration possible. Further, it could be a combination of all the factors that determine the limits on the highest acceptable rate, some come into play under certain conditions and some under others. It might take some time to identify resources and collect the required information and to make the right decisions. So, it is helpful if these information needs are identified as early as possible in the design, and to arrange for on-time delivery of this information, so that the design is not delayed by lack of knowledge. By examining the scope and the magnitude of the need, the designer sets the stage to perform the requisite Order of Magnitude Calculations.

Sometimes, the designer may be tempted to include multiple functions and constraints into the need statement. Although these may be relevant, the condition that the need statement should contain only the primary function and the primary constraint, forces the designer to think through the design challenge and to identify the key issues, and from these recognize the one issue that sets the magnitude of the design task. This leads to a better understanding of the total design task at hand.

3.1.4 Example: Tea Brewing Machine

The example of a tea brewing machine [22] is used here to work through each of the activities of the Need Analysis stage to illustrate the process.

Problem Statement

A small company wishes to enter the market with a household or office tea machine. It should take into account the desires and habits of many tea drinkers, namely to drink naturally brewed tea, but avoid the need to watch the device to stop the infusion process when the desired strength has been reached. It would also be convenient if the liquid could be made available in a container from which it can be served and if the device did not need constant attention, for instance to remove tea leaves.

Need Analysis – Recognition of the Need

It is possible to use a coffee making machine to brew tea, but this is rarely done because the conventional coffee making process differs substantially from the tea brewing process. It would be convenient to let a machine brew the beverage unattended while the consumer is performing other tasks typical of either the home or the office environment. So, there is a valid need for a tea brewing machine.

Gathering of Information

Based on the information given by the customer and looking more deeply into the tea brewing process, the following information has been gathered. The beverage known as tea is brewed from mixtures of broken leaves (fermented or unfermented) of the tea bush (*thea sinensis*). The quality and taste of the beverage depend largely on the quantity and proportions of essential oils, vegetable alkaloids, and tannins dissolved from the leaves, plus the effects of caffeine as a stimulant. Two general ways of introducing tea leaves are: using loose leaves in a pot, or using a pre-measured quantity of leaves enclosed in a porous bag. The term brewing indicates that the leaves are infused either by pouring boiling water on the leaves or by means of boiling water with the leaves in the water. The problem statement indicates that the system should be automated and the environment considered is for small offices or households, hence the size of the device should be small, so that it can be used on tabletops. The tea to be used is commercially available and the water is from faucets at homes and offices. The quantity of tea to be brewed at any one time is not large. The energy used should be an electric supply from the normal domestic outlets. Since it is a consumer product, safety of the user is of primary importance. Other requirements are: cost should be reasonable, the device should be user friendly, portable, easy to maintain, and have aesthetic appeal.

Identification of the Real Need

Having gathered the available information and gained an understanding of the design task leads to the development of the need statement. By performing Abstraction through the given statements, the need statement is, "Brew tea automatically from commercially available tea leaves for household consumption." Here the primary function is to 'brew tea from commercially available tea leaves' and the primary constraint is to automate this process. The term 'commercially available' refers to the tea leaves or tea bags that are available to the consumer at retail stores. The additional constraint for 'household consumption' indicates the operating environment and the targeted user. This precludes any solutions that would encompass commercial manufacturing of tea. The term 'brewing' indicates that a required amount of hot water (boiled) and tea leaves are brought together, and by the process of infusion for a set time period, tea is brewed.

3.1.5 Identification of Functional Requirements

Once the need statement has been defined, the next step is to identify the various functions that have to be met to satisfy the need. Just as a technical system can be divided into sub-systems and elements, similarly an overall function can be broken down into sub-functions of lower complexity [2]. The main objectives of breaking the function into sub-functions are:

- Simplification of the design into smaller sub-tasks
- Allow distribution of sub-tasks amongst various teams
- Facilitate the subsequent search for solutions

One of the methods used in developing of sub-functions is the Black-Box Method [1, 2] as shown in Figure 6. A design artifact can be considered as a transformer that takes in a set of inputs – energy, material, information, forces/moments and displacements and transforms them into a set of desired outputs. The designer gathers information about the necessary inputs by asking questions on the inputs: What is the type of energy that is required? How much? What materials are required? What is the quantity of the materials? Is there any information that is to be taken in as input? Are there any forces or displacements that are to be considered? Similarly, information on the outputs is gathered. This sets the stage for using the Black-Box approach and assesses how the device transforms the inputs to the required set of outputs.

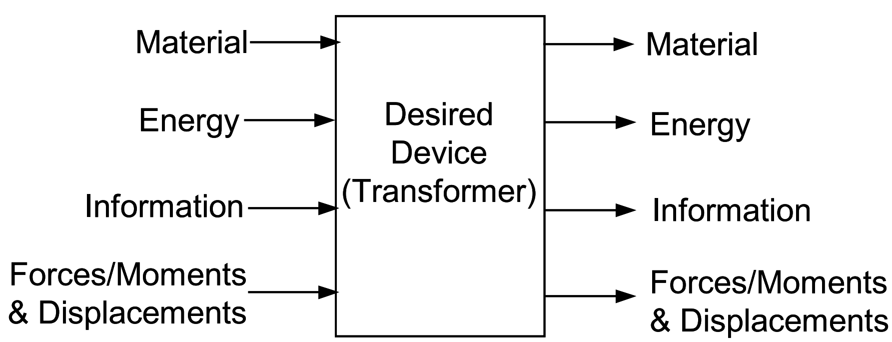

Figure 6: The Black-Box Approach

For the tea brewing machine example, the Black-Box approach is shown in Figure 7. The materials inputted are cold water and tea leaves, the energy is supplied, and for the information part, user signals that are used during the control of the automation process act as inputs. The outputs are hot tea, waste tea leaves, and signals to indicate the end of the process to the user. The information gathered on the quantities of the inputs and the outputs are used to determine the constraints and the design parameters, which will be illustrated in the following sections. The primary or first level sub-functions that have to be achieved to perform the main function are shown in Figure 8. The functions are typically stated as a noun-verb pair and are solution independent.

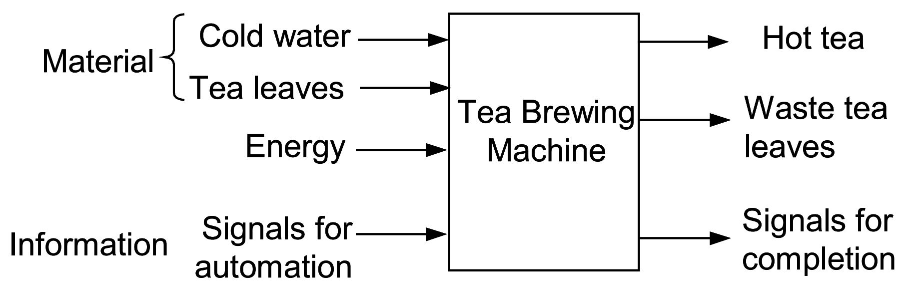

Figure 7: The Black-Box Approach for the Tea Brewing Machine

The typical breakdown of the functions and the organization of sub-functions into various levels is known as the function structure. The primary level or first level functions are those that have to be performed to satisfy the need statement regardless of the solution that is finally adopted. Each of the first level sub-functions is further broken down into second levels of solution independent functions, as shown in Figure 9. Functional Alternatives (#3.1 and #3.2) are those functions that satisfy the previous function (#3) by performing either one of the alternatives. These functional alternatives arise only when there are a small number of choices and each of these choices is at a level where they are still solution neutral. The lowest level functions are those for which further decomposition results in, at least, some solution dependent sub-functions. The goal is to build a solution independent function structure to the lowest level possible. It is seldom necessary to proceed beyond the third level. The constraints and the design parameters for the functions are explained in the following sections.

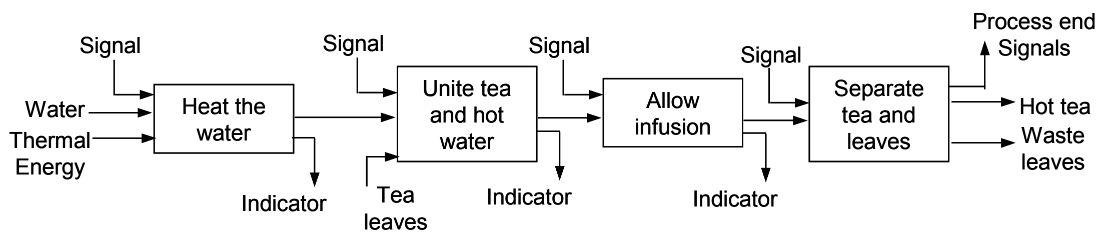

Figure 8: The Breakdown of the Primary Sub-functions for the Tea Brewing Machine

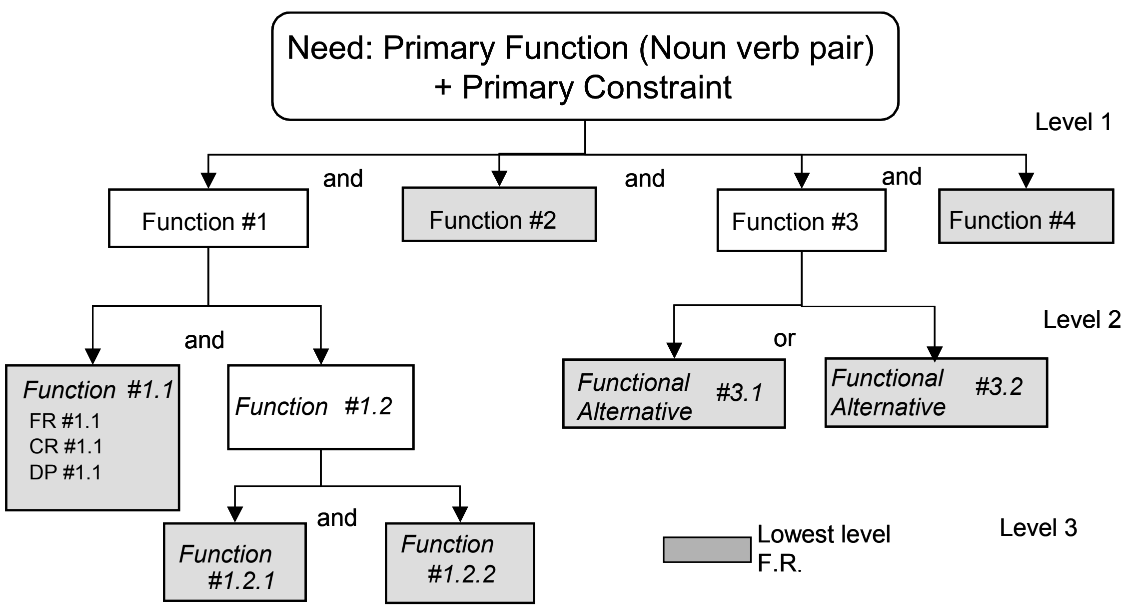

Figure 9: A Generic Function Structure

In order to construct a function structure for the tea brewing machine as shown in Figure 9, start with a model such as Figure 8 and list the first level functions. Then divide each of these functions into lower level functions. The initial breakdown of the first level functions into sub-functions is as follows:

1. Heat the water
    - Access electrical energy
    - Convert electrical energy to thermal energy
    - Contain the water
    - Transfer thermal energy to water
    - Initiate the heating process
    - Regulate the energy transfer
2. Unite tea and hot water
    - Contain tea leaves
    - Mix the tea leaves and water
    - Initiate the process
3. Allow infusion
    - Allow the process for a specified time period
    - Indicate end of infusion process
4. Separate waste tea leaves and tea
    - Activate the separation
    - Separate the tea leaves from the liquid
    - Contain the wasted tea leaves
    - Provide the brewed tea for the user
    - Signal the end of the process

The above listing is a starting point for the designer in developing the function structure. As he/she gains more information and insight into the design task, the function structure evolves and improves as illustrated in the following sections.

3.1.6 Identification of Non-functional Requirements

Non-functional requirements (NFRs) are solution-independent requirements that affect the whole device and must be satisfied by any design solution. They are constraints imposed by external considerations on the manner in which functional requirements are to be met. Non-functional requirements are frequently overstated. They come from sources that are difficult to challenge and since they are almost always negotiable, they should be thoroughly questioned. A good way to start the questions is to categorize them before attempting to rank them. A sample set of categories is listed below, so that it enables the designer to address each issue and to gain insight into the problem. The categories are:

1. Non-functional performance requirements: In this category the designer identifies the operating boundaries for the design task. Further sub-categories are:
    a. Environmental and operating conditions: The designer gathers information on the type of domain or environmental conditions that the device has to operate in. Typical information is on physical parameters like temperature, pressure, humidity, corrosive conditions and other such conditions. Also, information is gathered on the variability of these conditions and the range of values of these conditions.
    b. Size requirements
    c. Weight requirements
    d. Time restrictions
    e. Regulatory requirements: Due to testing procedures and validation, certain regulations are imposed on certain products. Knowing these requirements and making sure the design meets these requirements helps the designer.
2. Safety requirements: Safety is a major issue with any device that interacts with a user or during maintenance purpose. Another category is the impact on the environment, like emissions and effluence control.

   a. User safety requirements- these are best listed in hierarchy: must not kill, must not cause bodily injury, must not harm any person in any way other than bodily injury.
   b. Environment safety requirements- the listing here is: must not harm the immediate environment, must not cause harm to environment that may affect the user, must not cause harm to operating environs within the system.
3. Cost: This is one of the primary factors that drives product competition. The market is always looking out for things that are cheaper and work better. But at this stage of the design, the designer has to identify if there is a range, or an upper limit, on the cost of the device and other associated costs like operating and maintenance costs. It is usually better for the designer to relate cost to value. Cost requirements include:
   a. Cost price of the device
   b. Operating and maintenance costs
   c. Disposal costs
   d. Lifecycle costs
4. Ergonomics
5. Aesthetic appeal
6. Manufacturability and assemblability issues
7. Maintenance and operational issues
8. Life cycle, durability and reliability

Typically not all the categories may be pertinent, but the designer could identify early on if there are any 'show-stoppers', i.e., hard constraints that leave him/her with no leeway. While trying to gather information on the NFR's the designer would have to quantify certain parameters for the functions and the constraints. This is done in conjunction with the Order of Magnitude Calculations (OMC). The Order of Magnitude Calculations are explained in Section 3.1.8. The OMC is listed as a separate section for convenience in explanation. In actual usage, the designer applies OMC throughout the need analysis stage: in the quantification of the scope of the problem during the development of the need statement and during the development of the function structure in quantifying the FR's, NFR's and Constraint Requirements (CR's).

For the tea brewing machine, the non-functional performance requirements are,

1. Environmental conditions: The situation considered is a household or an office. So the environment is controlled, hence no extreme conditions exist.
2. Operating conditions: the device should be able to withstand temperatures of at least 120° C. Since the water is being heated to boiling point, high temperatures are experienced by the device.
3. Size requirements: To get an estimate of the size, the designer has to know the required capacity of the device. For example, the quantity of tea that has to be brewed at one time. A reasonable estimate would be a maximum of 2 liters (around 8 cups of tea), which translates to 2kgs of water. The desirable external volume of the device is less than 8000 cc, 20cm x 20cm x 20cm. That is 4 times the volume of the serving container, with a maximum height limitation of 25cm.
4. Weight requirements: Since the device is to be placed on a tabletop and portable, an estimate of less than 4 kgs including the water is desired. Thus, the empty tea machine should weigh less than 2 kgs.
5. Time restrictions: The brewing time from start to finish for the maximum capacity is desired to be less than 15 minutes. This includes a maximum time of 5 minutes for brewing and the remaining 10 minutes to be used for boiling.
6. Regulatory requirements: The device should meet any requirements that are placed for testing and validation purposes and the designer has to gather information on these regulations to determine if they affect the requirements.
7. Safety: Since there is heat and user interface, utmost safety of the operating user is important. A maximum temperature of 120° C for safety purposes limits the device. Also, the device would have to satisfy the safety requirements it needs to

be certified by the Underwriter's Laboratory standard UL–197 for commercial cooking appliances.

8. Cost: Considering an affordable price, the retail price for the device is desired to be less than $20.
9. Ergonomics and aesthetic appeal: Since the environment considered is indoor, user friendliness and aesthetic appeal is very much desired.
10. Other issues are that it must be easy to clean and maintain, and should be reliable.

The above NFR's and the quantification of the requirements act as a starting point for the designer to gain knowledge about the device. They also help the designer in determining the requirements that are non-negotiable and the ones that are negotiable. From the above requirements and from the Order of Magnitude Calculations detailed in Section 3.1.8, the only 'show–stopper' could be the retail cost of $20 that a designer has to consider seriously. The device can easily meet most of the other requirements in this case.

3.1.7 Identification of Constraints

Constraints are limits that are imposed on the functions and they define the envelope within which the function has to be satisfied. They often determine the difficulty of a design task. One of the effects of the constraints is that they limits the solution space, hence it is important to separate the real constraints from perceived ones in order to foster innovation. Usually, most of the non-functional requirements act as constraints on the operating functions.

3.1.8 Order of Magnitude Calculations

The purpose of the Order of Magnitude Calculations (OMC) is to quantify the performance envelope for both functions and constraints. This is achieved by creating engineering models and relationships, quantifying parameters, and the sensitivity of the system. This helps in quantifying critical functions and constraints, establishing evaluation criteria for concepts and/or for the embodiment of concepts. The OMC is applied throughout the need analysis stage, in determining the scope of the design task during the development of the need statement, and in the quantification of FR's, NFR's and CR's for the function structure. Through quantification the designer is able to determine the negotiability and non-negotiability of certain constraints.

In the case of the tea brewing machine, the primary need is to brew tea, which involves infusing hot water with the tea leaves. The designer has to determine at a higher level whether this is feasible based on the amount of water and tea to brewed. OMC to determine the amount of energy required to heat the water could be performed. The device has to hold 8 cups of water (2 liters), at 20°C to be heated to 100°C in under 10 minutes. The specific heat of water is 4.18 J/(gm. °C). The energy required is,

$$E = m * Cp * dT = (2000 \text{ gms}) *(4.18 \text{ J/(gm°C)}) * (100°C - 20°C) \approx 670 \text{ kJ}$$

The power required, $P = E/time = 670/ (10*60) \approx 1.1$ kW at 100% efficiency.

At 80% efficiency, the power required is ≈1.4 kW

Since, the power is supplied from a domestic electrical outlet, which is typically 15A and 110V unit. The maximum power that can be drawn is 1.65kW. Since, 1.4kW is less than the maximum 1.65kW, the values on the amount of water, tea leaves, temperature and time are reasonable and do not need to be changed.

3.1.9 Organization of the Function Structure

In this activity, the functions, together with the respective constraints and design parameters, are organized into various levels. A generic function structure was shown in Figure 9, where the CRs were the constraint requirements and the DPs were the design parameters for the respective functional requirements (FRs). Design parameters are technical characterizations of the function and/or constraint. These provide the units for the functional and constraint requirements. Order of magnitude calculations usually provide the magnitude of the design parameters.

The goal of the function structure is to: a) facilitate innovation and b) assist in identifying interfaces. The two main tests for a good function structure are that: the lowest level functions are solution independent; and independence of functions is maintained. Independence of functions requires a one-to-one mapping of design parameters and functions [16]. The general characteristics of a function structure are that when one moves upward in a function structure, it reveals 'why' a function is required, and when one moves downward it reveals 'how' a FR should be met. All FR's in a function structure must be performed by all the solutions.

An initial function structure for the tea brewing machine is shown in Figures 10a and 10b. It contains the various functional requirements (FRs) with the associated constraint requirements (CRs) and the design parameters (DPs). By repeated questioning on the FR's, CR's and DP's the designer gains insight into the design task. With additional information gained, the function structure gets evolved and refined. The successive evolution of the function structure for the tea brewing machine is illustrated in the following paragraphs.

The designer deliberates through the initial function structure by questioning each of the functional requirements, constraints, and design parameters in order to improve the function structure and also to understand the design better. In the case of the tea brewing machine example, the improved function structure is shown in Figures 11a, 11b and 11c. This function structure contains some additional functionality and modifications in the constraints and design parameters. When we consider the safety aspects and to ensure that the device does not overheat, the initial function structure does not have the necessary function listed. This is incorporated in the new function structure as FR 1.5: Limit maximum heating, as shown in Figure 11a. The two sub-functions FR 1.5.1 and FR 1.5.2 considers the two situations when there is no water while being heated and when there is water during heating.

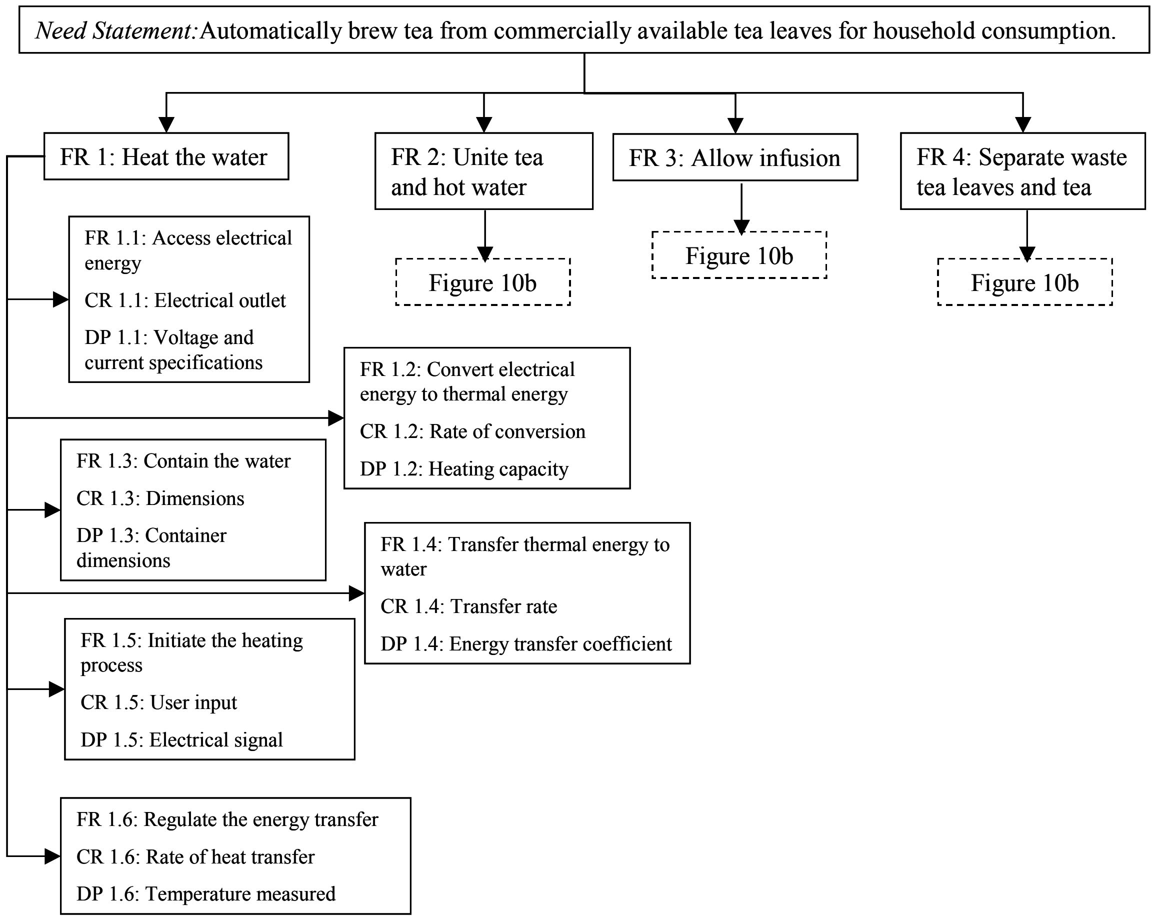

Figure 10a: Initial Function Structure for the Tea Brewing Machine

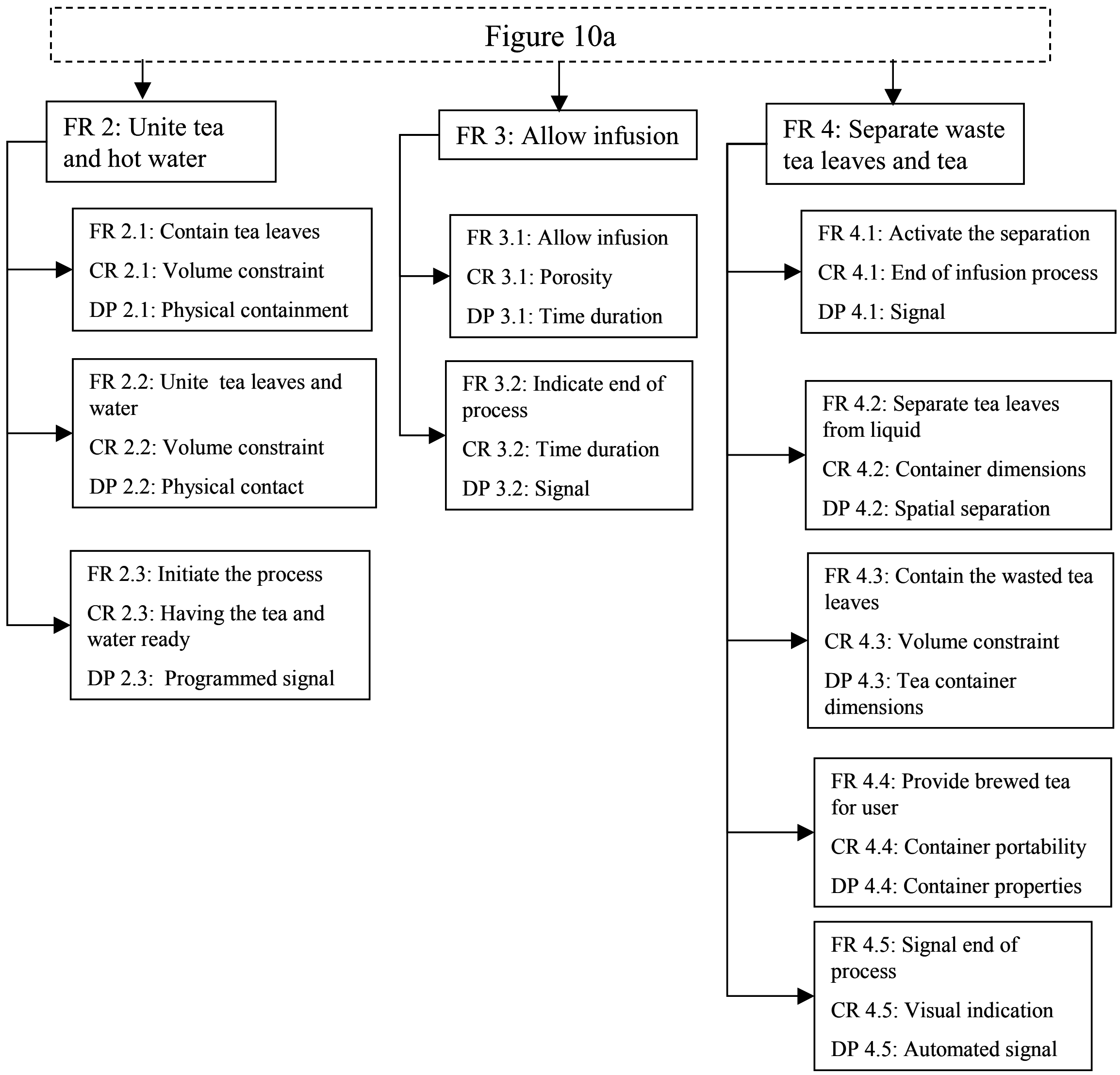

Figure 10b: Initial Function Structure for the Tea Brewing Machine (FR2, FR3 and FR4)

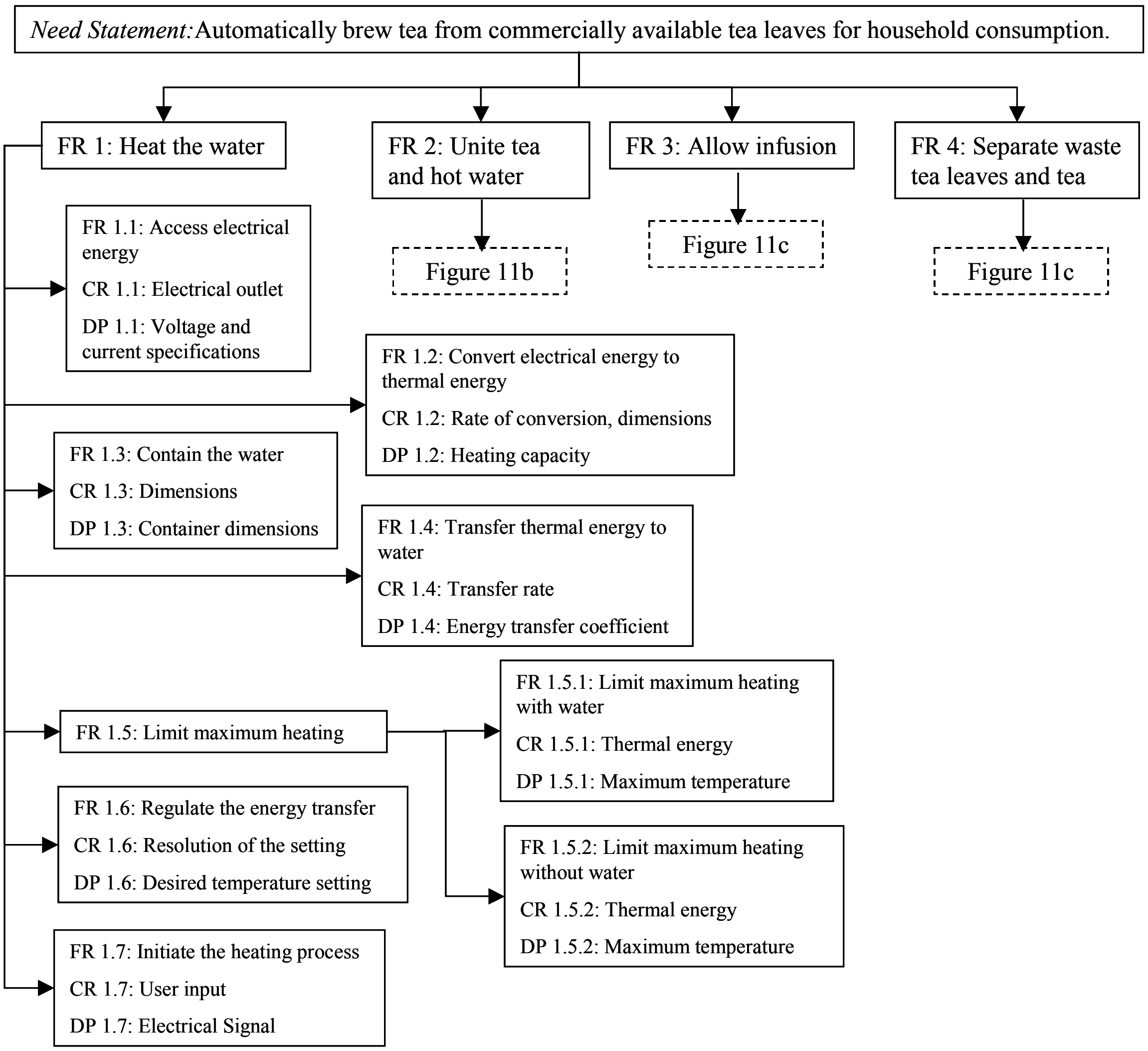

Figure 11a: Improved Function Structure for the Tea Brewing Machine

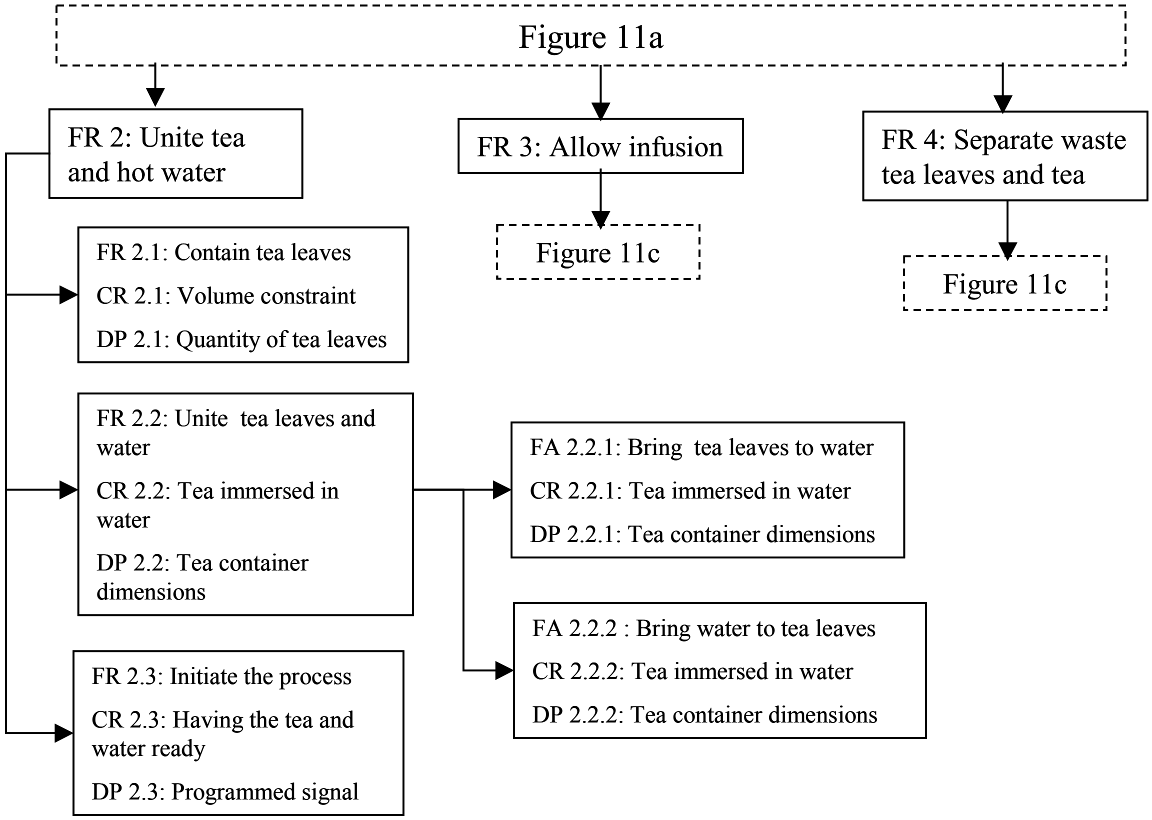

Figure 11b: Improved Function Structure for the Tea Brewing Machine (FR2)

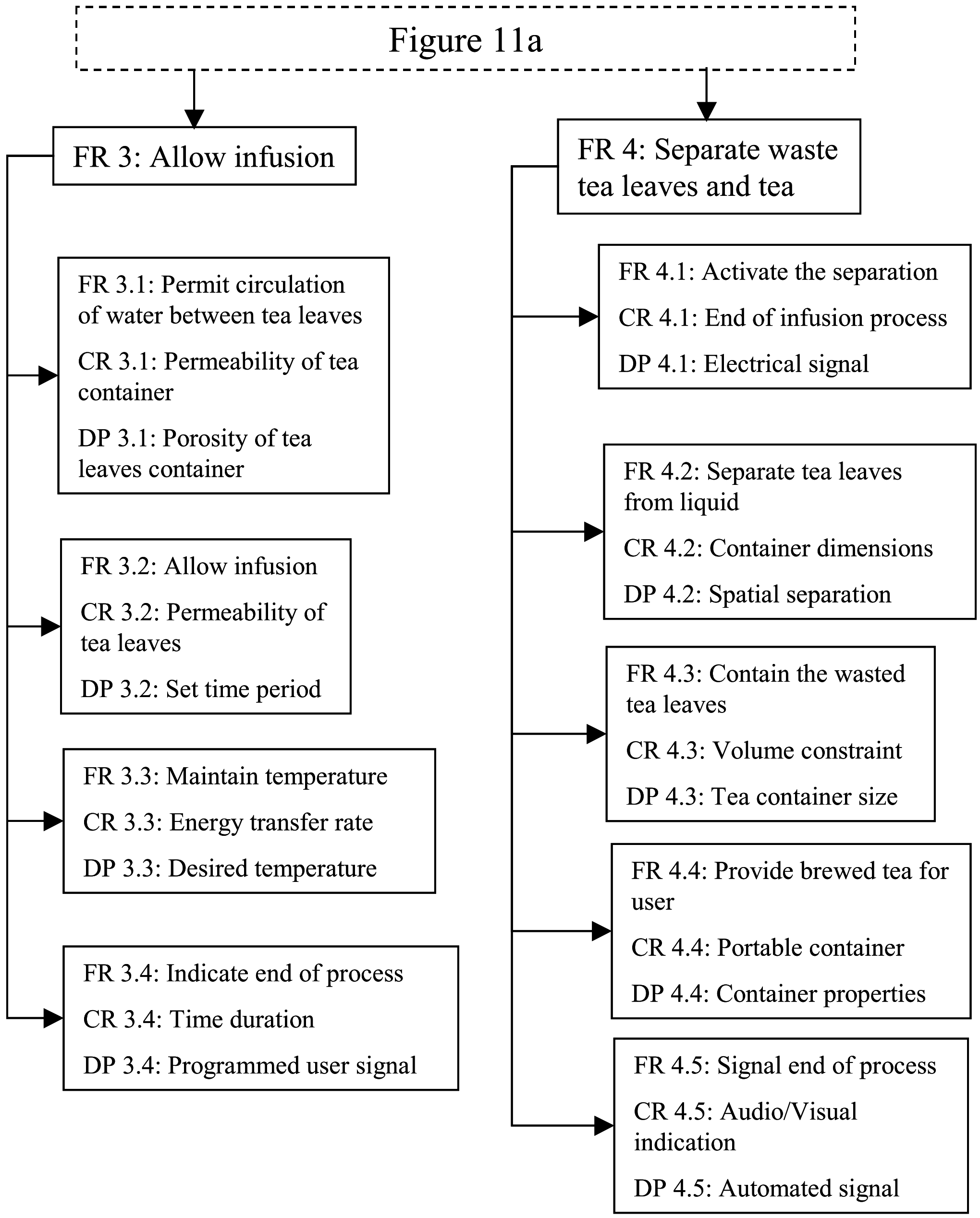

Figure 11c: Improved Function Structure for the Tea Brewing Machine (FR3 and FR4)

A possible new requirement now arises, on the setting of the temperature to which the water is to be heated. This is incorporated by FR 1.6: Regulate the energy transfer, whose constraints are the resolution of the temperature and the design parameter is the set temperature. There have been some improvements under FR 2: Unite tea and hot water. The DP for FR 2.1 earlier was physical containment of the tea leaves, but this DP does not properly reflect the parameter for the containment of the tea leaves like the size and the quantity of tea leaves that would dictate the tea container size. The FR 2.2: Unite tea leaves and water has two Functional Alternatives, FA 2.2.1: Bring tea leaves to water and FA 2.2.2: Bring water to the tea leaves. Either one of the alternatives can fulfill FR 2.2. Also, the constraint for FR 2.2 is that the tea leaves have to be immersed in the water, and the design parameter (DP) is the size of the tea container i.e., its dimensions.

In Figure 11c, FR 3: Allow infusion, did not recognize a need to circulate the water between the tea leaves nor did it maintain the temperature of the brewed tea. These functions have been added to the function structure as FR 3.1 and FR 3.3, as shown in Figure 11c. The constraint CR 4.5: Audio/Visual indication has been changed to include the possibility of having an audible signal to be used to indicate to the user that the process has been completed instead of just the visual cues. For the above functional requirement, the heating aspect, the uniting of the tea and water, the infusion and the separation of the tea from the leaves all require some control function. This means that the designer, when looking at solutions to the above FR's, would have to consider the controllability aspect of the solutions, which falls in line with the earlier primary constraint in the need statement, namely that the process must be automated. By going through the process of interrogation and questioning of the function structure, the designer gains a better understanding of the problem and is able to address issues that he/she may not have considered previously.

3.1.10 Development of Design Requirements

The design requirements are the overall requirements that the design has to meet. They are the evaluation criteria by which the various conceptual designs are judged. These are based on the performance requirements plus on the non-functional requirements. They identify what the system or artifact must do and how well it must be done. The requirements should be quantified as precisely as possible to avoid ambiguity, misunderstanding and potential conflicts later in the design process. The design requirements associated with the FR's derive from the constraint requirements and design parameters assigned to each function.

In the case of the tea brewing machine, the design requirements for the functional part are listed below:

- From FR 1.1 – the design requirements are 110V, 15 A rating. This will safely supply 1.4 kW of power to heat the water, as shown in the Order of Magnitude Calculations.
- From FR 1.2 – the design requirements are based on the 1.4kW required for the heating capacity of the element.
- From FR 1.3 – the container should be able to hold a maximum of 2 liters of hot water/tea. And the dimensions of the container should be within can be modified according to the overall device.
- From FR 1.4 – there should be efficient transfer of thermal energy to the water. Additionally this should be achieved in a safe manner. The constraints on this are the maximum time allowed to heat the water, which is around 10 minutes.
- From FR 1.5 – in order to limit the maximum temperature reached by the heater and the water for safety purposes. The maximum temperature is 120° C with the water and 50° C without the water.
- From FR 1.6 – the user can set the desired temperature of the heated water. The range can be in 75°C - 100° C with ± 5° C.

- From FR 1.7 – the signal to initiate the tea brewing process is done by the user by activating a signal.
- From FR 2.1 – the tea leaves container should be able to hold an equivalent to a maximum of 10 standard bags of tea.
- From FR 2.2 – the container dimensions should be able to contain 10 bags of tea and the required water.
- From FR 2.3 – Initiate the process of infusion, once the tea leaves and the water are ready for infusion.
- From FR 3.1 – the tea container should be porous to permit the mixing of water and tea leaves. Care should be taken here, as there may be a potential conflict with FR 2.1. FR 3.1 determines the minimum porosity or hole size of the container and the maximum size is determined by FR 2.1.
- From FR 3.2 – the infusion process is done for a variable time period, which is set by the user. The controller should receive the signal and hold the infusion process for the specified time. This could vary from 1 – 5 minutes.
- From FR 3.3 – temperature is to be maintained during the infusion process. This FR determines the heat transfer during the infusion. The temperature is variable between 75°C - 100° C with ± 5° C.
- From FR 3.4 – a signal to indicate the end of the infusion process, which is based on the ending of the time duration.
- From FR 4.1 – once the infusion process has ended, the controller activates the separation process.
- From FR 4.2 – in order to separate tea leaves from the liquid, the tea leaves would have to be spatially separated from the brewed tea.
- From FR 4.3 – this involves containing the waste tea leaves for disposal. This is similar to FR 2.2, but not coupled.
- From FR 4.4 – the final brewed tea should be in a container that should hold a maximum of 2 liters of tea for the user. This user should be able to handle the container and dispense the hot tea from the container.

- From FR 4.5 – the device must indicate via audio and visual means the end of the brewing process. Hence, the loudness or the decibel level of the audio signal and the luminance of the visual signal are considered.

The general list of design requirements containing the non-functional requirements for the tea brewing example is listed in Table 1.

Table 1: The List of Design Requirements for the Tea Brewing Machine

Criteria	Value	Desired/ Wish
Volume of tea brewed	<2 liters	D
Quantity of tea leaves	<10 bags	D
Time for the total process	< 15 minutes	
Time for heating (8 cups)	< 10 minutes	
Time for infusion (variable)	1-5 minutes	D
Temperature for heating (pre-infusion) the water	75°C - 100° C with ± 5° C	
Temperature to maintain the heated water (infusion)	75°C - 100° C with ± 5° C	
Overall size of the device	<8000cc	D
Max. dimensions of the device	20cmx20cmx25cm	
Full weight of the device	<4 kgs.	D
Retail cost	<$20	W
Safety specifications	UL -197	D
Ease of cleaning and maintenance		D
Aesthetics		W
Reliability		W

3.2 IDENTIFICATION OF INFORMATION AND RESOURCE NEEDS

During this stage, one of the activities that the designer performs is to identify the resources and the information needed to perform the design. After developing the function structure, and determining the functional requirements and the design requirements, the designer has a better understanding about requirements for a design solution. At the end of the need analysis stage, the designer is able to identify the resource and knowledge needs required to pursue any design solution. These are:

1. For the device to perform: Allocation of resources in energy, material, information, and users.
2. To manufacture the required device:
    a. Allocation of resources: Energy and material needs.
    b. Recognition of information needs: Delivery of on-time information by specialists and information on the resources.
    c. Recognition of knowledge needs: Areas where breadths or depths of knowledge are required.
    d. Facility capabilities: manufacturing processes and space constraints.
    e. Identification of required personnel: Specialists in manufacturing, materials, manufacturing and marketing.
    f. Finance: allocation of finance for capital and running costs.
    g. Innovation: identification of areas that could be used for protection of intellectual property.
    h. Time constraints: Time to market, parts delivery schedule and time constraints on resources.

Prior to pursuing any solution, the designer has to identify two things; the knowledge and resources that are available, and the ones that are not at hand but are needed in order to pursue the design. Earlier we have seen how the device acts as a transformer. This transformation of resources can be thought of as occurring in two different aspects. The first aspect addresses the transformation of the desired set of inputs to the outputs in order to fulfill the functional needs of the device. The second aspect addresses the needs in producing the device. As shown in Figure 12, the design as a transformer is indicated by aspect 1, the latter part is indicated by aspect 2.

The first aspect enables the designer to perform the activities in the need analysis like the development of function structure and design requirements. The second aspect enables the designer in identification of informational and resource needs necessary to carry out the design tasks. Aspect 1 is usually the view of an engineer and aspect 2 is the view of a manager or organizer. Here both the views are considered and required in order to produce the design, as both are coupled with one another.

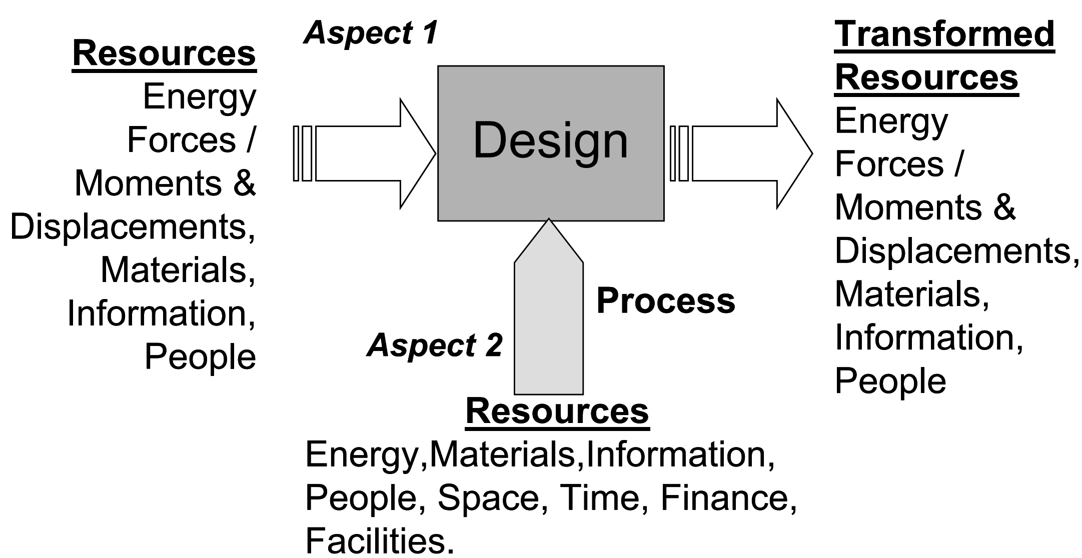

Figure 12: Design as a Transformation Process

In the case of the tea brewing machine, the development of the function structure and the design requirements addressed the first aspect. Considering the second aspect for the example, certain issues come to the front that the designer has to address and gather information about:

- If the device is to be made by mass commercial production, the manufacturing processes and materials have to be chosen accordingly.
- The materials could be plastics and metal based on the constraints.
- The device has to be UL–197 certified. So, the designer has to gather the required information for certification.
- The personnel required are in the domain of plastics and metal manufacturing, electrical supply and controls, ergonomics, aesthetics and safety.
- The designer has to organize the teams and the delivery of on-time information and input by the specialists.
- Capital costs and the time-to-market have to be identified.
- Marketing and shipping issues like packaging and supply have to be identified.
- Areas in the design or manufacturing of the device that require protection of intellectual property have to be identified.

3.2.1 Planning for Innovation Opportunities

One of the goals of the need analysis stage is to enable the designer to be innovative and open up opportunities for innovation. By keeping the function structure and design requirements solution independent, the designer keeps the solution space wide. Also, by the function structure breakdown, the designer can identify certain functions and features in the design that are candidates for innovation and patent protection. By identifying these features early in the design process, the designer can gather information and protect the intellectual property from the competitor.

3.3 DISCUSSION

Need identification is the step where a non-technical and configurational design task is converted to a real need. The need is analyzed extensively to identify the functions, constraints and the parameters. The designer should be objective and avoid creating solutions throughout this stage, as the aim of this stage is to be solution independent to foster innovation. Analyzing the need also deepens the designer's understanding of the task and the domain. This is extremely useful later in the design process and is facilitated by being quantitative. The knowledge gained through the need analysis and the outputs are carried over to the conceptual design stage. The outputs of the need analysis stage help the designer in identifying and managing of resources like people, materials required, manufacturing processes. The designer has a better understanding of the problem and is able to utilize the assistance of various experts as and when necessary. Also, this stage identifies areas in the design that may require patent protection.

4 OBJECT FUNCTION METHOD

Humans have a tendency to categorize and classify information. When put into a new situation, we immediately want to compare it with prior information and knowledge. This has its advantages and drawbacks. In situations where the problem is a variant of an existing one, the solution is invariably found by modifying an existing solution. Breakthrough solutions are rare. Nevertheless, the ability to modify and compare with prior knowledge is very useful. But, in certain cases, where both the problem and its domain are new, variations and modifications of existing solutions invariably fail to produce the desired result.

A large number of design needs, often called problems, belong to the above category of variants of existing solutions. The need focuses the designer on improving the existing device or design. These situations are well suited to the Object Function Method. In this method a designer views an existing device in terms of objects and relationships and identifies the improvement needed. As before, by abstracting beyond the present realm, the designer looks at objects in terms of their core functionalities and properties. This prevents the designer from being fixated on the existing solution and opens up opportunities to innovate. The primary goal of the Object Function method is to change the way a designer performs need analysis and develops a function structure. Concentrating on the functional relationships between the objects reveals the critical deficiencies in the existing solution and identifies the critical parameters that may need to be addressed. By persistent abstracting and questioning, the designer is able to view the need from a solution independent point of view.

One of the main methods that has been used in the development of the function structure has been the Functional Analysis Method or the 'Black-Box' approach [1, 2] illustrated in the previous section. Usually, the conversion of the set of inputs into the set of outputs is a complex task inside the Black-Box, which has to be broken down into sub-functions. Cross claims that there is no really objective, systematic way of breaking the main need into sub-functions [1]. The analysis into sub-functions may depend on factors such as the kind of components available for specific tasks, the necessary or preferred allocation of functions, and the designer's experience. This technique is ideal for solving a design task that is new or does not have any prior solution. In cases of improvement on existing designs, the tendency of the designer is to examine the current design and then work backwards from it to identify the functions, sort of like reverse engineering. The usage of the Object Function Method in the development of the function structure addresses this deficiency. Additionally, its usage in the need analysis stage assists in identification of critical parameters for the functions and aids in reformulating the design task into a solution independent function structure, thus preventing fixation and enabling innovation.

The idea of looking at a design using objects and functions is based on the Closed World Method of USIT developed by Sickafus [23]. The USIT methods are systematic procedures used in technological problem solving. The Object Function Method subscribes to the view of the Closed World method in viewing the problem in terms of the objects and their functional relationships. The goal here is not to try to solve the problem but to understand the design task and to study the design task from a solution independent perspective. The Object Function Method has been modified to be simple and to fit into the spirit of the IIDE methodology by incorporating the underlying design philosophies of Abstraction, Critical Parameter Identification and Questioning.

4.1 BACKGROUND

The Unified Structured Inventive Thinking (USIT) developed by Sickafus [23] is a structured process for setting up and attacking technological problems. It is primarily based on the Systematic Inventive Thinking developed by Horowitz and Maimon [24] and partly on TRIZ by Altshuller [25]. The primary techniques used in USIT are the

Closed-World (CW) Method, the Particles Method and the Solution Procedures. Since the focus is on the Closed-World diagram, which is part of the CW method, this method and the CW diagram are explained briefly in the following section.

4.1.1 Closed-World Method

In the Closed-World method, different perspectives of the problem and its objects are developed in the form of heuristic devices: A closed-world diagram; object-attribute-function statements and diagrams; a single-object function analysis; and a qualitative-change graph. First, the objects are arranged into a CW diagram, which shows the functional relationships between the objects as intended by the designer. The criterion for selecting the objects is that they should be relevant to the 'problem,' that is, if the object is removed, the problem statement changes. If removal does not change the 'problem' then the object is excluded. Object-attribute-function statements are generated, using information in the CW diagram, in order to identify and characterize the effective attributes of the CW objects. The object-attribute-function diagram is constructed to serve as a heuristic device in the application of solution techniques. The qualitative change graph is used to plot the favorable or unfavorable trends in the problem situation that would occur if a desired parameter were varied.

A simple CW diagram is shown in Figure 13. The diagram is a hierarchical, branched structure that displays the functional relevance of the selected objects. The criteria for constructing this diagram require that every object be functionally related to the object above it either by being in physical contact with it or by affecting it in a desired way. This branched structure begins with the top object (A) and flows through other objects united by functional relationships. The top object is selected as the most important object. Its significance justifies the existence of the subordinate objects. Each of the remaining objects on the list is connected according to its functional relationship to the object immediately above. The subordinate object B is functionally related to its superior object A if together they perform a function or if object B assists A to perform its function. If no functional relationship can be found and the following subordination conditions are not satisfied, the object may belong in a separate CW diagram or may be placed aside as a neighborhood or environmental object. The conditions for subordination are, the subordinate object (B) must be related to its immediately superior object (A), by:

- Being in physical contact with A,
- Affecting A in a desired way,
- Being present because A is present,
- Becoming redundant if A is removed, and
- Being present after A was present (i.e., A was selected first).

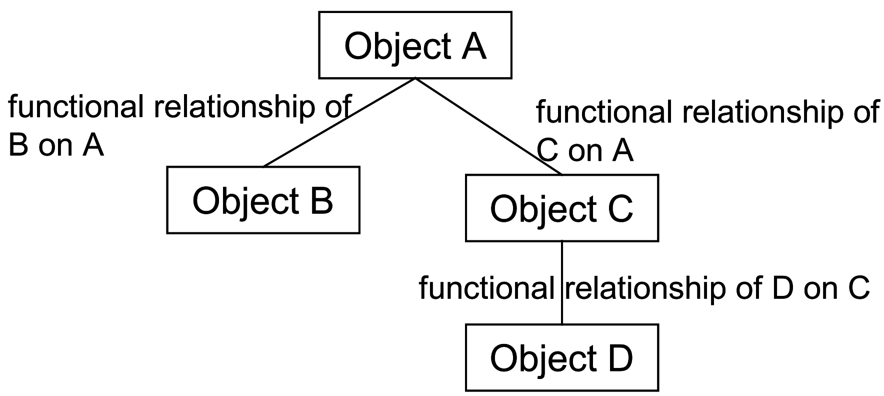

Figure 13: Branched Structure of CW Diagram Showing Object Connectivity

Objects are tangible items that exist of themselves and can interact with each other when in contact. Interaction is the process of altering the metrics of an object's attributes. Certain intangible items that are able to modify the attributes of tangible items, fields in particular, are not objects. Fields are attributes of their source objects. Examples of objects are things having mass or other attributes that enable them to interact with each other, or signals that can be detected and interpreted.

4.2 OBJECT FUNCTION METHOD

One of the drawbacks in the CW diagram is the issue of finding the most important object. The selection of the most important object to head a CW diagram depends on where the boundaries of the system or sub-system bounds are drawn. This identification depends on the skill of the designer and on his/her sense of the most important object in the design. In this dissertation, the primary goal of the Object Function Method is to facilitate the activities that the designer performs in the need analysis stage. Specifically, the Object Function Method as used here, explores the objects and their functional relationships as an effective means for gathering information about the design task and for the development of the function structure. The hierarchical emphasis on identifying and placing objects from the CW diagram is dropped so as not to restrict the designer. The designer selects the relevant objects and develops an Object Function diagram with the objects and their functional relationships. By applying the design philosophy of Abstraction, Critical Parameter Identification and Questioning to the objects and functions, the designer gathers information about the overall design task (Need) and identifies the functions and sub-functions (FRs) needed to solve the design task. By doing this, the designer reframes the problem from a specific configurational design to one that is solution independent, thus opening opportunities for innovation. Another aspect of this method is that it facilitates identification of critical design parameters and conflicts within the task at hand. This way of using and applying the Object Function Method are explained in the following sections.

4.3 USE OF OBJECT FUNCTION METHOD IN DEVELOPMENT OF FUNCTION STRUCTURE

In order to use the Object Function Method to gather information about the design task and to identify the functional requirements, we first draw the Object Function diagram. This diagram consists of the various objects identified by the designer and their functional relationships. The procedure for developing an Object Function diagram is listed below,

1. Identify the objects:

   These are entities or physical bodies that are relevant to the problem. The concept of "objects" is defined to be more than just physical things or systems. The list includes all "objects" that absolutely must be present for the needed device or system to function. In addition to physical objects the list includes environmental objects (air, water), sources of energy (power, heat), information and "users," i.e., animate and inanimate "users" of the device that input to or outputs from the needed device.

2. Identify and establish the relationships between the various objects:

   Relationships between objects can be either physical contact or a functional coupling where one object affects or acts on the other object.

A general schematic of the Object Function diagram is shown in Figure 14. The direction of arrows together with the function indicates the effect Object A has on Object B, i.e., function A-B. In some cases, there may be multiple interactions between the objects and their functions. These can be represented as shown between objects A and D.

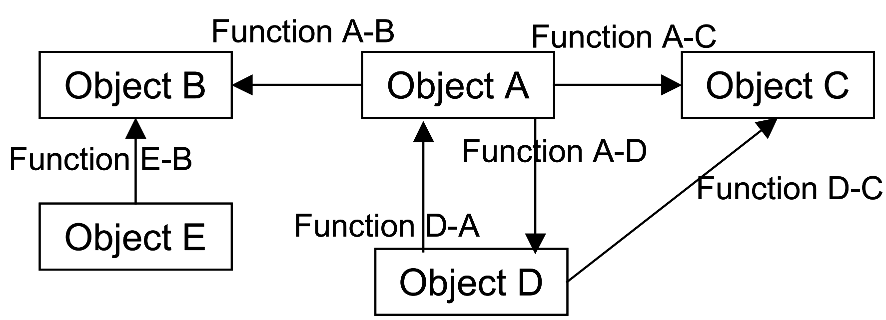

Figure 14: A General Representation of the Object Function Diagram

In some cases, there may be more than one function between two objects. It becomes necessary to distinguish between the primary function and the secondary functions and also to distinguish between the useful function and the harmful one. In such cases, the Object Function diagram is modified to include the above relationships and is shown in Figure 15. An example of such interactions is elaborated in Section 4.5. There are three interactions between object A and object B. The primary function, function A-B, is shown in bold and the auxiliary function is shown without the bold lettering. The complete lines are the useful function and the dashed lines indicate functions that are harmful and needs to be improved. The representation of useful and harmful functions has been incorporated from Altshuller's Substance-Field Analysis [25].

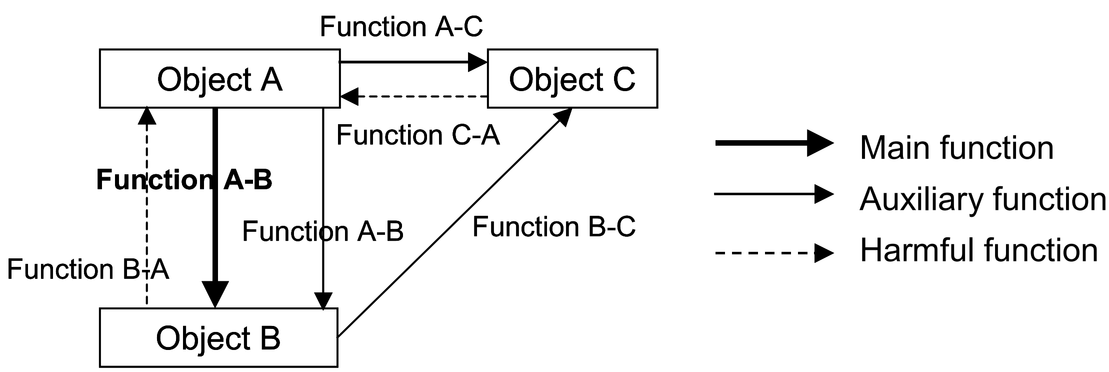

Figure 15: Representation of Main, Auxiliary and Harmful Functions in the Object Function Diagram

Consider the example of the door-lock design to illustrate the usage of the Object Function Method. The device considered is the traditional hinged door with a latch lock combination, single handle, and hand-held key. The need here is to improve upon the existing design of the door-lock combination. In order to construct the Object Function diagram, we first need to identify all the objects relevant to the design. The objects are:

- Physical objects: the lock mechanism, door, the frame together with the wall, door handle, latch and key.
- Users: Authorized user, unauthorized user.
- Source of energy: Human or mechanical power
- Information: Indicators to show whether the door is locked or not
- Environment: Environmental conditions.

The designer by redrawing the boundary of the problem could go into the details of the lock mechanism and draw another Object Function diagram. Next, the various interactions between the objects are identified and there are no hierarchical placement of the objects and functions. The objects together with the functional interactions are shown in Figure 16. There may be more than one functional relationship between the same set of objects. The designer has to be cognizant of the most important one.

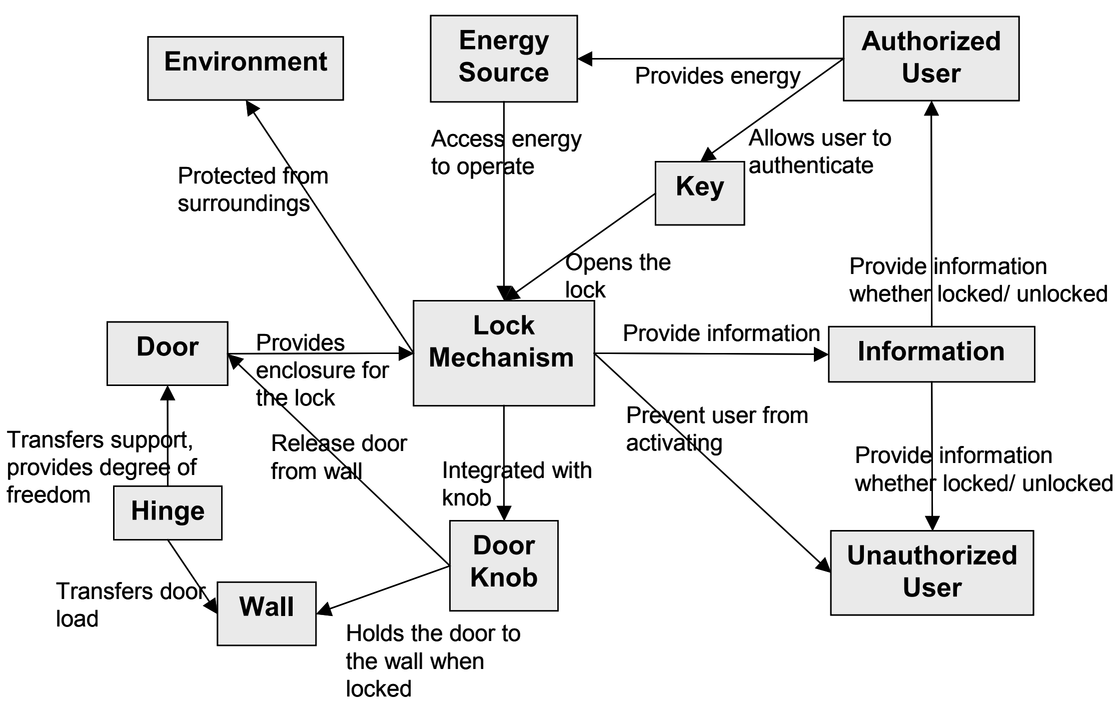

Figure 16: Object Function Diagram for a Door Lock Mechanism

By applying the design philosophy to each of the objects, the designer can extract the core functionality of the objects and identify their functions. In doing so, the designer also gains additional information about the device. In effect the designer performs the following activities of the need analysis stage, gathering of information, the identification of the real need and identifying the functional requirements. In the case of the door-lock example, the objects and their functional relationships have been identified. This is an initial attempt to study the design and the aim is to use this initial step to progress deeper and identify the core functions and the real need. The process is illustrated as follows,

- Lock mechanism – The primary functions of this object are to provide access to authorized user who has the key for authenticity and to prevent access to the unauthorized user. Other functions are that it has to integrate with the door knob during the opening and locking operation; provide information, if necessary to the user regarding the status of the lock mechanism; access energy for operation; be protected from the outside environment. The above functions are gathered based on the interactions between the objects and by the questioning process.
- Key – The functionality of the key is to authenticate the authorized user. It is a means by which the lock mechanism recognizes an authorized user. The designer can ask questions like, when is a key a key? What constitutes a key? Is the access both ways? What type of security is to be performed by the key? How should the authorization be done? Is a special type of checking like eye scan, fingerprints, etc. necessary? What is the purpose? By performing abstraction on the functionality, he/she can determine the role of the key.
- Authorized user – The questions that need to be asked are: who is an authorized user? What is meant by authorization? The answers would lead to the authorized user is one who has access to the space beyond the door. The user usually has the key to authenticate his access.

- Unauthorized user – the user who does not have the key to open the lock mechanism. Also, the lock mechanism should prevent the unauthorized user from opening the door.
- Information – Is information required to indicate whether a door is open or closed? What type should the information be? What are the other areas in which information needs to be determined? The designer, by gathering answers to the above questions, can determine whether the information is needed and the type of information necessary.
- Energy source – Typically the user provides the source of energy to activate the lock. The question arises: is this always true? Can another energy source be provided?
- Environment – What type of environs is the door-lock combination located? Is it inside a building, i.e., controlled surroundings, or is it exposed to nature? If exposed to nature, what are the conditions?
- Door knob – This interacts with the door and the wall, keeping the door in a closed position. The lock mechanism and the knob could be integrated. Is the door knob necessary?
- Door – By questioning the functionality of the door, the designer determines that the door is the primary object in this scenario. It separates the two spaces or rooms and provides access between the spaces. The lock comes into play when one of the spaces becomes restricted. It also provides the enclosure for the lock mechanism. But, the designer could question, should the enclosure be provided in the door? Could it also be provided in the wall? In addition, the door is connected to the wall by means of a hinge or support that allows motion for the door. Also, how should the door be activated?
- Hinge – This transfers support from the door to the wall and also provides the door with a degree of freedom in motion. Are there other means by which this function could be achieved? When is a hinge a hinge? Is the hinge relevant to the problem and the lock?

- Wall – In the context of this design, this object physically separates the two spaces and provides no access. By asking such similar questions, the designer gains insight into the problem.

Based on the above questioning and examination, the designer is able to gain insight into the design task and is able to question each of the constraints and gather information about the design task. The objects enable identification of the areas that the designer should focus on. For example, it can be seen that removing the hinge or the wall does not change the 'problem' and thus these objects do not affect the design and could be removed from the Object Function diagram. By Questioning on the objects, the designer is able to gather the required information. For example, what are the types of environments that the lock mechanism needs to be protected from? What is meant by preventing access to unauthorized user? Does this include forcible entry? Does this translate to the load requirements on the door-lock-wall interface? Also, since an enclosure needs to be provided for the lock, are there any space constraints in the door or the wall? Then the information for requirements for the key determines the type of key and its constraints. The requirements for an authorized and unauthorized user could also be identified. Is an external energy source required? The type of environs that door is to be used in are identified and that would correlate to the wall and the hinge requirements. So, by examining each of the objects and the functions and by performing the need identification for each of them, the designer is able to gather the required information to perform the task.

Based on the results of the above need identification, the designer could come up with the need statement of the lock mechanism "*To allow authorized access to an area through a door.*" By abstracting the functionalities of the objects, the initial set of functional requirements are shown below,

- Allow authorized access
    - Recognize authorization

  - Prevent unauthorized access
  - Indicate locked or unlocked position
  - Activate locking or unlocking
  - Provide energy to open the door to allow entry
- Enclose mechanism
- Lock or unlock the door
  - Access energy for locking or unlocking
  - Receive signal for locking or unlocking
  - Activate mechanism to lock
  - Activate mechanism to unlock
  - Hold in unlocked position
  - Hold in locked position
- Secure the door to the wall

Once the initial set of functional requirements have been identified, the designer could follow the remaining activities in the need analysis stage to develop the function structure further by identifying the constraints and the design parameters, as shown in the previous section. To summarize, the procedure for the Object Function Method is as follows:

- Identify the objects.
- Identify and establish the relationships between the various objects.
- Perform the design philosophy of Abstraction, CPI and Questioning on the objects and their relationships to gather the information and identify the key issues.
- Develop a need statement and the breakdown of the functional requirements.

This usage of this method in this section primarily assists the designer in performing the first four activities in the need analysis stage. A study to evaluate the effectiveness of this method in the development of the function structure and the usage in identification of the critical parameters and coupling issues in the design is shown in the following sections.

4.4 VENDING MACHINE EXAMPLE AND RESULTS OF THE STUDY

In order to test the Object Function Method, a study was conducted on a group of senior undergraduate students (49 students) who were learning the design process and were in the first semester of the two semester design sequence. The study was conducted after they had been taught the need analysis stage of the design process. That is, they were familiar with the terminology and the activities of the need analysis stage, e.g., the need statement, function structure development and the black-box approach. The study consisted of two parts. In the first part the students were required to develop a set of functional requirements for the design of a Coke (Soda) Vending Machine. In the second part of the study, the same set of students were briefly taught about the Object Function Method and then they were required to develop an Object Function diagram. Based on the diagram the students were asked to develop a set of functional requirements for the design of the same Coke Vending Machine considered in the first part. The results from the two parts were compared and tabulated. The same problem was given in order to determine any changes or differences in the submitted functional requirements. There is a possibility that after working through the first part, the students had a better understanding of the problem and were able to do better the second time. To measure that possibility, the Object Function diagram was also evaluated. The assumption was that evaluating the Object Function diagram together with the students' selection of the functional requirements for the Vending Machine would provide a good indication of its effectiveness in aiding novice designers in developing a better set of functional requirements.

The first part of the problem given to the students was to develop a need statement and the functional requirements for a Coke Vending Machine. The time allowed to complete the task was one week. The only information that the students had about the development of function structures was given in class, i.e., the Black-box approach. At the end of the week when the students turned in the first part, they were given part two of the study, at which time the students were taught briefly about the Object Function Method with an example and were given handouts. They were asked to develop an Object Function diagram and a set of organized functional requirements for the same Coke Vending Machine. The time given for this task was also one week. A total of 49 students participated in this study. The example along with the evaluation and results are explained in the following paragraphs.

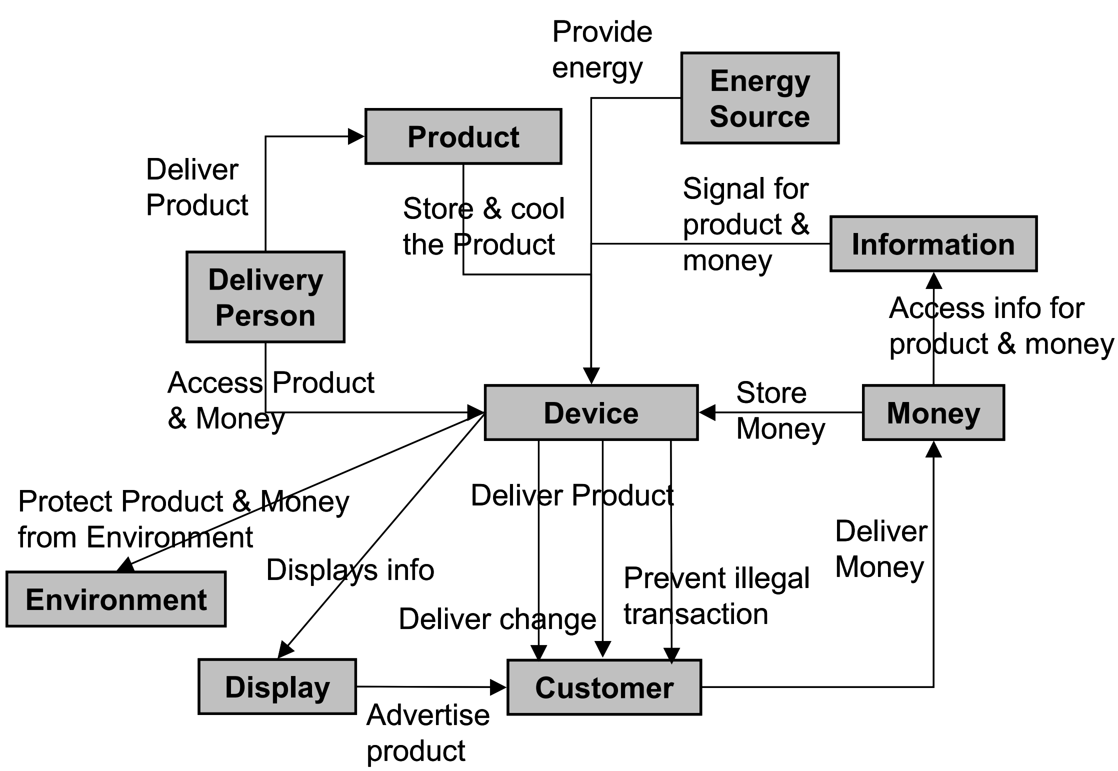

Figure 17: The Object Function Diagram for the Coke Vending Machine

4.4.1 Coke Vending Machine Example

Consider the Coke Vending Machine. The objects in this case are – the device, the product dispensed, the customer, information about product and money, the money, the delivery person, the energy source, the environment and the display. One could go into detail and get more objects, but for this purpose these are sufficient, as they capture completely the various interactions and objects. The objects and their interactions are listed below and shown in Figure 17.

The function of the device is to store and cool the product and then deliver it to the customer after doing a monetary transaction. The need statement for the device could be stated as 'Dispense product to the customer after proper monetary exchange.' The primary function is to dispense the product to the customer and the primary constraint is to do it after the proper monetary exchange. The initial breakdown of the functions based on the interactions between the objects are shown below,

- Store the product
    - Receive the product from the delivery person
    - Store the product
- Keep the product cool
    - Access energy for cooling the product
    - Remove thermal energy from the product
    - Transform the removed energy
    - Store the removed energy
- Deliver product to customer
    - Receive signal for type of product to dispense
    - Deliver the product
- Provide information about product and money
- Enable monetary transaction
    - Receive money from customer
    - Verify the amount

  - Provide the change
  - Send signal to authorize delivery of product
  - Store the money
  - Provide access to delivery person
- Protect from harmful environmental conditions
- Protect against illegal transactions
- Advertise the product

Further the designer could go through the various steps described previously under the design philosophy and gather information about the design. This could be information on the type of product, the number of products to store and dispense, the cooling temperature (if the product is to be cooled), transformation of the thermal energy, storage or disposal of the removed energy, the type of monetary transaction, what types of transactions are allowed, details about the accessibility to the delivery person, protecting the device from illegal transaction and the environment, etc. Based on the above information gathered and the functional breakdown, the designer can perform the next activities in the need analysis stage.

4.4.2 Results of the Study

As mentioned earlier, a study was conducted with a group of 49 students to evaluate the effectiveness of the Object Function Method in developing a function structure. There were two parts to the study, in the first part they were asked to develop a function structure for the Coke Vending Machine based on the instructions given in the regular class. In the next part, the same set of students were asked to use the Object Function Method by drawing an Object Function diagram and then using the design philosophy to identify and relate the objects and functions to develop a function structure. The evaluation consisted of comparing the two function structures and the object-function diagram communicated by the students. The evaluation criteria are shown below:

- Function structure

  - Improved function structure
  - Similar function structure
- Object Function Diagram
  - Good diagram
  - Decent diagram

The criterion for assessing the function structure is based on comparing the two structures. The criterion for assessing the Object Function diagram was either good or decent. It was determined a good diagram if they included certain objects and functions relating to the delivery person or the advertisement display. If they followed the instructions given but did not consider the above objects it was considered decent. The results of the study are shown in Table 2. The categories are good Object Function diagram and improved function structure, good Object Function diagram and same function structure, decent Object Function diagram and improved function structure, decent Object Function diagram and same function structure, and finally lack of effort shown in the study. The last category was included when proper evaluation could not be done based on the lack of effort or incomplete effort by the students. From the data, we can see that 20 students (50% of effective group) had a good Object Function diagram, i.e., they were able to identify the delivery person or the advertisement objects. From the 20 students, 14 of the students had improved function structures as a result of the good Object Function diagram, which is significant. The number of students who improved their function structure but only had decent Object Function diagrams was 6. Based on this result, we could conclude that the Object Function Method is a viable tool for the development of function structures.

Table 2: Results of the Study Correlating Object Function Diagram and Function Structure

Evaluation Criteria	Number of Students
Good OF dig. + Improved FS	14
Good OF dig. + Same FS	8
Decent OF dig. + Improved FS	6
Decent OF dig. + Same FS	12
Lack of effort	9
Total	49

4.5 IDENTIFICATION OF CRITICAL PARAMETERS USING OBJECT FUNCTION METHOD

As mentioned earlier, typical design tasks usually relate to existing designs. There is a need to improve a certain feature or to rectify a problem in the design. In the two previous examples, the Object Function Method was used in enabling the development of a function structure and the gathering of information. However, this method is similarly useful in the identification of critical parameters in the functions and providing the designer early insight into key parameters and coupled parameters in the design.

Consider a need to improve the design of a basic transverse flow heat exchanger. The schematic of a typical heat exchanger is shown in Figure 18. The heat exchanger under consideration consists of a mantle, pipes, pipewalls supporting the pipes, a pipewall movement compensator (necessary in order to account for pipe dilation effects), and two internal hangers to support the pipes. The heat exchanger is of the transverse-flow type, the heating medium enters the mantle at M1, flows over the pipes and departs at m1. The heated medium enters through the pipes at m2 and exits at M2.

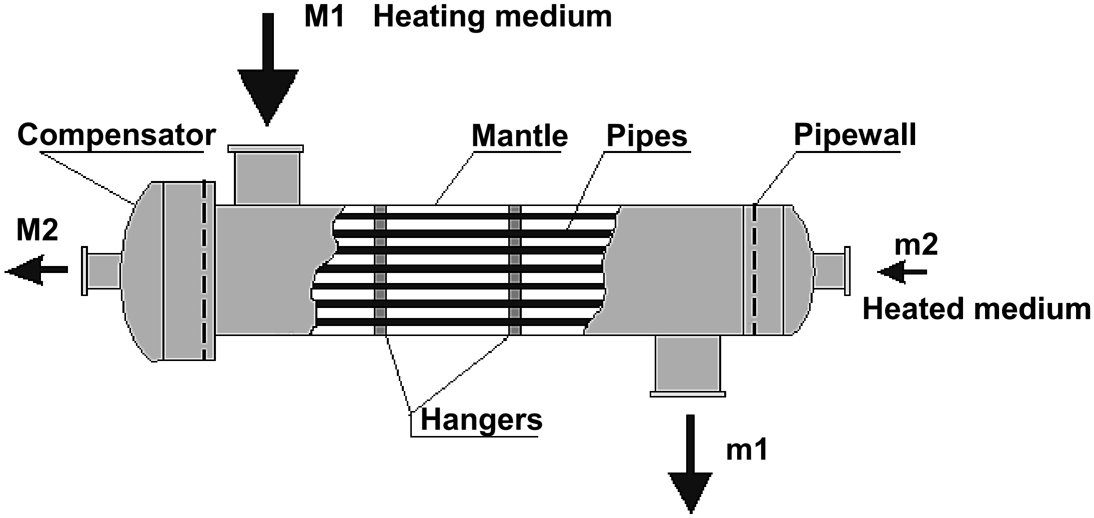

Figure 18: Schematic View of the Heat Exchanger

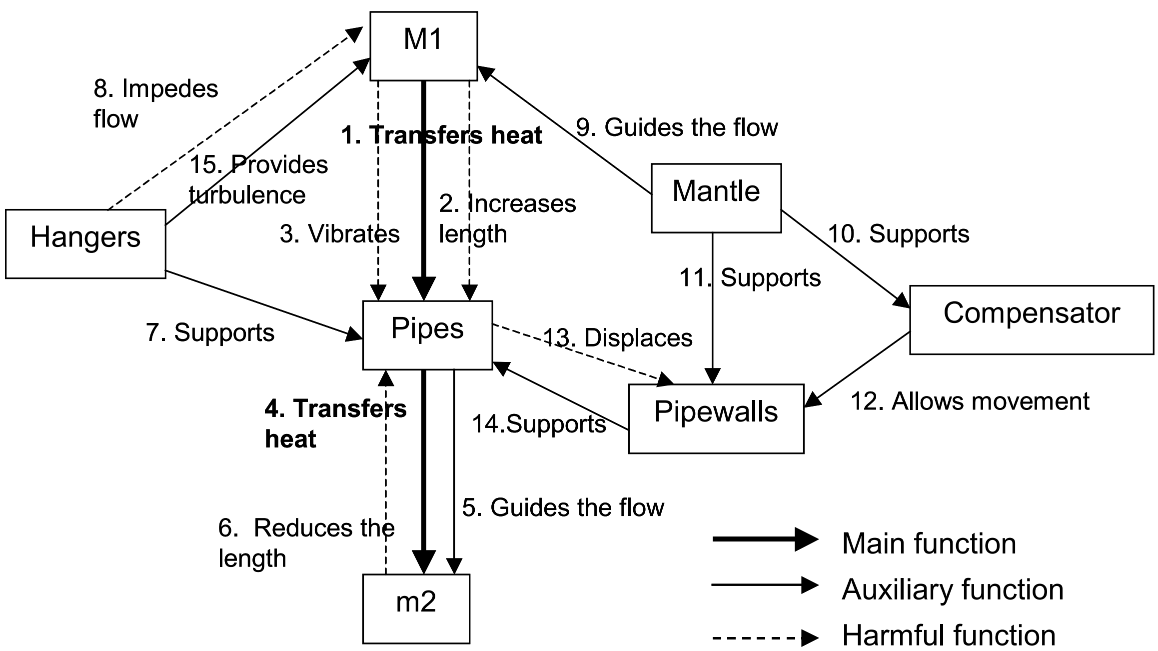

Figure 19: Object Function Diagram for the Heat Exchanger

To develop the Object Function diagram, the objects are identified. In this case they are: the two flow media M1, m2; mantle; pipes; pipewalls; hangers; and compensator. The various interactions between the objects and the Object Function diagram are shown in Figure 19. In this diagram, the functions are numbered and classified as the main functions, auxiliary functions and harmful functions. The harmful functions are those that need to be eliminated or improved in order to improve the design. This representation helps the designer to focus his/her efforts in identifying the key functions and their uses. The direction of the arrows indicate the relationship from one object to another, for example, M1 (object) transfers heat (function 1) to the pipes (object). The various functions between the objects are listed below:

1. M1 transfers heat to the pipes
2. M1 increases the length of the pipes
3. M1 causes vibrations in the pipes
4. Pipes transfer heat to m2
5. Pipes guides the flow of m2
6. m2 reduces length of the pipes
7. Hangers supports the pipes
8. Hangers impedes the flow of M1
9. Mantle guides the flow of M1
10. Mantle supports the compensator
11. Mantle supports the pipewalls
12. Compensator allows movement of the pipewalls
13. Pipes displaces the pipewalls
14. Pipewalls supports the pipes
15. Hangers provide turbulence to the flow of M1

The above listing of the objects and their functions are entered in Table 3. The functions that are in italics are the core functionalities of the object that has been abstracted. For example, the function of M1 is to transport thermal energy; the function of the pipes is to prevent the two fluids from mixing while enabling heat exchange between the two fluids. The direction of the arrow indicates the effect that the first object has on the other, for example, M1 in the first column has three functions that relate to the pipes (in top column), i.e., transfers heat to the pipes, increases length of the pipes and vibrates the pipes.

From Table 3, we can see that the pipes interact with M1, m2, pipewalls and hangers. The designer, in order to gain insight into the problem, breaks down the interaction further into various parameters of the objects that are affected by the respective functions. This breakdown is shown in Tables 4a and 4b. By identifying the various parameters that are affected, the designer can identify if these parameters are coupled within the functions. The information shown in Tables 4a and 4b is an extension of Table 3. Here the Objects are further broken down into their respective parameters and the functions that interact between the objects and their parameters are indicated by the function number as shown in Figure 19 and Table 3. For example, in function 1: M1 transfers heat to the pipes, the parameters of M1 that are affected by the function are: coefficient of heat transfer, velocity of M1 fluid and thermal energy. The parameters of the pipes that are affected by this function are aspects of thermal energy like thermal conductivity, thickness of the pipes and surface area of the pipes.

Table 3: The Functions Between the Objects in the Heat Exchanger Problem

↗	**Pipes**	**M1**	**m2**	**Pipe-walls**	**Compen-sator**	**Mantle**	**Hangers**
Pipes	*Prevents mixing of two fluids* *Enables heat exchange*		**4.Transfers heat** 5.Guides the flow	13. Displaces			
M1	**1.Transfers heat to pipes** 2.Increases length of pipes 3.Vibrates	*Transport thermal energy*					
m2	6. Reduces length		*Transport thermal energy*				
Pipe-walls	14.Supports			*Allow pipe displacement* *Prevent mixing of the two fluids at the interface*			
Compen-sator				12. Allows movement	*Compensate for pipe displacement*		
Mantle		9.Guides the flow		11. Supports	10.Supports	*Enables heat exchange*	
Hangers	7.Supports	8.Impedes the flow 15.Provides turbulence					*Support the pipes*

Note: The arrow indicates the flow of the function from the object in the row to the object in the column. The text in italics are the core functionalities of the object. The numbers and the remaining text are the main functions (bold), auxiliary and harmful functions.

Table 4a: The Breakdown of the Functions Between the Objects and Their Parameters in the Heat Exchanger Problem – Part 1

	Objects affected	**Pipes**				**M1**				
Objects that Affects	Object Parameters	Thermal energy(Thermal conductivity, thickness, Sectional area (dia))	Length	Structure	Location	Coefficient of heat transfer	Velocity (flow rate)	Thermal Energy	Mass (amount of fluid)	Contd… in next table
Pipes	Thermal energy(Thermal conductivity, thickness, Sectional area (dia))									
	Length									
	Structure									
	Location									
M1	Coefficient of heat transfer	1								
	Velocity (flow rate)	1		3						
	Thermal Energy	1	2							
	Mass (amount of fluid)			3						
M2	Coefficient of heat transfer									
	Velocity (flow rate)									
	Thermal energy		6							
Mantle	Structure (dimensions)						9		9	
Pipe-walls	Structure (dimensions)			14						
Compen-sators	Structure (dimensions)									
Hangers	Structure			7		15	8,15	15		

Note: The numbers in the table represent the function numbers indicated in the Object Function diagram and Table 3.

Table 4b: The Breakdown of the Interactions Between the Objects and Their Parameters in the Heat Exchanger Problem – Part 2

	Objects Affected by	**m2**				**Mantle**	**Pipe-walls**	**Compen-sators**	**Hangers**
Objects that Affects	Object Parameters	Coefficient of heat transfer	Velocity (flow rate)	Thermal energy	Mass (amount of fluid)	Structure (dimensions)	Structure (dimensions)	Structure (dimensions)	Structure (dimensions)
Pipes	Thermal energy(Thermal conductivity, thickness, Sectional area (dia))	4	4	4					
	Length								
	Structure		5		5				
	location						13		
M1	Coefficient of heat transfer								
	Velocity (flow rate)								
	Thermal Energy								
	Mass (amount of fluid)								
m2	Coefficient of heat transfer								
	Velocity (flow rate)								
	Thermal energy								
Mantle	Structure (dimensions)						11	10	
Pipe-walls	Structure (dimensions)								
Compen -sators	Structure (dimensions)						12		
Hangers	Structure								

Note: The numbers in the table represent the function numbers indicated in the Object Function diagram and Table 3.

The following example illustrates the use of Tables 3 and 4. From Figure 19, we can see that the pipes have to be long for better heat exchange and short for compactness. In addition, the pipes contract due to m2 and expand due to M1. Consider the portion of the design as shown in the Figure 20. The three objects are: the medium M1, pipes and hanger. M1 affects the pipes adversely by introducing vibration and increasing the length. In order to control the vibration, the hangers are used, but by introducing this, an additional problem of impeding the flow of M1 is created. As can be seen from Table 4a, when we look at the object hangers in the first column, its property of structure affects the structure of the pipes (by function 7) and the velocity flow rate of the pipes (by function 8). The reason these two functions are coupled is because by changing the parameter of the hanger it improves one function but reduces the effectiveness of the other function. Other examples of coupling are, from Table 4a when we consider the length of the pipes, it is affected by the thermal energy of M1 (function 2) and thermal energy of m2 (function 6). From Table 4b, the structure of the pipewalls affects the location of pipes (function 13), structure of mantle (function 11) and structure of compensator (function 12). Similarly, the mantle structure affects the pipewalls structure (function 11) and the structure of the compensator (function 10).

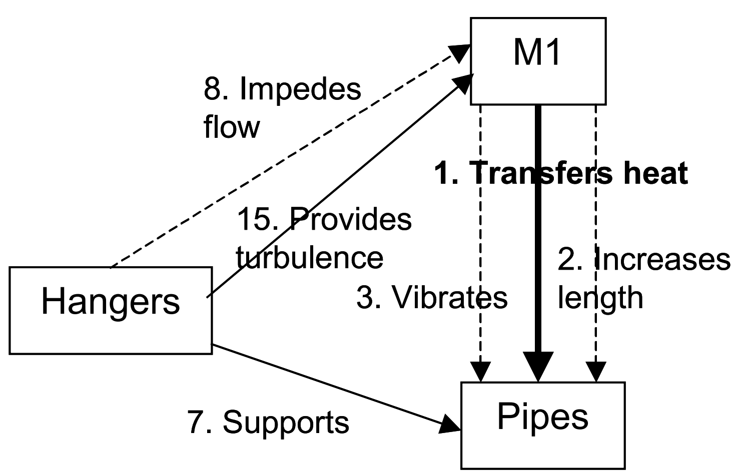

Figure 20: M1, Pipes and Hanger Interaction Model

If the designer applies the fundamental design philosophy to these issues, he/she could identify the critical parameters and identify the essence of the problem. For example, by questioning the need for the hanger, the designer can determine that the function of the hangers is to prevent the vibration of the pipes. This is achieved by providing supports and reducing the amplitude of vibration. The key question is to reduce the vibration and to identify the cause of the vibration. Also, the designer can address if this functionality could be provided by the pipes, like making the pipes self-supporting. This example illustrates how the Object Function diagram aides in identifying the coupled functions and also the parameters involved in the design.

4.6 DISCUSSION

In this section, the Object Function Method was explained and its usage in the activities of the need analysis stage and in the development of the functional requirements was illustrated. The use of the fundamental design philosophy is an integral part of this method. The Object Function Method along with the philosophy helps the designer to gather information, extract the functionalities of the objects and their interactions, identify critical parameters and to recognize coupling. Further, a study was conducted to evaluate the effectiveness of this method in the development of functional requirements and the results indicate that this method is a viable tool in the need analysis stage. The advantage of Object Function Method is that the designer is able to put the design considered on paper by means of the objects and their interactions, this provides a clear view about the task at hand. By externalizing the problem, the designer can focus on specific issues in the design and enable divergent thinking of the problem.

5 THE CONCEPTUAL DESIGN STAGE

Conceptual design is the seminal phase in the engineering design process. This phase determines the level of product innovation, the efficiency of the product and the effectiveness of the downstream stages of the design process. It is the phase where creativity, engineering science and practical knowledge are brought together to develop innovative solutions that optimally address a given need. The goal of the conceptual design phase is to establish the core technical conceptual solution around which the remainder of the design is embodied. This is the stage where innovation has the largest leverage with respect to its influence on the quality of the final design.

Considerable research has been done on means for enabling designers to create designs in a systematic manner, to handle the complexities of a design, and to provide a platform for enhancing innovation and the effectiveness of the resulting design. The classic works of Pahl and Beitz [2], together with those of Ulrich and Eppinger [6], Cross [2], and Ullman [10], address the whole engineering design process. Research on creative and rational methods [2, 6], concept search techniques by French [14], creative problem solving techniques by Altshuller [25] and Sickafus [23] and parameter analysis models by Jansson [20, 21] have focused on the concept design stage of the engineering design process. The aim of their research was to enable designers to think creatively and to combine these creative ideas with engineering science to produce viable creative solutions. With this aim, and also to address the pedagogic goals of teaching the design process, a Concept-Configuration Model for the conceptual design phase was developed. This approach is based on the Parameter Analysis Model but with several key enhancements.

The activities in the conceptual design stage are shown in Figure 21. A decision starts with the most critically important of the solution-independent, lowest level functional requirements in the function structure. The designer will search for multiple (usually three) conceptually different solutions to this 'need'.

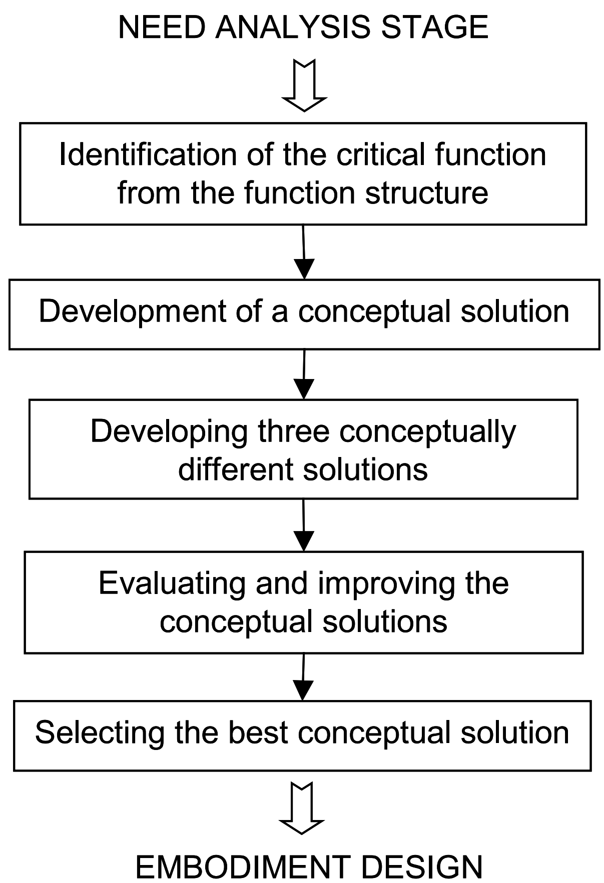

Figure 21: Activities in the Conceptual Design Stage

Briefly they are:

- Identification of functional need from the function structure:
  Based on the function structure developed from the need analysis stage, the lowest level solution independent function that is critical to the design is chosen.
- Development of a conceptual solution:

The chosen function now becomes the original need and the Concept-Configuration model is used to develop viable conceptual solutions. During this process, the critical issues of the design are identified and embodied. This is achieved by looping through the Concept-Configuration-Evaluation spaces in the Concept-Configuration model explained in the later sections of this section.

- Developing at least three conceptually different solutions:
  In this stage, at least three conceptually different solutions are developed using the Concept-Configuration Model and the looping process. This disciplined search for multiple, conceptually different solutions provokes the designer to be innovative and to think in domains that he/she would not normally explore. This enables innovation.
- Evaluating and improving the conceptual solutions:
  Once at least three viable conceptual designs are developed, they are compared with each other based on the selection criteria developed earlier in the design requirements. This highlights the strengths and weaknesses of each solution. The goal of the designer is to convert the weaknesses into strengths by either borrowing ideas from other solutions or by incorporating new ideas. The primary goal is to have at least three comparable and superior designs.
- Selecting the best conceptual solution:
  Based on the selection criteria developed, the designer along with the team is able to select the best solution that is suitable to be carried forward to the final design stages.

5.1 PARAMETER ANALYSIS

The conceptual design stage involves searching for the scientific principles and technologies that can potentially be exploited to satisfy a given design need. The generated concept is developed into a reasonable configurable solution by providing form and structure. The resulting configuration is evaluated with regard to how well it satisfies the design requirements. The outcome of the concept design phase is a fully developed conceptual design solution. The principles of Parameter Analysis are used as a conceptual design methodology as shown by Jansson [21], Condoor et al. [26] and Kroll et al. [27].

Parameter Analysis is a model for a cognitive thought process that consists of concept and configuration spaces as shown in Figure 21. These spaces can be thought of as domains where a particular mode of thinking and activity is performed. In Concept Space, thinking is in a fundamental scientific mode. The goal is to discover fundamental scientific principles or concepts that have the potential for development into configurations that will satisfy the given need. In Configuration Space, the thinking process is configurational and embodiment oriented. In this space the concepts are implemented physically and given form and structure. In this model, concept development can be viewed as an iterative process of oscillating from configuration space to concept space, making changes within the concept space, and then moving to new areas within the configuration space corresponding to further creative generation of configurations based on these ideas. The process of moving from concept space to configuration space can be thought of as realization or particularization – that is, bringing to reality in a particular physical form, technical concepts identified within the concept space. Movement from configuration space to concept space can be thought of as abstraction or generalization – that is, generalizing from the particulars of a specific physical configuration to a broader conceptual understanding in order to find a concept that can be used to improve upon the previous configuration. A good design practice advocated by this process is to consciously and sequentially move from one space to another in order to avoid fixation on solutions. This enables the designer to be receptive to innovative solutions.

As shown in Figure 22, there are three types of activity within Parameter Analysis. They form an iterative loop - Parameter Identification, Creative Synthesis and Evaluation. The first activity, Parameter Identification, consists primarily of the recognition of the dominant technical parameters or issues in the problem. The word 'parameter' in Parameter Analysis is used to describe any issue, factor, concept, or influence that plays a dominant part in developing an understanding of the problem and pointing to potential solutions. The second activity, Creative Synthesis, represents the generation of a physical configuration based on a concept recognized within the parameter identification step. Since the process is iterative, many configurations are generated as the process unfolds, not all of them are pertinent in the end. However, developing the physical configuration for a concept allows one to see new key parameters, which then stimulates a new direction for the process. The third activity, Evaluation, is an important step because one must consider to what degree a specific physical realization is a possible solution to the entire design task.

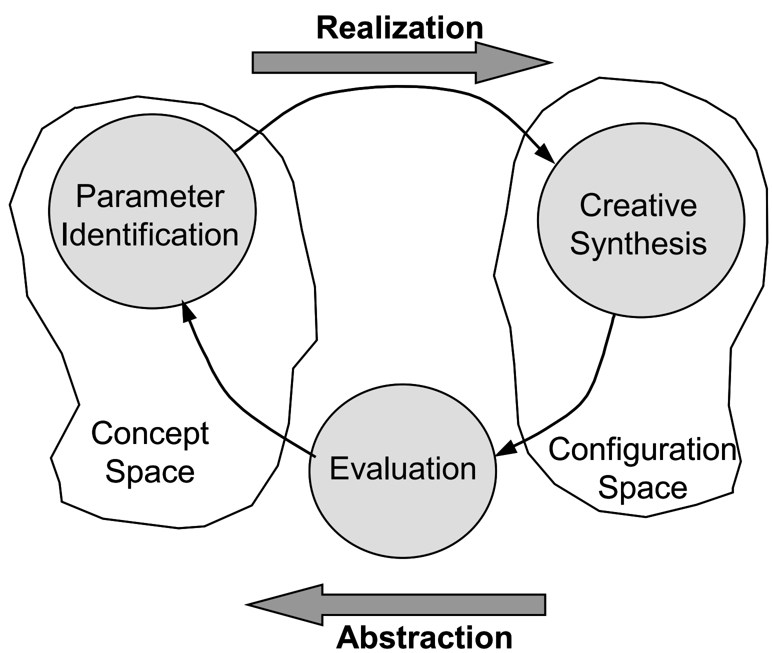

Figure 22: Parameter Analysis Methodology [21]

The major consequence of this approach is that the burden of creative activity is shifted from creative synthesis - generation of physically realizable configurations - to parameter identification. Also, this approach recognizes that a good design is a synthesis of a series of good ideas or concepts, rather than just one good idea.

5.2 CONCEPT-CONFIGURATION MODEL

A design methodology was developed at the Institute for Innovation and Design in Engineering, Texas A&M University [17, 18] to provide an effective means of teaching the design process to neophyte designers and also, to better understand the design process itself. This methodology incorporates methods and techniques from a variety of sources to provide a cohesive and comprehensive approach to the design task. The core of this approach is a design philosophy that emphasizes abstraction, critical parameter identification, and questioning. In the conceptual design stage of the design process the primary methodology is the Concept-Configuration Model, as shown in Figure 23.

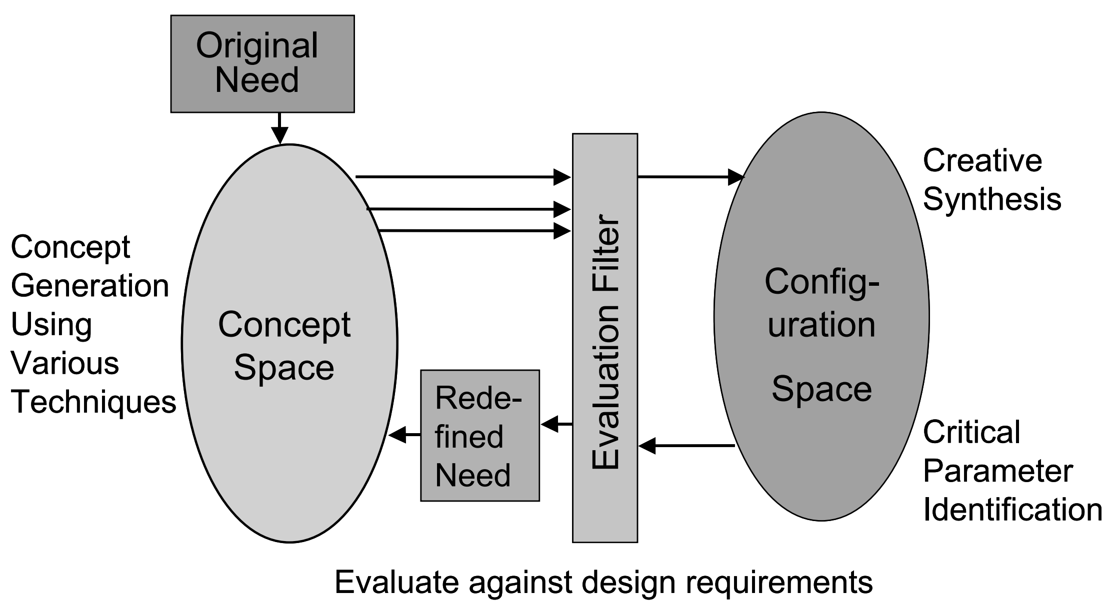

Figure 23: The Concept-Configuration Model

As seen from Figure 23, this model is primarily based on the Parameter Analysis model but with some key modifications and refinements that are discussed in the following paragraphs. In the Concept-Configuration Model there is a conscious, cognitive movement back and forth between Concept Space and Configuration Space. The Concept Space represents the ideas or concepts that can be used to satisfy the original need. The Configuration Space represents the embodiment of such ideas to provide form and structure.

Preceding the concept design stage is the need analysis (or problem formulation) stage. In this stage the core of the design problem is identified as the 'need statement'. The problem is then broken down into multiple levels of solution-independent functional requirements all of which must be satisfied by any solution to the given need statement. Each functional requirement has an associated design parameter and a primary constraint requirement. The key criterion for a good function structure is that all functional requirements should be solution-independent and should not be coupled [16]. The critical functional requirement is identified from the lowest level functions and this becomes the first input into the concept design stage as the Original Need shown in Figure 23. The key issue in the development of concepts is the identification of the critical parameter for the Original Need, where this parameter is the technical characterization of the function that must be performed.

The Original Need is carried into the Concept Space, where ideas, concepts, or scientific principles are discovered to satisfy the given need. Evaluation is performed on these concepts based on how well they meet the constraint requirements. A concept that passes this Evaluation is carried into the Configuration Space. In the Configuration Space, creative synthesis takes place and form and structure is given to the concept. During creative synthesis several configurations may unfold that may not be attractive for further development. The feasibility of any configuration is evaluated by identifying the critical parameter that must be met if that embodiment is to be successful in meeting the given 'Need'. In this model, evaluation is thus done both on the concepts and on the configurations with regard to how well these meet the design requirements. This is in distinct contrast to Parameter Analysis, where only the configurations are evaluated. During evaluation, the designer compares the performance capabilities of the proposed configuration to the desired capabilities. An objective evaluation allows the designer to separate the good designs from a number of plausible but inferior designs. Thus, designers can more readily focus their efforts on developing potentially good solutions and not invest time into developing the more mediocre designs. Additionally, the evaluation helps the designer gain new insights into the design task and identifies new parameters to be considered for the next round of concept searching.

The success of the evaluation lies in identifying from among many relevant parameters, the critical one that will make or break a design. This key parameter in the chosen configuration is identified through critical parameter identification. The critical parameter may be a weakness in the embodiment that creates conflict or one that will make it difficult for the embodiment to meet the quantified design requirements. Overcoming this weakness then becomes a new need that must be satisfied before the proposed concept can be considered acceptable. Addressing this weakness becomes the Redefined Need. The identification of this need is done using the methods mentioned in the need analysis stage, that is using abstraction, critical parameter identification and questioning to determine the real need. To meet this Redefined need, concepts or ideas are again generated and the looping process continues. As illustrated in Figure 24, this is an iterative process. The designer would be expected to traverse through three to four loops before a concept is either fully developed (and accepted as viable) or rejected as unsatisfactory.

Proper identification of the key parameter for both the Original Need and the Redefined Need is critical, as this parameter dictates the path for concept searching and consequently leads to effective and efficient concept design development. A good design practice advocated by this methodology is to consciously move in a sequential manner from one space (concept or configuration) to another. This enables the designer to be receptive to innovative solutions and not get fixated on one idea. This approach recognizes that a good design is frequently based not on one good idea, but is rather founded on synergistically combining a series of good ideas.

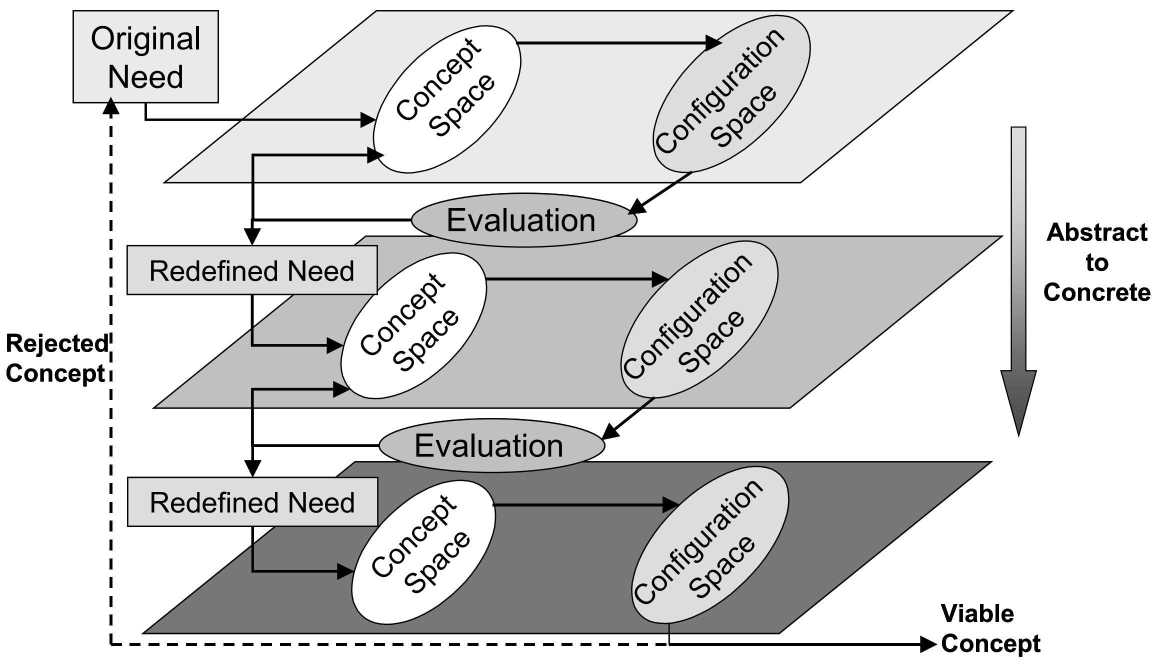

Figure 24: The Concept-Configuration Looping

Typically, in the conceptual design stage, three or more conceptually different competitive solutions are developed. Each of these has been cycled through the concept-configuration looping shown in Figures 23 and 24 to a stage where an objective evaluation of the proposed concepts is possible. The output of the conceptual design stage is a viable conceptual design that is selected by the designer based on a thorough evaluation.

5.3 CONCEPT EVALUATION AND SELECTION

One of the problems that a designer faces once the conceptual solutions have been generated is choosing the best solution with which to proceed. The two types of conceptual weaknesses [15] that are usually manifested are, the final concept chosen is weak due to lack of thoroughness in conceptual approach. Thereafter, no amount of attention to detail requirements will recoup the situation. The second type is when the final concept chosen is strong and the best possible within the constraints, but due to lack of thoroughness in the approach, the reasons for its strength are not known or fully understood. Hence, in order to minimize the possibility of the wrong choice of concept, it becomes essential to carry out concept evaluation and selection in a progressive and disciplined manner. This disciplined approach necessitates a number of rules and procedures, which when followed lead to significant improvements not only in concept formulation but also in selection.

5.3.1 Concept Evaluation Procedure

The procedure for concept evaluation and improvement has been adapted from the work done by Pugh [15]. The outline of the procedure is as follows:

1. Develop at least three conceptually different solutions to the design task at hand to the same level of detail in each case.
2. Establish a concept comparison and evaluation matrix, which compares the generated solutions with each other, against the criteria for evaluation. A generic matrix is shown in Table 5.
3. The evaluation criteria are based on the functional requirements and design requirements developed for the design task in the need analysis stage.
4. It is important that the criteria chosen should be unambiguous, concise and specific, quantifiable and independent of one another.

5. Choose a datum with which all the other concepts are to be compared. If a design or designs already exist for the product area under consideration like a benchmark product, these must be included in the matrix and always form the first datum choice.
6. When considering each concept or criterion against the datum, use the following legend:
    - A plus sign (+) means *better than*, *less prone to*, *easier than* and so on, relative to the datum.
    - A minus sign (-) means *worse than*, *more expensive than*, *more difficult to achieve*, *more complex* and so on, relative to the datum.
    - An 'S' sign meaning the *same* as datum is used when any doubt exits as to the whether the concept is better or worse than the datum.

Table 5: A Generic Evaluation Matrix

	Concepts		
Criteria	**1**	**2**	**3**
A	+	-	D A T U M
B	+	S	
C	-	+	
D	-	+	
E	+	-	
F	S	-	
Total +	3	2	
Total -	2	3	
Total S	1	1	

7. Make an initial comparison of the other concepts with the datum using step 6. This establishes a score pattern in terms of number of +'s, -'s and S's achieved relative to the datum.
8. Assess the individual concept scores. If certain concepts exhibit exceptional strength rerun the matrix with the strengths removed.
9. Try to improve the -'s in each of the concept solutions by readdressing those concepts based on the solutions with +'s or S's.
10. If a strong pattern of concepts does not emerge, change the datum if the datum is one of the solutions, and reassess the pattern.
11. Repeat steps 7 through 10 till one particular concept persists. Let the emergent strong concept be continued forward to the next stage.

Having completed the initial evaluation comprising a number of runs, the designer would have acquired,

- Greater insight into the requirements of the specification;
- Greater understanding of the problem;
- Greater understanding of the potential solutions;
- An understanding between the interactions between proposed solutions, which can give rise to additional solutions;
- Knowledge of the reasons why one concept is stronger or weaker than another.

5.4 DISCUSSION

The conceptual design stage is the key stage that determines the level of innovation for the design. The Concept-Configuration Model is the primary method in this stage. Some of the key points emphasized by the Concept-Configuration model in order to be innovative and effective are (1) Proper critical parameter identification, (2) Oscillate between the Concept and Configuration Spaces, and (3) Positive communication between Concept-Configuration-Evaluation spaces. One of the issues in the methodology is the evaluation of the outputs. One of the main reasons attributed to the difficulty in generation of solutions to the need is the inadequate identification of the critical function and its critical parameter, which is used as the original need for the Concept-Configuration looping. The difficulty in concept stage could be to an extent attributed to the lack of thoroughness in approach in the previous stages. The concept selection process in effect addresses the quality of conceptual solutions and enables the designer to revisit the solutions and to improve upon them.

6 CONCEPT SEARCH TECHNIQUES

One of the drawbacks to the Parameter Analysis model is the combination of critical parameter identification and concept searching into one activity of Parameter Identification. In the Concept-Configuration Model, these activities are consciously separated. Identifying the redefined need addresses parameter identification, and by feeding it back into the concept space, the concept searching is addressed in the Concept Space. By doing this, concept searching does not become restrictive as in the Parameter Analysis model. In fact the search is opened to include many of the traditional techniques like brainstorming, analogic thinking, patent searches [2, 6] and newer problem solving techniques like TRIZ [25] and USIT [23]. As postulated by Cross [1], the combination of creative methods and rational methods provide an ideal platform for the designer to generate concepts and simultaneously provoke his/her creativity.

Presently there is a need for concept search techniques within the Concept Space of the Concept-Configuration Model. As seen in the previous section, in the concept-configuration looping, a concept is progressively developed into a feasible conceptual solution. This is achieved by cycling through the Concept and Configuration spaces alternatively. There is a progressive change in the type of need that is to be addressed as the designer moves down through different levels of looping. Initially, at the start of the process, the Original Need is defined by a solution independent critical function that is to be satisfied. Hence, this leads the designer to identify the fundamental principle or effect that could achieve the task. As this concept is developed in the configuration space, the critical parameter that is a weakness in the embodiment is identified. A new redefined need is identified to address this weakness. This need is at a configuration level, that is, it addresses the configuration of the chosen concept. This is different from the Original Need, which was solution independent. As the designer cycles through each loop, the need progressively changes from a solution independent abstract form to a more configurational solution dependent form. In order to be effective and efficient in solution searching, the types of solution space or domains that the designer searches for concepts or ideas to address the given need would have to account for this progressive change of the need. The primary goal in this dissertation is to address the above requirement. This has led to the development of a cohesive set of techniques and methods that enable the designer to provoke creativity and promote idea generation within the framework of the IIDE design methodology. Some of the basis and inspiration for the techniques are described in the following section.

6.1 BACKGROUND

6.1.1 TRIZ – 40 Principles

The Theory of Inventive Problem Solving or the Russian acronym TRIZ is a knowledge-based systematic approach to problem solving developed by Genrich S. Altshuller [25]. This method is drawn from the analysis of inventions from various industries, technologies and fields of engineering. TRIZ involves a systematic analysis of the system to be improved and the application of a series of guidelines for problem definition. TRIZ classifies innovative problems and offers corresponding problem-solving methods for each class of problem. Altshuller observed that there are 39 "Standard Features," - standardized names for the many thousands of parameters that engineers, scientists and technical professionals use to describe a technical system. He also observed that there are only 40 Inventive Principles behind all existing patents, and that these principles address each of the 1,521 possible standard technical conflicts that are possible (39 times 39). In other words, for each conflict between two standard features, there are one or more inventive principles that serve as a generic solution.

A designer or problem-solver first formulates the problem in the form of a technical conflict. Formulation of the problem in "conflict" form means that if the initial problem were solved by changing one parameter (or standard feature), some other parameter (or standard feature) would then become worse. Hence, by identifying the technical conflict, the designer, based on a matrix developed by Altshuller could identify the set of 40 principles that could be used to solve the problem.

Some of the 40 principles are: Segmentation, taking out, asymmetry, nested doll, equipotentiality, changing of color, dynamics, periodic action, skipping, feedback and so on.

6.1.2 USIT Solution Techniques

The Unified Structured Inventive Thinking (USIT) developed by Sickafus [25] is a structured process for setting up and attacking technological problems. It is primarily based on the Systematic Inventive Thinking (SIT) developed by Horowitz and Maimon [24]. The SIT method was initially based on TRIZ and was further worked upon and modified to its present form. The primary techniques used in USIT are the Closed-World (CW) Method, the Particles Method and the Solution Techniques. The Solution Techniques are similar to the 40 principles used in TRIZ in that they are used to identify potential solutions. The difference here is that USIT does not employ any technical contradiction. The USIT approach analyzes the problem into three components: objects, attributes and functions, and each of the techniques are organized to apply to the components. The solution techniques are:

- Uniqueness – applies to all three components in identifying unusual characteristics
- Dimensionality – applied to the attributes
- Pluralization – applies to identifying solutions in objects
- Distribution – applies to the functions
- Transduction – applies to attribute-function-attribute chains.

6.2 CONCEPT SEARCH TECHNIQUES AND THE METHODOLOGY

In order to be optimal, the search techniques would have to take into account the progressive transformation of the need from a conceptual solution independent form to a configurational solution dependent form. The techniques for searching of concepts based on fundamental principles and effects, and the domains one could search for these concepts are shown by various researchers like Pahl and Beitz, Ullman and French [2, 10, 14]. The 40 principles of TRIZ [25] and the Solution Techniques of USIT [23] apply to problems that are more configurational. In this dissertation, these techniques are brought together and modified to fit the requirements of the IIDE methodology. The 40 principles of TRIZ have been modified into four groups based on the frequency of suggestion and applicability in the TRIZ matrix. These four groups are: Pluralization, Transformation, Dimensionality and Self-Help. The Uniqueness technique from USIT is modified to apply to the aspect of functions and its parameters and is represented as Spatial and Temporal Functionality. The contribution of this dissertation is the unique organization and implementation of the concept search techniques in the IIDE design methodology. The techniques and the method for using them to search for concepts are shown in Figure 25.

The concept search techniques are layered into four stages:

1. Stage 1: This consists of the techniques to Search for fundamental principles and Simplification. These techniques enable the designer to search for concepts and principles that he/she could use to address the solution independent functional requirement. The output from this stage is a set of ideas or concepts that the designer could use to develop them further and are taken into configuration space for development.
2. Stage 2: This contains the technique of Spatial and Temporal Functionality. This enables the designer to look for solutions in spatial and temporal domains of the function. The solution techniques in this stage are optimally placed between

stages one and three, as the solution spaces they address are neither conceptual nor too configurational. This stage typically comes into play when the designer has taken a concept from stage 1 through one loop and has identified a redefined need. The designer now starts his search for concepts for the redefined need in stage 2. The outputs of this stage are solution sets that address the given need and are taken through a second concept-configuration loop.

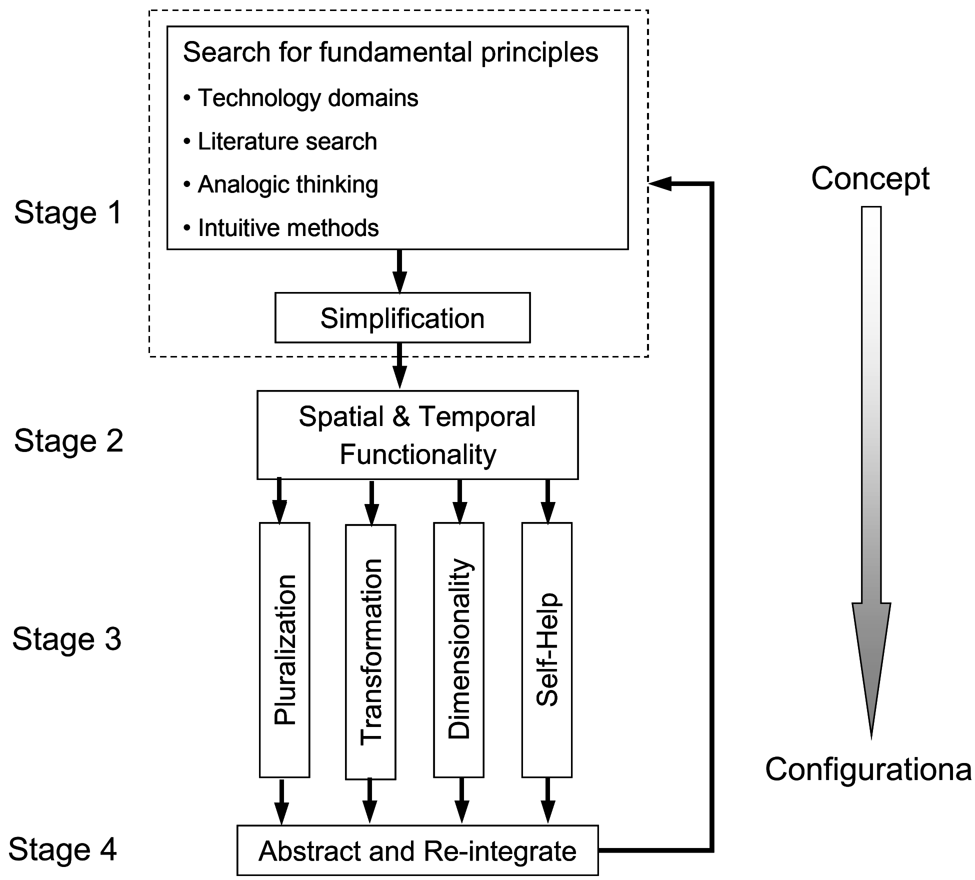

Figure 25: The Concept Search Techniques

3. Stage 3: This consists of the techniques of Pluralization, Transformation, Dimensionality and Self-Help. These techniques enable the designer to search

for solutions when the need is in a more configurational form. These techniques are typically used for solution searching when the designer has progressed in his looping process and the concept has been developed significantly. The techniques address weaknesses in the embodiments of the functions and provide the designer with solution sets. The areas they typically address in the embodiments of the design are form, shape and material. These techniques are grouped together and shown in parallel in Figure 25. This indicates any one or a combination of these techniques could be used to search for solutions.

4. Stage 4: This consists of the techniques to Abstract and Re-integrate. If, after going through the above three stages, the designer still has not found any satisfactory solutions, he/she could abstract and restate the need. In effect the designer consciously reverts to the basic design skills and works towards clarifying the need. As before, this enables the designer to break out of paradigms and by restating the need, he/she opens up solution sets that were not considered earlier. The results from this stage are fed back to stage 1 to continue the process of concept searching.

The details and the usage of the above stages are illustrated in the following sections.

6.2.1 Stage 1 - Search for Fundamental Principles

Initially when the designer looks for ways to address the solution independent functional requirement (original need), he/she starts by searching for concepts, fundamental principles or effects that will enable a to be designed device to perform the needed function. The fundamental principle is the basis on which the concept is developed further into a potential solution. Hence the identification of a proper effect or principle becomes extremely critical.

The designer asks the question "How can I achieve the given function?" By looking for principles that could at a conceptual level address his/her need, the designer is able to identify a concept to develop further. The areas and domains in which the concepts or fundamental principle can be searched or identified are:

Technology search: Look for 'physical principles' or effects in various technological domains like mechanical, electrical, magnetic, hydraulic, chemical and natural. This involves having knowledge of the principles, within each technology so that the designer is able to recall them. Other ways of accessing such information is by talking to experts in those domains or searching in handbooks or databases that lists these principles.

Literature search: Look into published literature, technical journals and search patent databases. Patent literature is generally a good source of ideas. Altshuller developed his principles and methods by analyzing numerous patents [25]. There are two main types of patents: design patents and utility patents. Design patents cover the look or form of the idea in a visual sense. The term utility is effectively synonymous with function because they cover how the device works, not how it looks. For the designer, searching in utility patents is preferable when looking for concepts for achieving the function. The designer could also search in reference books or trade journals. Many good ideas are published in trade journals that are oriented toward a specific discipline. Some are targeted to designers and thus contain information from many fields.

Analogic thinking: Look at analogies in other domains or systems. Analogies are useful in studying the behavior of the system and providing additional solution sets. Typically, a designer remembers or sees a solution that is used in another product or domain, and then a thought arises, "How can I use this idea to solve my problem?" Such cross referencing of solutions from other domains and identifying the fundamental concept in that solution, leads to adding of ideas that are used to solve the current problem. A good approach is to identify the task (as a solution independent FR) that needs to be performed. Then search in other domains where similar tasks occur. The way that this task is performed is identified, adapted and modified for implementation as a new conceptually alternate solution for the original need. One rich domain for such analogs is nature. Nature is and has been an inspiration to many a designer when searching for ideas to solve a problem. The development of VELCRO fastener in 1940s by George de Mestral is one such example. He noticed that his dog's coat and his pants were covered with cockleburrs. His curiosity led him to study the burrs under a microscope, where he discovered their natural hook-like shape. This was to become the basis for a unique, two-sided fastener - one side with stiff "hooks" like the burrs and the other side with the soft "loops" like the fabric of his pants. The result was VELCRO brand hooks and loop fasteners, named for the French words "velour" and "crochet."

Intuitive methods: Designers often discover solutions for problems by intuition, that is, solutions come to them in a flash after a period of search and reflection [2]. These solutions suddenly appear as conscious thoughts and often their origins cannot be traced. There are several methods of encouraging intuition and opening paths by the association of ideas. The simplest and most common of these involves critical discussions with colleagues. Provided such discussions are focused and do not stray from the original task. These methods are typically based on persistent activity of constructive questioning and involve group dynamics to generate the widest possible range of ideas. The methods rely strongly on the stimulation of memory and on the association of ideas that have never been considered in the current context. Some such intuitive methods are: Brainstorming, Synectics, Gallery Method, Delphi Method and Method 635. One of the advantages of such methods is the involvement of people from various fields leading to generation of a wide range of ideas. The major disadvantage of these methods is that the ideas generated are not focused to the problem at hand and may lead to lots of ideas being rejected. However if these ideas are transformed to 'concepts' through effective abstraction, they can be classified and evaluated. The effective usage of concept-configuration looping is a powerful tool for opening thoughts and recognizing associative ideas, thus enabling intuition.

6.2.2 Stage 1 - Simplification

This technique is part of stage 1 and goes along with the search for fundamental principles. The activity in this step enables the designer to simplify the fundamental concept or principle identified, based on analogy or technology search, to fit the current need and task considered. For example, when a designer has identified a solution in a particular product that addresses his need. The designer would then automatically start to think how he/she could apply that solution to his need. This would require the designer to think at a conceptual level. This process of extracting the conceptual basis from a specific product solution, so that it could be applied to the given need is addressed by Simplification. At another level, when a designer has identified a fundamental principle, but needs modification from its abstract conceptual form, so that it could be applied to the given problem is again addressed by Simplification. Often the designer does this process subconsciously or unknowingly when searching for ideas. The separation of this technique externalizes the thinking process and forces the designer to focus on the problem at hand. The search for fundamental principles typically addresses the designer's question, "How can I achieve this function?" The simplification technique addresses the question, "How can I use this potential solution to my design problem?" In effect this forces the designer to focus the search for concepts. This process may be characterized as 'convergent thinking' when the designer searches a wide field of fundamental principles for concepts and rapidly converges to those best suited to the need. The other aspect is 'divergent thinking' when the designer based on a particular configurational solution, performs abstraction and extracts the conceptual basis of the solution to widen the search for concepts. This is in keeping with the spirit of the IIDE methodology which aims to enable a designer to perform effectively, efficiently and innovatively.

Consider a simple example: there is need to transport cars from point A at one elevation (say at the bottom of a hill) to point B at a different elevation (say at the top a hill). Based on the analogies of the canal example, ideas for the solutions for the transportation of the car could be found by using the technique of simplification. A continuous road would be similar to the Suez Canal where there is a continuous water medium. An escalator type of solution would be similar to the Panama Canal, which uses locks in its design, in this case the steps would be analogic to the locks. Then the canal solution used at Ronquiéres could be analogic to a cable car carrying one vehicle at a time. The technique of simplification involved extracting the conceptual basis in each of the canal solutions and applying it to develop solutions to the transportation of the car.

6.2.3 Stage 2 - Spatial Functionality

This technique in Stage 2 enables the designer to search for ideas or concepts by examining the spatial domains of the function or the need to be addressed. By asking questions like, “Where does the function perform?” By examining the various characteristics of the function spatially, the designer provokes idea generation. This enables the designer to consider solution sets and domains that have not been considered before. For example, a function could be performed at another location or the function could be divided into many functions which perform at different locations. The placement of this technique in stage 2 is relevant because this technique is not at a conceptual level but at the same time is not configurational.

The technique of spatial functionality is grouped into four categories: Space, Order, Periodicity and Shape [23]. The designer, by Questioning in these areas and by using heuristics provokes ideas and thus, opens up solution sets for consideration. This is illustrated in the following paragraphs.

Space: a metaphor for position, location, area, volume, and existence. The designer can generate solutions by considering heuristics to trigger solutions, like:

- Introduce space: make a function depend on its location
- Increase space: delocalize functions
- Remove space: make a function independent of location
- Modify space: change the location of the function
- Control space: prevent motion; fix the path of motion

Order: a metaphor for composition, alignment, array, the antithesis of disorder, and chaos or randomness. The heuristics are:

- Introduce order: group by function or parameters
- Increase order: unite functions
- Decrease order: have fewer functions per object
- Remove order: introduce randomness, chaos or complexity
- Modify order: rearrange functions to other objects
- Control order: use a template

Periodicity: a metaphor for pattern, repetition, symmetry and uniformity, the antithesis of irregularity, unbalance or asymmetry. The heuristics are:

- Introduce periodicity: periodic placement
- Increase periodicity: change from a triangle to a star or to a cube
- Decrease periodicity: make functions asymmetric
- Remove periodicity: introduce unbalance
- Modify periodicity: change a pattern and frequency
- Control periodicity: make copies or clones

Shape: a metaphor for size, fit, finish contour, image and topography. The heuristics to consider are:

- Introduce shape: change straight line to curves; linear to non-linear
- Increase shape: go to higher order functions
- Decrease shape: go to lower order functions
- Remove shape: convert shape to lines or planes
- Modify shape: consider compound shapes
- Control shape: keep the shape flexible

A turn-signal shaft used in cars operates the turn-signal at one end; at the other end it is used to operate the windshield wiper switch. This indicates the implementation of the Spatial Functionality, specifically spatial separation of the two functions. Another similar example is that of a pencil which is used as a writing instrument at one end and as an eraser at the other end. The function of writing and erasing are separated in space utilizing the same object, in other words it is spatially separated. An example that illustrates the implementation of change in shape to solve a problem is that of a bolt head on top of a fire hydrant. Typically, bolt heads are hexagonal in shape. In order to remove the possibility of ordinary people handling the bolt head using regular wrenches, the shape of the bolt-head was changed to a pentagon.

6.2.4 Stage 2 - Temporal Functionality

This technique in Stage 2 enables the designer to search for ideas or concepts by examining the temporal aspects of the function or the need to be addressed. By asking questions, “When does the function perform?” and by examining the various characteristics of the function temporally, the designer provokes idea generation. This is similar to Spatial Functionality but it addresses the temporal aspect. Together with Spatial Functionality, the two techniques enable the designer to consider solution sets and domains that have not been considered before.

This technique is grouped into four categories: Time, Sequence, Periodicity and Rate [23]. By performing Questioning and based on heuristics, similar to Spatial

Functionality, the designer is able to generate ideas and consider new solutions. The usage of the heuristics in the four categories is illustrated in the following paragraphs.

Time: a metaphor for occurrence, instance, event and growth. One of the ways is to examine the active/inactive periods of the function, alter the temporal aspect of the function or control the time dependence. The heuristics to consider are:

- Introduce time: change a constant to a variable, introduce temporal aspect
- Increase time: increase time available to a function
- Decrease time: decrease time available to a function
- Remove time: change a variable to a constant, remove temporal aspect
- Modify time: alter the way the functions use time
- Control time: make a function time dependent

Sequence: metaphors for program, plans, clock and phase. The heuristics to consider are:

- Introduce sequence: partition multiple functions in time
- Increase sequence: increase the partitioning of time available to functions
- Decrease sequence: consolidate time intervals
- Remove sequence: remove partition of functions in time
- Modify sequence: change the order, consider pre- and post- actions of the functions
- Control sequence: control phase of a function

Period: a metaphor for alternation, harmony, rotation, cyclic or the antithesis of disorder. The heuristics to consider are:

- Introduce period: perform the function in a cycle
- Increase period: decrease frequency of when the function occurs
- Decrease period: increase frequency
- Remove period: introduce randomness
- Modify period: change frequency or period

- Control period: synchronize the occurring of the function.

Rate of events: a metaphor for speed, progression and learning. The heuristics to consider are:

- Introduce rate: allow uniform changes of a function
- Increase rate: allow less time per unit of the function
- Decrease rate: provide more time to perform the function
- Remove rate: make the function to occur constantly
- Modify rate: change the rate of occurrence
- Control rate: control the functional rate

Some examples that indicate the implementation of the temporal functionality are shown. When the lock of door is considered, it is active only when the door is closed and inactive when the door is open. Now, the hinge of a door is used only when the door is open. Thus, the hinge and the lock can be combined together as the operation of the two are temporally separated. This indicates the usage of examining active and inactive periods of the function.

6.2.5 Stage 3 - Pluralization

The technique of Pluralization, Transformation, Dimensionality and Self-Help are grouped in Stage 3. These techniques enable the designer to search for solutions when the need is based on a configuration. That is, the need is to address the weakness in a given embodiment or of an embodiment of earlier concepts. By Questioning and the use of heuristics the designer provokes ideas and opens solution sets. Some questions are, "How can I use pluralization to solve the need?" and "Can I introduce pluralization, by distributing the functions over the objects?"

The technique of Pluralization refers to the act of distributing functions over a set of objects. This technique is further broken down into various aspects for the designer to consider. They are:

Distribution: separate functions over objects or their parts; make an object easy to disassemble; increase the degree of fragmentation or segmentation.

Consolidation: unification of functions into fewer objects. Using the same object for multiple functions in different/same space or time.

Copying: using clones or parts of objects in performing the function. Use simpler, inexpensive copies and replace an object or process.

Examples of implementation of Pluralization are:

- Nitroglycerin is a very unstable mixture that is susceptible to mechanical shock. Alfred Nobel divided the nitroglycerin into many tiny volumes, each individually suspended within a porous inert material. This stabilized the nitroglycerin against shock and thus dynamite was produced. Thus, the technique of Pluralization was used to solve the problem.
- A single wedge can be used as a height adjuster, but when stacked as multiple wedges and combined it leads to a screw thread.
- A button, used as a device to open and close, when taken to the extreme of many buttons, leads to a zipper.

6.2.6 Stage 3 - Transformation

This technique enables the designer to search for solutions by looking at converting functions or the environment or both into other forms. By asking questions such as, “How can I convert the function to another form?” “How can I make the environment beneficial?” or “How to convert harmful nature to a more useful form?” These questions enable the designer to discover solutions. Other aspects of this technique that the designer should consider are:

Transform material properties: change materials; modify homogeneity or color or other aspects; change porosity; use composite materials.

Transduction: transform a parameter of a function into another by means of other functions.

Transition: change dimensions from 2D to 3D; go from linear to rotary motion; use spheroids; change phase of the given media; use phase transition e.g., modify the material state from liquid to gas or solid to liquid.

Modify the environment: Convert harmful nature to useful, e.g., by changing it to inert, vacuum or insulated; make the environment neutral.

Some examples that show the implementation of the Transformation technique are:

- Consider the flow of fluid through a pipe. The need is to create a mobile valve to isolate zones, so repairs on the pipe can be carried out with minimum loss of time. By considering the technique of transformation (specifically transition), a solution to freeze the liquid at both ends of the repair zone was discovered. The frozen sections act as valves while the repair was being carried out.
- An example of utilizing the technique of transformation (specifically transduction) is shown. To measure temperature by means of an electric charge, a combination of thermal expansion and piezoelectricity could be used to perform the required task.
- Utilizing lightweight and high strength composite materials is an example of usage of transforming material properties to solve the given need.

6.2.7 Stage 3 - Dimensionality

This technique enables the designer to search for solution sets by attacking the parameters or properties of the functions. By using heuristics and questions, the designer is able to discover solution sets. The various aspects of this technique that the designer could explore are:

Change the parameter: changing the property of the function or the parameter that is used to perform the function. These could be physical properties of the function like elasticity, concentration, strength, rigidity, etc.

Introduce a new parameter: by introducing a new parameter on the function the designer could achieve his/her task.

Substitution of a new parameter: replacing a parameter that is used to perform the function with another.

Examples that show the usage of Dimensionality are:

- The function of indicating an incoming call to the user of a cellular phone is usually done by a ring tone. This function can also be achieved by using vibration, when ring tones are not appropriate. This is an example of the technique of Dimensionality where the parameter – audio signal (ring tone) is substituted with a vibration.
- Vulcanizing of rubber to change its flexibility and durability is an example of changing the property of functions.

6.2.8 Stage 3 - Self-Help

This technique enables the designer by looking at the function or its parameters to serve itself by performing helpful actions. By using heuristics and questions on this technique the designer is able to discover solution sets. The various aspects of this technique that the designer could explore are:

Introduce feedback: this could be used to amplify or negate the function; changing the magnitude or influence of the function.

Reuse waste resources or energy: this involves reutilizing other resources to perform the function like "cogeneration."

Examples that show the usage of this technique are:

- Feedback is used in control systems to reduce error and noise. This utilizes the technique of Self-Help.
- Cogeneration in power plants involves reusing of heat for other purposes illustrating the use of Self-Help.

6.2.9 Stage 4 - Abstract and Re-integrate

In Stage 4, the techniques that are involved are Abstract and Re-integrate. During this stage, the need or task to be solved can be abstracted and re-stated for further clarification and insight. If the designer finds difficulty in searching for solution sets, the given need, which is at a configurational level, is abstracted and restated in a new form. This not only helps in avoiding fixation but also opens new solution domains that were not previously considered. This technique is primarily based on the process of Abstraction and Questioning. Utilizing the design philosophy and this kind of thinking provokes the designer into looking for solutions in domains that have not been previously considered, thus enabling innovation. The resulting ideas are again fed back into stage 1 and into the concept search cycle.

The process of converging to specific solutions and then, by abstraction, diverging the solution space to a wider field enables the designer to gain a better understanding of the design need. This is similar to the process in concept-configuration looping where the designer oscillates between the concept space and configuration space. In this case, the designer performs the convergence and divergence of solution spaces in the concept space. This oscillation between convergence and divergence enables the designer to become receptive to ideas and consider newer domains and solutions, thus enabling innovation.

6.3 EXAMPLE: TUNABLE FIBER BRAGG GRATING

In order to illustrate the application of the various Concept Search Techniques, the various design solutions developed to meet the requirements of a Tunable Fiber Bragg Grating are considered. In each of these solutions, the various fundamental principles and search techniques that have been used for the development of the solutions are identified and illustrated.

6.3.1 Bragg Grating Fundamentals

Optical fiber gratings are key components in modern telecommunications for controlling the paths or properties of traveling light. Basically, optical fibers are thin strands of glass capable of transmitting an optical signal containing a large amount of information over long distances with very low loss. They are small diameter waveguides comprising a core having a first index of refraction surrounded by a cladding having a second (lower) index of refraction, as shown in Figure 26. Typical optical fibers are made of high purity silica with minor concentrations of dopants to control the index of refraction.

Optical gratings are important elements for selectively controlling specific wavelengths of light within optical systems [28, 29]. Such gratings include Bragg gratings, long period gratings and diffraction gratings. Such gratings typically comprise a body of material and a plurality of substantially equally spaced optical grating elements such as index perturbations, slits or grooves.

A typical Bragg grating comprises a length of optical waveguide, such as optical fiber, including a plurality of index perturbations equally spaced along the waveguide length.

These perturbations selectively reflect light of wavelength λ_B (Bragg wavelength), which is based on the grating spacing Λ between successive perturbations and the effective refractive index n_{eff} of the propagating mode as shown in Figure 26 and listed in equation 1. This relationship in equation 1 is also known as the Bragg grating resonance condition. Light of wavelengths other than the Bragg wavelength essentially passes unimpeded through the grating.

$$\lambda_B = 2\, n_{eff}\, \Lambda \tag{1}$$

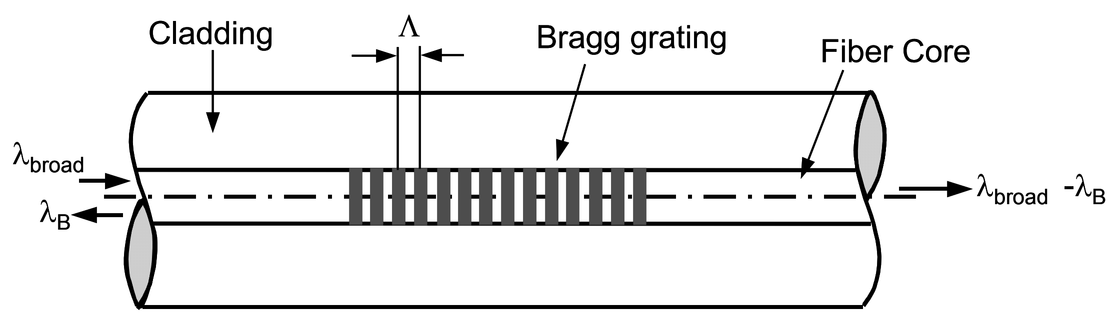

Figure 26: Schematic of a Simple Bragg Grating in an Optical Waveguide

The Bragg resonance condition depends on strain and temperature. The shift in Bragg wavelength with strain and temperature can be expressed as [28, 30],

$$\Delta\lambda_B = 2n\Lambda\left(\left\{1-\left(\frac{n^2}{2}\right)\left[P_{12}-\nu\left(P_{11}+P_{12}\right)\right]\right\}\varepsilon + \left[\alpha + \frac{\left(\frac{dn}{dT}\right)}{n}\right]\Delta T\right) \tag{2}$$

Where ε is the applied strain, P_{ij} coefficients are the Pockel's (piezo) coefficients of the stress-optic tensor, ν is Poisson's ratio, and α is the coefficient of thermal expansion (CTE) of the fiber material (e.g., silica), and ΔT is the temperature change.

Basically, there are two ways in which the Bragg wavelength can be changed or shifted. One way is to affect a required change in the grating spacing Λ and the other is to change the n_{eff}. Applying a strain on the fiber changes both the grating spacing Λ and the refractive index. The change in refractive index is due to the elasto-optic effect of the fiber. Other methods by which n_{eff} can be changed are: thermal methods by using the thermo-optic effect; or by changing the refractive indices of the core or cladding. The general 'rule of thumb' for the refractive index is $n_{eff} \approx (n_{core} + n_{cladding})/2$. Hence by controlling the refractive indices of cladding or core, one could effectively change n_{eff}.

The application of tunable Fiber Bragg Gratings (FBG) is primarily in optical telecommunications, where the FBG's are placed inline within the optical fiber. By varying the central wavelength (Bragg wavelength) λ_B of the FBG, signals of selected wavelengths can be filtered from the main telecommunication signals. The operating range of the telecommunication wavelengths is between 1530nm – 1565nm [28, 29], the bandwidth of each signal is 0.8nm. Other general requirements for the tunable FBG's are that the accuracy should be within ± 0.1nm and the device should have a quick response time (<1ms).

The primary constraint is the required operating range of the FBG; in some cases multiple FBG's of different central wavelengths are used to encompass the operating range. The central wavelength of each FBG can be tailored during the manufacturing of the FBG and then the FBG's can be tuned within the operating range.

In order to illustrate the usage of various principles and techniques, some embodiments of solutions for tuning the FBG are discussed in the following sections.

6.3.2 Mechanical Straining Solutions for Tuning of a Fiber Bragg Grating

One of the primary methods used in the tuning of FBG's is to change the grating spacing by straining the fiber. The methods induce tensile strain or compressive strain in the fiber and this changes the grating spacing. Some of the solutions that achieve the above requirement and are based on different fundamental principles or effects are shown below.

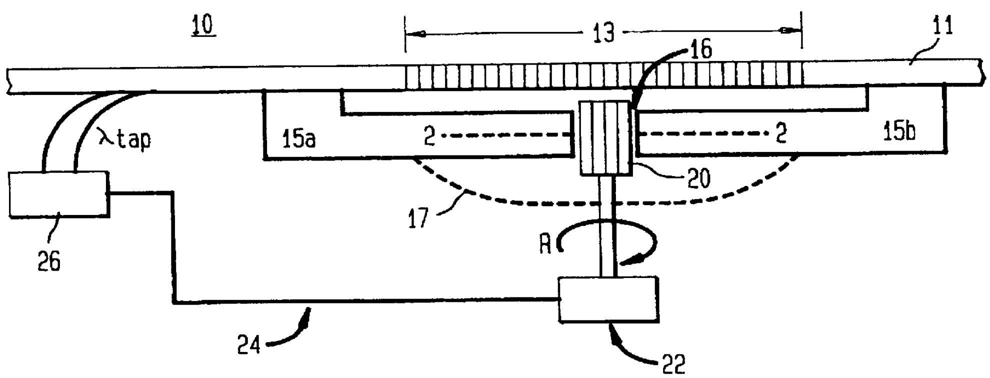

Figure 27: Electro-Mechanical Solution for Tuning a FBG by Inducing Tensile Strain [31]

Electro-Mechanical Tuning: In order to tune the Bragg wavelength, the grating spacing is changed by producing a tensile strain in the region of the fiber that contains the FBG. Electro-mechanical tuning involves using an electrical input and converting it to a mechanical (physical) displacement. An implementation of this method is shown in US Patent 5,999,671 [31]. This patent uses electro-mechanical means of inducing strain and is shown in Figure 27. Referring to Figure 27, the tunable device 10 comprises of an optical fiber 11 having a long-period grating (FBG) region 13. The FBG region is secured onto two rigid, load carrying bodies 15a and 15b. The bodies 15a and 15b are geometrically separated by a gap 16 but are mechanically coupled (pulled together) by a biasing element 17. In the gap, a wedge 20 is placed which upon actuation provides a predetermined (or programmed) amount of displacement or separation between the two load-carrying bodies 15a and 15b. This displacement induces a strain on the FBG thus tuning the FBG for the required wavelength. The wedge is coupled to an actuator 22, which is a linear DC servomotor. A feedback system 24 and wavelength detector 26 are coupled to the motor to complete the system.

In Figure 28, the parts A through C illustrate various configurations of the wedge 20, each showing the cross-sectional side views taken along the line 2-2 of Figure 27. Part A shows the wedge having a smooth but non-spherical configuration. This indicates the usage of *Spatial Functionality* in the modification of shape to achieve the desired variations. Part B shows the wedge having a circular configuration but with a plurality of protrusions on its outer surface to produce step-wise variation in the circumference. This configuration illustrates the usage of the technique of *Pluralization* and *Spatial Functionality*. Part D shows a linear-moving wedge with step-wise edges to produce the required displacements. This indicates the usage of *Spatial Functionality* and *Transformation* because linear motion is used to produce the required displacement whereas, in the previous two cases, circular motion was used.

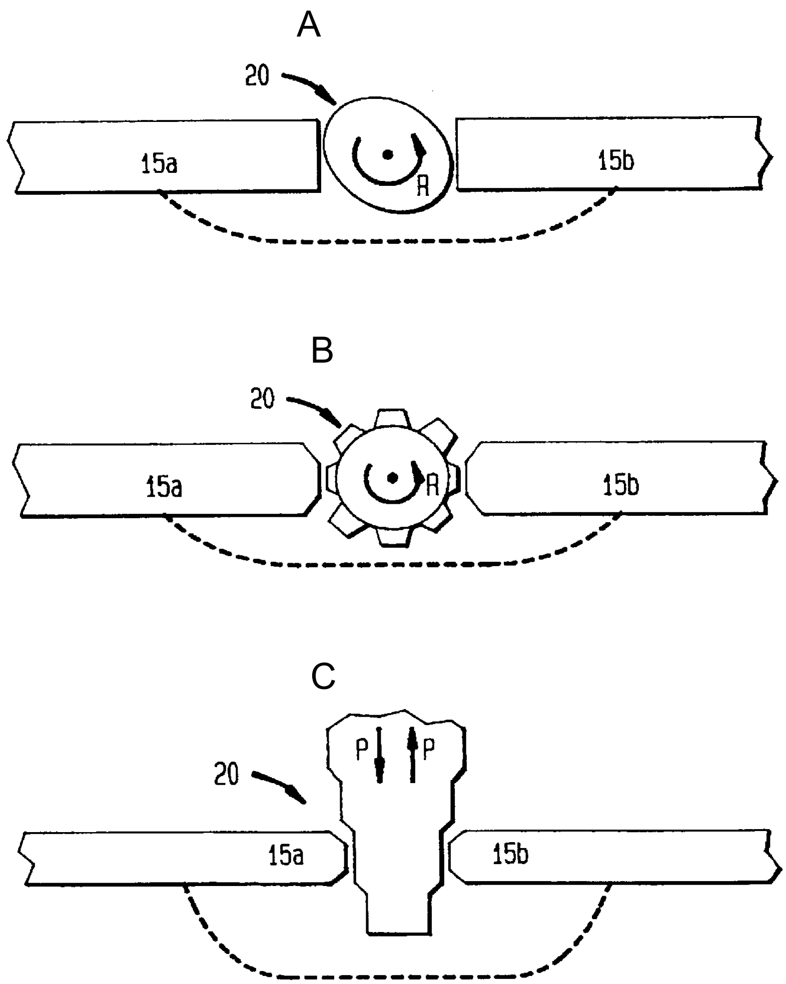

Figure 28: Configurations of the Wedge in the Electro-Mechanical Solution [31]

In the configuration shown in Figure 29 [32], the tuning of the FBG is achieved by inducing strain on the FBG by using mechanical displacement by means of threads. Referring to Figure 29, the optical fiber 31 is shown with a grating section 32 enclosed by a coaxial tubular member 33. The strain control members are shown at 34 and 35, and are fixed to the fiber at points 36 and 37. Adjustment member 34 is provided with thread 41, which engages thread 42 on one end of member 33. Adjustment member 35 is provided with thread 43, which engages thread 44 on the other end of tubular member 33. The thread counts between the two threads are different in order to produce fine displacements. Various methods could be used to activate the threads, like a rotary motor. The above embodiment is similar to the ones in Figure 28, in this case the actuation uses a thread instead of a wedge. This embodiment illustrates the implementation of *Pluralization* technique.

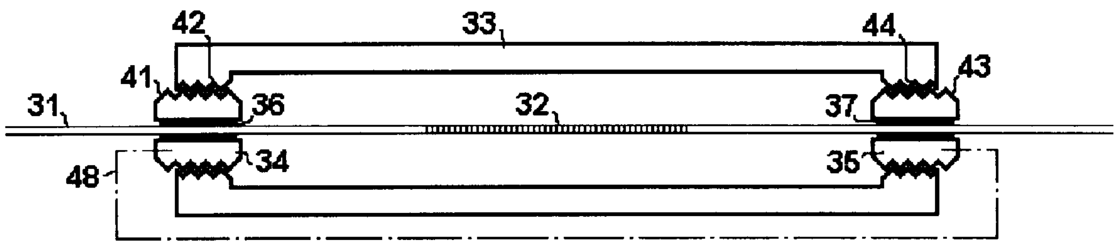

Figure 29: Solution Using a Mechanical Threaded Member to Induce Strain for Tuning a FBG [32]

Magnetostrictive Tuning: In this solution, the principle used is that of Magnetostriction. This refers to the change of dimensions of a ferromagnetic material when it is placed in a magnetic field. Specifically, the Joule effect deals with the change in length of a ferromagnetic material along the axis of the applied magnetic field when this field is changed. An implementation of this method is shown in US Patent 5,999,671 [31]. Figure 30 shows a schematic arrangement of a magnetostrictive solution. Referring to Figure 30, a tunable long-period grating device 10 comprising a length of optical fiber 11 that contains a grating region (FBG) 13 with a plurality of perturbations 12. The fiber at the grating region 13 is secured at region 18 to a body 14 of magnetostrictive material which transmits compressive or tensile strain. The body 14 is a cylinder concentrically surrounding the fiber grating region 13. An electromagnet (solenoid) 19 is placed adjacent to the body 14 for providing a controllable magnetic field to strain the body along the direction of the fiber grating. Application of short duration magnetic pulses can be used to alter the length of body 14 and hence the length (and spacing) of the attached fiber grating 13.

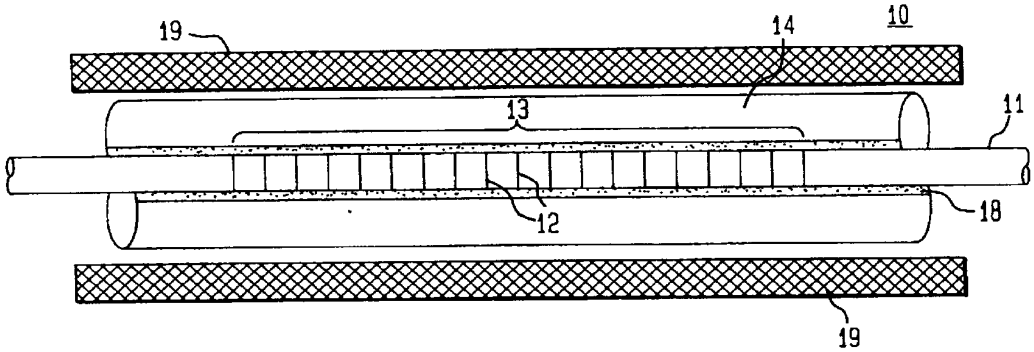

Figure 30: Tuning of FBG Using Magnetostrictive Solution [31]

The magnitude of magnetostriction depends on the materials used for the body 14. However, the magnitude of magnetostriction could be amplified by altering the physical dimensions of the body 14. In order to be able to tune to a wider range of wavelengths, the strain has to be increased (based on this embodiment). The implementation of *Spatial Functionality* and *Transformation* techniques is shown in Figure 31, where the length of the body 14 is increased to amplify the strain induced. The body 14 has a length l_2, and the grating region has length l_1, here length l_2 is substantially longer than l_1. The fiber 11 is attached adjacent to substrate 60 at point A, and attached to the magnetostrictive body 14 at point B. The magnetostrictive body is attached to the substrate at point C. With this configuration, the magnetostrictive strain on the fiber is amplified by the ratio of l_2 / l_1. One of the drawbacks in this device is that the dimensions of the device increases with increasing amplification.

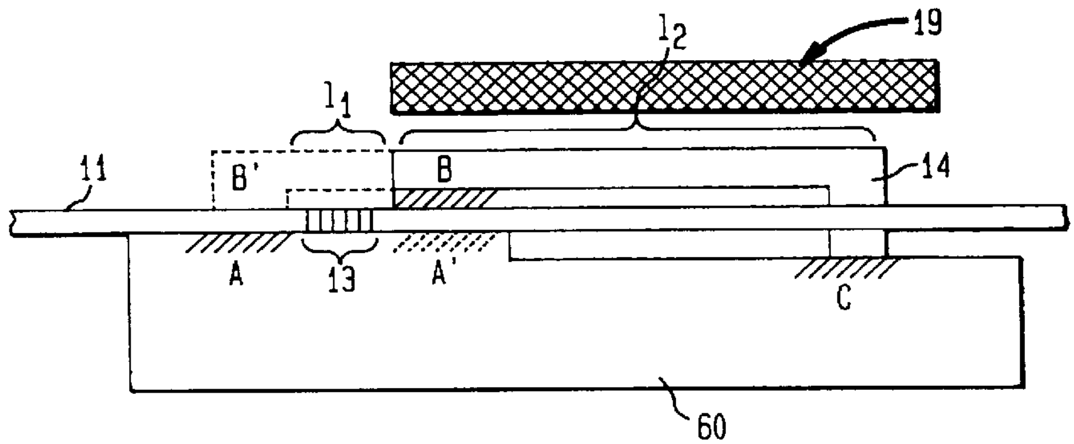

Figure 31: An Embodiment to Amplify Strain for the Tuning of FBG Using Magnetostrictive [31]

Figure 32 shows an alternate arrangement for amplifying the magnetostrictive strain. The magnetostrictive body 14 comprises a stack 70 of interconnecting and alternating non-magnetic layers 71A, 71B, 71C and magnetostrictive layers 14A, 14B, 14C. This way the total length of the layers is increased without increasing the length of the device. The electromagnet 19 is placed adjacent to the layers and the bodies are attached at region 18. The above embodiment indicates the usage of *Pluralization* in achieving the amplification of magnetostrictive strain without increasing the length of the device.

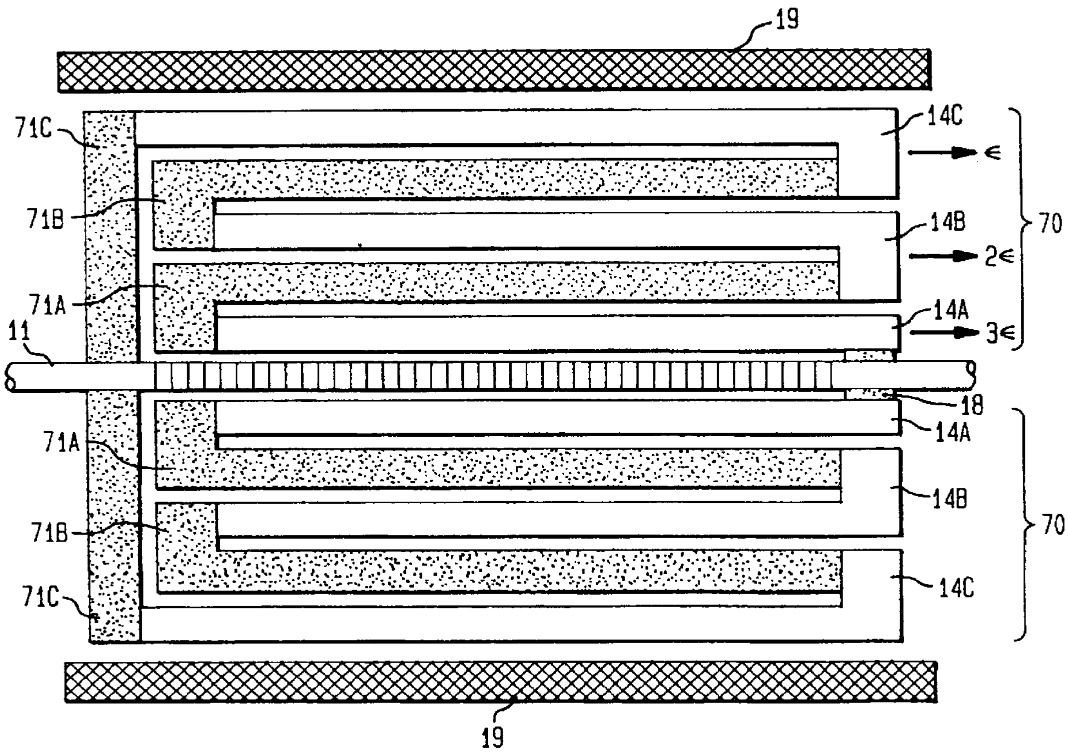

Figure 32: An AlternateEmbodiment to Amplify Strain for the Tuning of FBG Using Magnetostrictive [31]

In order to span a large range of tunable wavelength, many gratings with different center wavelengths and tuning ranges are placed within an embodiment. This implementation shows the usage of *Pluralization* and is illustrated in Figure 33. Referring to the figure the various gratings are 12A to 12H, which are mounted on two different magnetostrictive bodies 14A, 14B at the attachment regions 18e. Each of the gratings have a different Bragg wavelength and tuning ranges to encompass the overall tuning range.

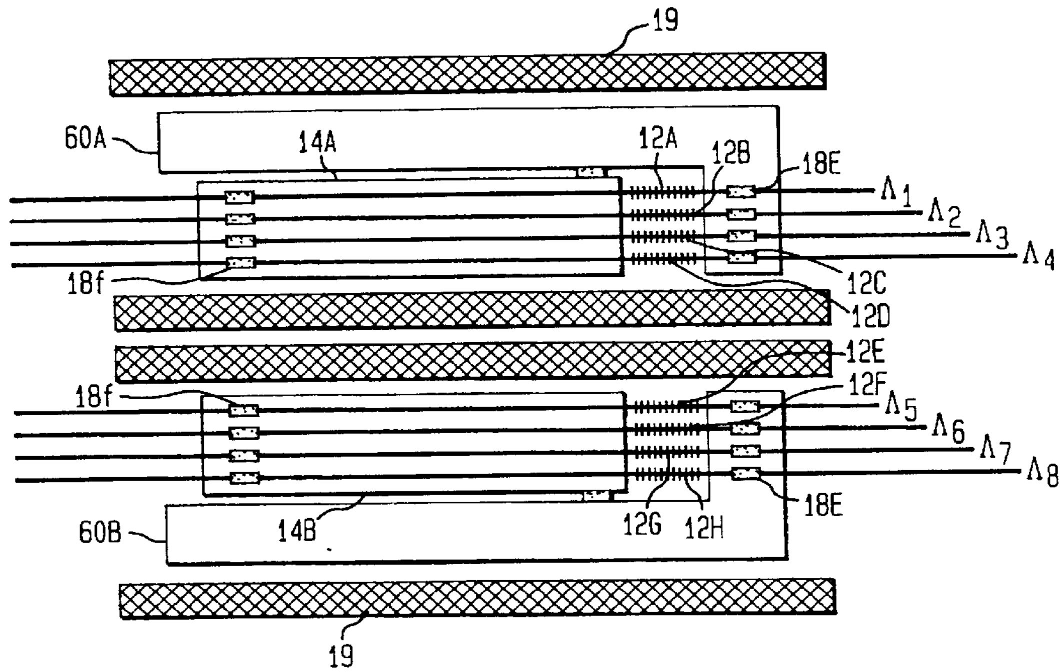

Figure 33: An Embodiment for the Tuning Plural FBG Using Magnetostrictive [31]

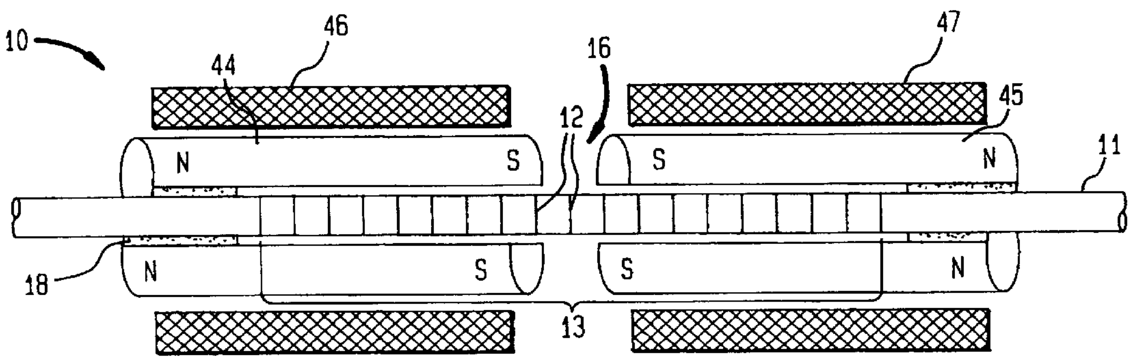

Figure 34: An Embodiment for Magnetic Strain Tuning of FBG [31]

Magnetic-Force Tuned Gratings: In this solution, magnetic repulsion or attraction, such as the use of ferromagnetic or its components, is used to induce strain in the fiber grating. Referring to Figure 34, the tunable fiber grating device 10 comprises of a length of optical fiber 11 including a grating region (FBG) 13. The fiber is secured at the attachment region 18 to pair of magnets 44 and 45 having a small gap 16 between them. The magnets have their poles aligned in opposing directions, and hence the application of the magnetic filed will force the magnets apart from each other producing a tensile strain in the fiber.

Mechanical Tuning Using Piezoelectric Effect: In this solution the fundamental principle or effect used is the Piezoelectric effect. Certain crystals become electrified when subjected to compression or tension. The electric charges developed on the faces of the crystal are proportional to the pressure. This effect is reversible, that is, an electric field alters the shape of the crystal producing tension or compression. An embodiment that uses the solution is used in US Patent 5,007,705 [33] and is shown in Figure 35. Referring to Figure 35, a piezoelectric cylinder 15c is utilized to stretch a length of optical fiber 16 that is wound around the circumferential surface of the cylinder. The optical fiber 16 includes the fiber section 11 having the Bragg grating embedded in it. The fiber 16 is stretched and the Bragg grating is tuned as the cylinder 15c expands with an application of an electrical signal, generated by a source 17. The above embodiment illustrates the use of *Transition*, where a cylinder is used to induce strain. Other embodiments could use a linear stack of piezoelectric elements to which a section of the fiber 16 containing the grating is bonded at each end of the stack. By application of an electric signal to the piezoelectric stack, a tensile strain is induced in the fiber. This illustrates the use of *Pluralization* where multiple piezoelectric elements are used. Other arrangements similar to the cylinder configuration, where the FBG is strained using circular or radial configurations are shown in US Patent 6,240,220 [34].

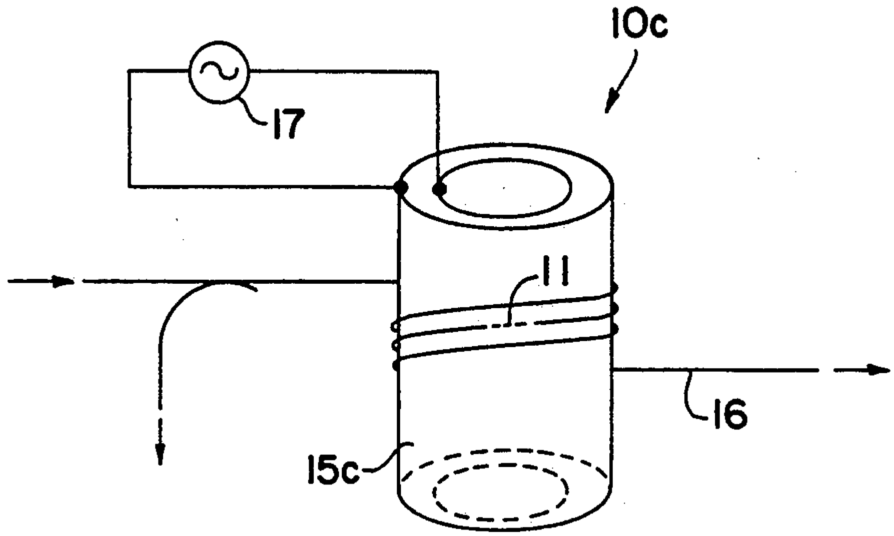

Figure 35: Mechanical Tuning of FBG Using the Piezoelectric Effect [33]

Other Fields and Effects: US Patent 5,007,705 [33] illustrates the usage of other fields and effects to tune the FBG. By using special coatings on the fiber section, which contains the Bragg grating, the application of various fields could be used to tune the FBG. The coating could be sensitive to modulating magnetic fields (e.g., Nickel coating), electric fields (e.g., Poled PVF_2 coatings), or acoustic fields. The above solutions show the variety of fundamental principles and effects that are used in tuning a FBG by straining the fiber.

6.4 CASE STUDY: NEEDLE COUNT DESIGN

The following example is provided to illustrate the process in the Concept-Configuration Model and the concept search techniques. Some details have been omitted but the critical information that is needed to carry out the task has been provided.

6.4.1 Background

During surgery, careful count is kept of all surgical needles before and after the operation to ensure that no needles are accidentally left behind. A surgical needle package consists of eight needle-suture combinations wrapped in a foam package. If any package contains either seven or nine needles it poses an unacceptable risk for miscounts of needles at the start of surgery. It is therefore imperative for the needle manufacturer to ensure that precisely eight needles are present inside each package. So, before shipping, verification that a package contains the correct number of needles is critically important.

In manufacturing, needles and sutures are manufactured separately and then combined to make a needle-suture combination. The required number (eight) of such needle-suture combinations are packed in a foam package and sterilized at the end of the process. At the start of the process, the needle-suture combinations are manually counted and placed in the package. An operator prepares a package in 30 seconds. Typically, 15 operators are at work at any one time.

Some of the needles are extremely delicate and small. They are made from 420 stainless steel, with a length of 0.859 ± 0.005 inches and a diameter of 0.018 inches. The needles are curved at an angle of 160 degrees. The suture is made from polyglactin – a polymer. The suture diameter is 0.006 – 0.010 inches, and the suture length ranges between 17.3 – 19.8 inches.

6.4.2 Need Analysis

A brief Need Analysis stage is explained to show the design process. The first step in a Need Analysis is to pose some questions through which we can gain insight into the design task. In this example, relevant questions would be:

- What is the purpose of the device/system and why is it required?
    - The purpose is to count the number of needles

  - To ensure that the correct number of needles (eight) are present in the package
- When is the device/system required?
  - It is required after the package is closed (ensuring correct number of needles are present in the closed package)
  - Checking before or after packaging, as long as, the correct number of needles are present (questioning the previous requirement and modifying it)
- Where is the device/system to be used?
  - In a manufacturing environment
- What constraints does the environment impose?
  - Clean room conditions
  - Should not affect time for packaging
- Who is the user/consumer?
  - Operator
- What constraints do the suppliers impose?
  - They cannot maintain accurate tolerances on the suture and foam package.

Using this information, the following Need Statements can be developed iteratively,

- Count the needles in real-time without opening the package.
- Determine whether the correct number of needles are present in real-time.
- Ensure the correct number of needles in each package without affecting production cycle time.

Notice the increasing level of abstraction and increasing precision in the definition of the task to be performed. The Need Statement went from being specific and constraining ("count without opening") to a more abstract form that has more clearly defined the scope of the design task.

The Function Structure developed from the final Need Statement is shown in Figure 36. This identifies the various functional requirements that must be met. These have been organized into a layered structure of primary or level 1 and secondary or level 2 functions that are carefully worded so as to be solution-independent. The FA's represent the functional alternatives of the FR 2.1: Measure property.

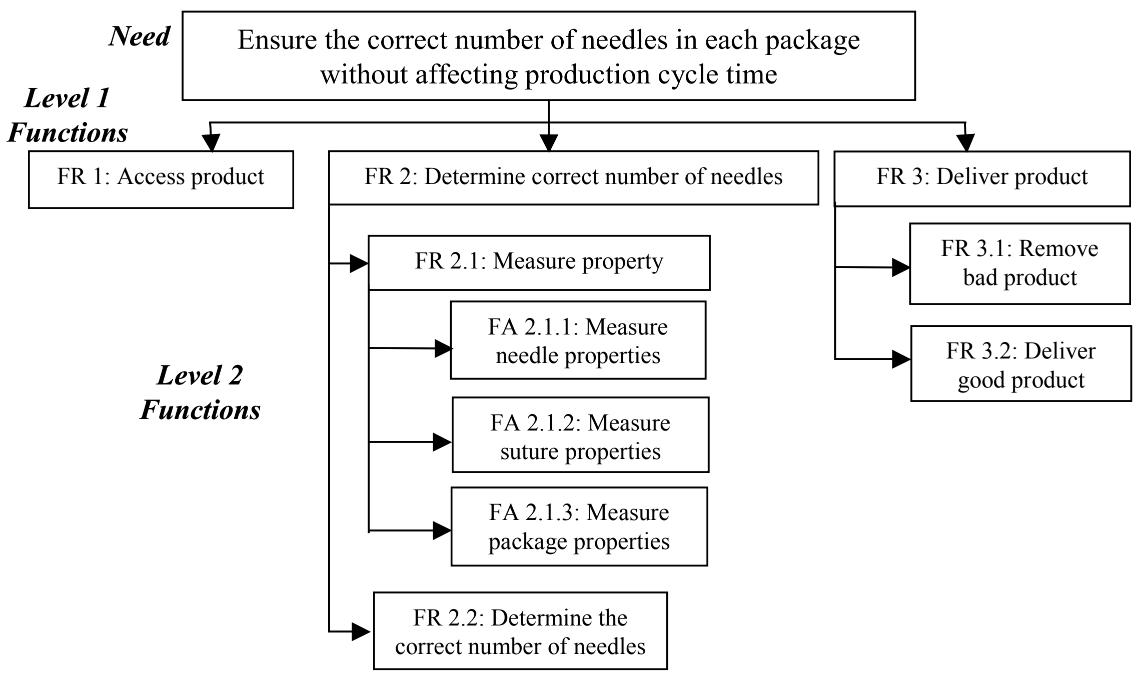

Figure 36: Function Structure for the Needle Count Example

Through critical parameter identification, certain issues that strongly influence the design task can be identified. These include:

- Mass, volume and surface area are some of the parameters that can be measured for the needle-suture combination;
- Mass of the package can be measured;

- Weighing the package or measuring the suture properties will not give the desired discrimination. As the manufacturing tolerances in the foam and suture are too large.
- Any of the needle properties should give the desired discrimination between 7, 8 and 9 needles. That is, from the measured value it is to be determined if there are less than 8, equal to 8 or more than 8 needles.

Hence, the critical functional requirement that must be met for the design to work is, "Measure property." The function and the associated critical parameter is, "Ability to measure properties *and provide the required discrimination between 7, 8 and 9 needles*."

6.4.3 Concept Generation

The next step is to generate concepts that satisfy the critical function and address the critical parameter. The properties that could be measured for the needle-suture combination are:

- Needle (420 stainless steel): Physical – weight, size and volume; Electrical; Magnetic; Capacitance; Thermal; and Visual.
- Suture (Polymer/natural fiber): Physical – weight and dimensions.
- Foam Package (paper and foam): Physical – weight, size and volume.

It has already been noted that tight tolerances are difficult to maintain for the sutures or the foam packages. Weighing the needle, suture and foam package combination is therefore unlikely to be satisfactory, as discrimination between 7, 8 and 9 needles is required. The option is to focus on the needle (420 stainless steel) alone as manufacturing tolerances can be maintained. Hence, the areas best explored for potential concepts relate only to the needles. Using the search for fundamental principles, the technology domains that can be utilized are listed:

- Physical measurement – Measuring physical aspects like weight, size and volume. This would be difficult as the weights of suture and package also come into play.

- Visual measurement – Use of X-ray or digital imaging techniques enable distinguishing and measuring the needles.
- Electrical – Measuring needle properties via eddy currents or electromechanical means.
- Magnetic – Measuring needle properties by using magnetic methods.
- Capacitance – Measuring needle properties by using capacitance methods.
- Thermal – Measuring needle properties by means of thermal methods. This may be difficult to pursue as it may damage the needle or suture.

For the sake of brevity, only the development of the magnetic concept is pursued and described below.

6.4.4 Magnetic Solution

The evolution of a magnetic solution using the Concept-Configuration Model is given below.

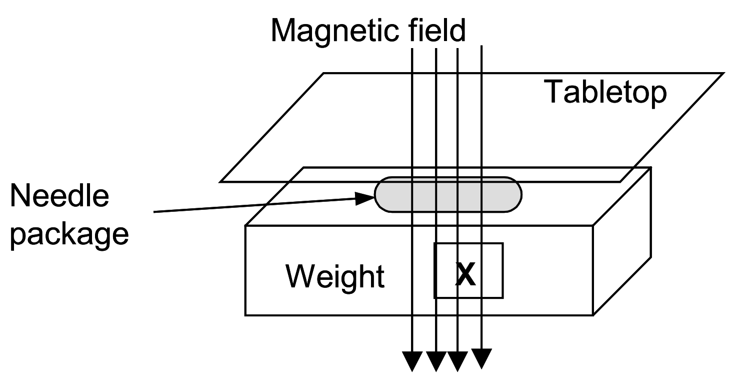

Figure 37: Schematic Arrangement of the Magnet and the Needle Package

Loop 1:

Concept Search (CS): From technology search, the idea is to measure the magnetic properties of the needle by laying the package in a magnetic field.

Configuration (CFG): Measure the magnetic force on the needles; Apparent Weight = Gravitational pull on package + magnetic force on the needles. Using a weighing scale in this configuration, the package is placed on the scale and a magnetic field is brought on the package. This configuration is shown schematically in Figure 37.

Evaluation and Critical Parameter (EVAL): The magnetic field increases the force exerted by the needles on the scale while not influencing the apparent weight of the package or sutures. As a result, discrimination is better. The tolerance of the package still has significant impact.

Loop 2:

CS: Using the techniques of Simplification and Temporal Functionality, the solution is to eliminate the effect of the tolerance of the package by measuring the magnetic attraction before packaging.

CFG: The operator places the needle-suture combination without the packet on the weight table. The operation is similar to loop 1.

EVAL: Discrimination is improved, but the variability of the suture length still affects the measurement.

Loop 3:

CS: Using the technique of Simplification and Temporal Functionality, eliminate the influence of the suture by subtracting its weight.

CFG: Weigh the needle-suture combination twice. Once in the presence of a magnetic field and once without the field present. The value would indicate the effect of the needles only.

EVAL: Discrimination is better and this method can also be used after packaging. The drawback is – two weighings increase the cycle time.

Loop 4:

CS: By Abstracting and Questioning: "Is there another way to measure the magnetic force?"

So far the magnetic force was measured on the needles with the needle-suture combination on the weight table. This increased the number of measurements as shown previously. In order to reduce the number of weighings and to find a better way to determine the effect of the magnetic force on the needles, the need is abstracted and re-stated. Another way of measuring the magnetic force is to measure the force of attraction on the magnet itself instead of the needles. This idea is arrived at by using the technique of Spatial Functionality.

CFG: The operator places the needle-suture combination on a table. The magnet is placed on the weighing scale. The arrangement is shown in Figure 38. The force of attraction, when the needles are placed on the tabletop and come into the magnetic field, is measured by the change in weight shown by the weigh scale.

EVAL: This method can also be used after packaging the needles. Experiments reveal that the needles become oriented in the magnetic field. This results in a loss of discrimination or needle gets damaged when they are in the package.

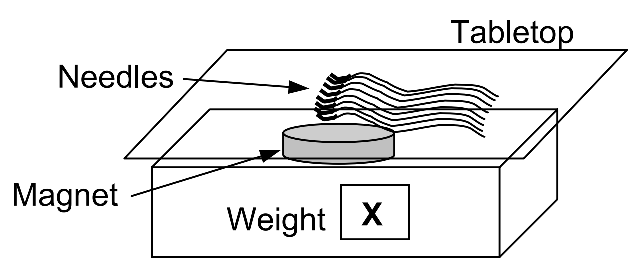

Figure 38: Schematic Arrangement of the Magnet and the Needle-Suture Combination

Loop 5:

CS: Controlling the orientation of the needles in the field can eliminate the needle damage. This can be achieved by changing or controlling the magnetic field. This solution is achieved by applying the technique of Transformation on the magnetic field.

CFG: A uniform field can be created by using a powerful rare-earth magnet and placing the needles within a certain distance from the magnet.

EVAL: This method provides a reliable needle count. This can be implemented before or after packaging. It requires calibration and demagnetization of the needles.

At this point, the key issues that would have to be addressed in developing a magnetic solution have been thoroughly explored. The iterative concept-configuration looping process that was followed has: (1) provided the designer with a deeper understanding of the task; and (2) built up the designer's confidence that the proposed conceptual solution is viable and worthy of being carried forward. The magnetic solution can now be set aside and attention can be focused on developing other conceptual alternatives (visual, electromechanical, capacitance, etc.) through a process similar to that followed above.

6.5 CREATIVITY STRATEGY

Creativity is an integral part of the conceptual design phase and is the primary driver for innovation in the design process. The ability to take a creative idea into a viable creation is the hallmark of an innovative engineering designer. Creativity can be thought of as a process of making unconventional associations between mental objects, resulting in novel and useful solutions. Within the field of creativity research, considerable work has been done in categorizing the creative process [35]. The significant influence on the definitions of the creative process has been Kneller's five-stage model [36]. The stages in the model are 'first insight', 'preparation', 'incubation', 'illumination', and 'verification.' The above works have influenced primarily the theoretical content of the creative thinking module [37]. The work that has influenced the efforts of Jeffries et al.

[37] is that of Robert Dilts on Creativity Strategy [38, 39]. Dilts developed this strategy primarily through his study of Walt Disney as an innovator and genius. The goal was to develop a model by which creativity could be better understood and taught to others. By studying innovators, he tried to capture their way of thinking into a model. The result is his Creativity Strategy.

The model is separated into three distinct phases: Dreamer, Realist, and Critic. The three phases work in a sequence: the work generated in the Dreamer phase is sent to the Realist, who in turn passes it to the Critic, and who feeds it back to the Dreamer. This cycle through each of these phases continues as shown in Figure 39. Although each phase is distinct, the cyclic nature of the process in the Creativity Strategy stresses the importance of each and their dependence on each other. No one phase is more important than another in the overall scheme of things.

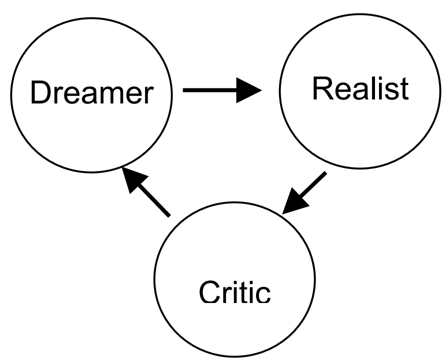

Figure 39: Creativity Strategy

The Dreamer Phase is the first phase of the model. It can be characterized by the question, "What if …?" with the emphasis on "Anything is possible." The aim of this phase is to generate as many concepts and ideas, and to select the ones with most potential. The Dreamer is not concerned with what is practical or possible, only with imagining what could be. In other words, if we could do anything what would we do?

Having selected an idea or concept, this is then given to the Realist. The Realist now tries to turn the idea selected by the Dreamer into a practical and feasible solution. The Realist phase can be characterized by the question, "How could …?" The emphasis here is on how to make the idea work and the aim is to create a specific and practical solution. This solution is then turned over to the Critic. The Critic is all about evaluation. The role of this phase, on one level, is of rejection and criticism. On another it is about feedback, with emphasis on positive and constructive criticism. The role of the Critic can be characterized by the question, "Yes, but …!" The Critic is there to point out all the things that the Dreamer or Realist may not have considered.

Having gone through the cycle once: from Dreamer, to Realist, to Critic, the concerns and issues that the Critic has raised are fed back to the Dreamer, for a second cycle. Now with the scope more focused, the Dreamer can generate ways to better address specific issues. The cycles continue till a level of resolution has been reached that best satisfies the overall objectives of the project under development.

The similarities between the Creative Strategy and the Concept-Configuration Model described here are obvious. The Dreamer Phase in the Creative Strategy is similar to the Concept Space, the Realist is similar to the Configuration Space, and the Critic is similar to the Evaluation. From the Concept-Configuration Model we find that to be truly innovative and effective, one has to maintain unambiguous and supportive communication between the three phases, the procedures of abstraction and critical parameter identification enable in doing that. It is particularly interesting to note that Dilts has independently come up with a creativity model similar to the Concept-Configuration Model. This further lends credence to the Concept-Configuration Model as a framework that encourages innovation in the conceptual design stage of the design process and, provides a good platform and framework for the designer to efficiently develop innovative and effective solutions.

6.6 DISCUSSION

The key to effective and efficient concept searching is the identification of the principal function and the critical parameter associated with that function. This is the basis for searching of concepts. If the critical parameter is not identified properly, it leads the designer onto the wrong path thus wasting time and resources. The goodness of the output from the Concept Design Stage depends on the goodness of the input it receives from the Need Analysis Stage. Hence, when the designer finds difficulty in developing concepts for the given need, one of the reasons could be a lack of thoroughness in the identification of the principal function and critical parameter. The Concept Search Techniques along with the methodology shown bolster the aim of enabling the designer to be efficient, effective and innovative in the design process. As shown in this section, the Creativity Strategy is strikingly similar to the Concept-Configuration Model. This strategy further emphasizes the importance of effective communication between the Concept-Configuration-Evaluation spaces.

7 ASSESSING THE EFFECTIVENESS OF THE DESIGN METHODOLOGY

The engineering design methodology developed at the Institute for Innovation and Design in Engineering (IIDE) at Texas A&M University adapts, incorporates and integrates methods and techniques from a variety of sources to provide a cohesive approach to the design process. The core of this approach is a design philosophy that emphasizes abstraction, critical parameter identification, questioning, and a cognitive process of concept-configuration looping. This philosophy, along with the design process, is taught in senior undergraduate and graduate engineering design courses at Texas A&M. The students understand and experience the design philosophy and apply the design process to real-world design projects provided by industry partners.

The methodology has evolved over a period of several years into what it is today and will undoubtedly continue to evolve and improve in the future. The evolution process is driven largely by feedback from current and former students and from the technical staff of the industry partners. Ongoing research into design methods is another important source for enhancements and improvements to the process. The final designs produced and the feedback from the staff of the industry partners provides one mechanism for assessing the effectiveness of the design methodology. The designs produced by the student teams are also assessed independently for their quality by the participating faculty and by senior-level engineering managers from the partnering companies. These assessments consistently and strongly suggest that the process described is effective and efficient, and encourages innovation. Indicative of the success of the program is the return, year after year, of the industry partners with new and significant design challenges for the student teams. A typical academic year cycle sees over a dozen different projects being conducted with over 100 students enrolled for the two-semester design sequence.

Despite all the positive feedback that has been received over the years, it was felt to be desirable to perform a systematic comparative evaluation to determine the effectiveness of the design methodology. All senior students in mechanical engineering take two sequential design courses and are exposed to the design process and methodology. A truly comparative evaluation between two groups, one familiar with the methodology and the other not, would be extremely difficult to accommodate and would require changes in the curricula. However, two different sets of students are available; those that have yet to formally take the senior design sequence and those that have formally taken one semester of the two design course sequence and are familiar with the design methodology. Importantly, there are no pre-existing differences between the two sets. All students would have taken the required courses prior to starting the senior design course sequence, which they take in their final year. Having identified these two sets of students, the next step was to identify what critical aspects of the methodology needed to be evaluated. Finally, a design challenge had to be formulated that both sets of students could capably perform within a reasonable time period. This led to an evaluation that focuses on the need analysis and conceptual design stages, and usage of the core techniques of abstraction, critical parameter identification, and questioning in these early phases of the design process. The required output was a set of fully developed conceptual solutions. The goal was to investigate the relationship between how well these aspects of the design methodology were followed and the quality of the resulting design solutions produced.

The design challenge posed was to design a toy for a blind child in the age group of 5 to 8 years. The two sets of students considered were those who have not formally been exposed to the design methodology (henceforth termed MEEN 445 students) and those who had previously used the design methodology for one semester (henceforth termed MEEN 446 students). The study was conducted on all the students in the two groups. The same design challenge was given to both sets of students. Two independent evaluators did the evaluation. The first graded all the reports submitted and the second graded one-sixth of the reports that were selected randomly. The primary goal of having a second, independent evaluator was to assess the consistency of the first evaluator and to identify any bias on the part of the first evaluator. The details of the study, namely the design challenge, the evaluation process, the evaluation criteria, some observations on the process followed by the two sets of students and other relevant details are provided in the following sections.

7.1 DESIGN CHALLENGE

The statement given to both sets of students was:

The problem is to design a toy for a blind child in the age group of 5 to 8 years. The toy can have any number of functions. Analyze the problem (need) and develop at least three designs. Give sketches to show the concepts considered, the configurations, and the final designs.

Use the sections provided (in the following pages) to organize your thoughts and to report your design. Provide reasonably detailed explanations on your approach to the problem and the means by which you tackled the design. Use your imagination and have fun.

Write your name, the last five digits of your Student ID (SID), your class and your section number on this page only. Write the last five digits of your SID on the top right-hand corner of subsequent pages. Use additional pages if necessary.

The report format given to the students had the above statement on the front page and blank pages named Problem Analysis, Specifications, Concepts/Configurations, Final Design 1, Final Design 2, Final Design 3, and Feedback. There was no restriction on the resources they could utilize so long as it was an individual effort. The time provided for this challenge was one week. The students from both groups turned in a total of 148 design reports. Sixty-four reports of this total were from students in MEEN 445 (part one of the two semester senior-level design course) who were in the initial stages of their introduction to the design process described here. The other 84 reports were from students in MEEN 446 (part two of the two semester senior-level design course) who had previously studied and practiced applying the process when they had been enrolled in the MEEN 445 design course in the previous semester.

7.2 EVALUATION PROCESS

Prior to starting the evaluation, certain procedures were followed. The reports that the students returned consisted of a title page, followed with their work on subsequent pages. The title page completely identified the student but only a partial student identification number appeared on the top of each of the subsequent pages. In preparation for the evaluation, the title page was separated from the main reports. All the reports sans the title page from both subsets, MEEN 445 and MEEN 446, were collected, shuffled and combined into one larger set by a person who was not the evaluator. Reports to be evaluated were selected randomly from the combined larger set by the evaluator(s) and they did not have any indication whether a particular report was from a MEEN 445 or MEEN 446 student. This was an attempt to ensure that the evaluator(s) graded the reports objectively and in a blind manner. Each report was evaluated mainly for two things - the quality of the design and the effective use of the design methodology during the process.

The criteria that were used to grade the reports were:

- Effort (Grade from 1 to 10)
  This was used to assess the effort that a student had put into the report. A score of 10 indicated a large effort on the part of the student.
- Design Methodology (Grade from 1 to 5, with 1 - worst and 5 - best)
  The focus here was on the usage of the methodology and on following a systematic design process. Emphasis was placed on abstraction, critical parameter identification and questioning. The assessment was on the process as communicated by the

students. The methodology assessment was further separated into assessments of the Need Analysis and the Conceptual Design.

- Need Analysis: The factors that were used here were the definition of the need, identification of the requirements, development of the functional requirements, identification of critical issues, and the translation of uncertain parameters into quantitative requirements.
- Conceptual Design: The main factor here was the innovation demonstrated through the ideas generated. This was addressed by assessing the designs for variety. The other factors considered were the usage of concept-configuration looping in the final embodiments, identification of critical issues within the concepts, and the effective embodiment of the concepts.

- Variety (Grade from 1 to 3)

  This criterion assessed the degree of innovation in the designs presented. Recall that the task was to generate at least three conceptually different designs. Conceptually different designs are those solutions whose fundamental concept is based on a different technological principle or effect. Variants of the same concepts or principles are not considered conceptually different. The score here indicates the degree of conceptual difference in the solutions presented.

- Design Quality (Grade from 1 to 5, with 1 – worst and 5 - best)

  Judgments on the quality of the proposed solutions were primarily based on the final development of the designs, the viability of the embodiment and the communication of the designs through proper sketches. Other factors considered were the details of the embodiment – general size and dimension specifications, the development of functionality, safety, power usage, materials, and configuration details.

7.3 EVALUATION RESULTS AND ANALYSIS

In order to investigate any correlation between using a design process and the design quality and the variety of the resulting design solutions, the data between each category were compared and statistical correlations were performed. The results of these analyses are summarized in the following tables.

Table 6: Comparison Between the Use of the Design Process and the Resulting Design Quality

MEEN 445 and MEEN 446 Combined								
Score for Design Process		**Score for Design Quality**					**Total**	**%**
		Worst				Best		
		1	**2**	**3**	**4**	**5**		
Worst	**1**	20	29	10	4	-	**63**	43%
	2	3	18	13	5	1	**40**	27%
	3	-	2	13	5	1	**21**	14%
	4	-	-	6	9	1	**16**	11%
Best	**5**	-	-	-	3	5	**8**	5%
	Total	**23**	**49**	**42**	**26**	**8**	**148**	100%
		16%	33%	28%	18%	5%	100%	
Correlation Coefficient between Design Process and Design Quality = 0.69								

The study was conducted on all the students who attended the two courses and no sampling of students from each course (set) was done. Table 6 shows the results for the total number of reports (148), MEEN 445 and MEEN 446 students combined, receiving a particular pairing of scores for Design Process and Design Quality. For example, four reports have received a score of 1 for their design process and a score of 4 for their design quality. A statistical correlation coefficient between Design Process and Design Quality for this data gave a result of 0.69. Recall that a correlation coefficient of greater than zero indicates a positive correlation with 1 being the best i.e. complete correlation, around zero indicates no correlation, and below zero indicates a negative correlation.

The correlation values vary between –1 and 1. The value 0.69 indicates a very large positive correlation between following the design process and the resulting design quality as suggested by Cohen [40] and Hopkins [41]. The interpretations of the various ranges of correlation coefficients are shown in Table 7. The above value suggests that following the design methodology leads to a higher quality design solution.

Table 7: Interpretation of Statistical Correlation Coefficient Ranges [41]

Correlation Coefficient	Descriptors
0.0 – 0.1	Insubstantial, zero
0.1 – 0.3	Small, minor
0.3 – 0.5	Medium, moderate
0.5 – 0.7	High, Large, major
0.7 – 0.9	Very high, very large
0.9 – 1.0	Nearly or practically perfect

To get a better understanding of the data in Table 6, the scores of the Design Process and Design Quality have been categorized into Poor and Good. The Poor category contains the scores of 1 and 2, the Good category contains the scores of 4 and 5. The score of 3 is not considered because it indicates average performance. The data in Table 6 has been reformulated into four categories between the use of Design Process and the resulting Design Quality, as shown in Table 8. The four categories are:

1. Poor Design Process – Poor Design Quality,
2. Poor Design Process – Good Design Quality,

3. Good Design Process – Poor Design Quality,
4. Good Design Process – Good Design Quality.

Table 8: Comparison Between the Use of the Design Process and the Resulting Design Quality into Four Categories

MEEN 445 and MEEN 446 Combined: 148 reports.
Correlation Coefficient between Design Process and Design Quality = 0.69

Design Quality / Design Process		Poor			Good	
		1	2	3	4	5
Poor	1	**1.** 70 reports 47 %			**3.** 10 reports 6 %	
	2					
	3					
Good	4	**2.** 0 reports 0 %			**4.** 18 reports 12 %	
	5					

From Table 8, some interesting results that can be seen are:

- 0 % of the reports are in Good Design Process – Poor Design Quality: This indicates that following the design process strongly reduces the chances of producing designs of poor quality.
- 12 % of the reports are in Good Design Process – Good Design Quality: This further highlights the point stated above and reaffirms that following the design process increases the possibility of producing designs of good quality.

- 6 % of the reports are in Poor Design Process – Good Design Quality: It is possible to produce good quality designs without following a design process, but as seen with the whole picture, this likelihood is small.

The next step was to examine the relationship between which subset a report belonged to (MEEN 445 or MEEN 446) and the resulting design quality. The student identification numbers on the graded reports were matched to the cover pages and the 148 graded reports were separated into MEEN 445 subset and MEEN 446 subset. Table 9 shows the same data that was previously shown in Table 6, but subdivides it according to whether the reports were from the MEEN 445 subset or from the MEEN 446 subset. For Design Quality, the MEEN 445 subset had a mean score of 2.36 and a standard deviation of 1.06, whereas the MEEN 446 subset had a mean score of 2.86 and a standard deviation of 1.10. A statistical analysis of variance test (t-test) was done between the mean scores of the two groups on Design Quality [42]. This was done to determine if the means of the two groups showed significant difference on the measure of Design Quality. That is, the design quality from the average student in the MEEN 445 group would be lower than the average student from MEEN 446 group. The t-test conducted between the means of the two groups on Design quality showed that the level of significance is $p< 0.01$. This value indicates that the difference in the means between the two subsets is significant 99% of the time and is not caused by chance. Hence, an average student in the MEEN 446 subset would have a superior design quality as compared to an average student in the MEEN 445 subset.

Table 9: Comparison of the Results for Following the Design Process and Resulting Design Quality for Students from the MEEN 445 and MEEN 446 Subsets

MEEN 445	**Score for**						
Score for	**Design Quality**					**Total**	**%**
Design Process	**1**	**2**	**3**	**4**	**5**		
1	14	18	6	3	-	41	64%
2	-	7	6	3	1	17	27%
3	-	-	3	2	1	6	9%
4	-	-	-	-	-	0	0%
5	-	-	-	-	-	0	0%
Total	14	25	15	8	2	64	100%
	22%	39%	23%	13%	3%	100%	
						Design Quality Mean =	2.36
						Standard Deviation =	1.06

MEEN 446	**Score for**						
Score for	**Design Quality**					**Total**	**%**
Design Process	**1**	**2**	**3**	**4**	**5**		
1	6	11	4	1	-	22	26%
2	3	11	7	2	-	23	27%
3	-	2	10	3	-	15	18%
4	-	-	6	9	1	16	19%
5	-	-	-	3	5	8	10%
Total	9	24	27	18	6	84	100%
	11%	29%	32%	21%	7%	100%	
						Design Quality Mean =	2.86
						Standard Deviation =	1.10
						Correlation Coefficient between Design Process and Design Quality =	0.76

Analyzing the MEEN 446 subset, the correlation coefficient between Design Process and Design Quality for this subset gives a result of 0.76. This value indicates an even stronger relationship (refer Table 7) [40, 41] than that which was inferred from the value of 0.69, which was previously calculated for the whole group. Based on the data from Table 9, an issue of concern is that 53% of the MEEN 446 students have scored 2 or below for Design Process overall. This can be attributed to two reasons; the first is that although the student knows the process, he or she did not apply it. The second reason could be that the student did not understand the process well enough to be able to apply it. The latter reason is important feedback for the faculty team teaching the course. A possible explanation could be that the students find it difficult to adjust to the design philosophy and methodology, as it requires different thought processes than the students have been accustomed to over the previous three to four years of their academic program. Those students, 44% of the MEEN 446 subset, who scored 3 or more on the Design Process and simultaneously scored 3 or more on the Design Quality, have been able to learn the process and adapt their thinking style and have produced better designs.

The data shown in Table 9 was reformulated into the same four categories as used previously and is shown in Table 10. The results that the analysis of this data showed are:

- 61% of MEEN 445 students are in Poor Design Process- Poor Design Quality: It is expected that the MEEN 445 students would exhibit no design process, but this shows that 61%, which is significant, of the students have produced a design of poor quality.
- 11% of MEEN 445 students are in Poor Design Process – Good Design Quality: This indicates that it is possible to produce designs of good quality without following any process, but the likelihood is small.
- 0 % of MEEN 446 students are in Good Design Process –Poor Design Quality: This number is striking as it indicates that following the design process properly would not yield any poor quality designs and this is further confirmed by the next two points.
- 22 % of MEEN 446 students are in Good Design Process – Good Design Quality: This number is twice that of the MEEN 445 group who have produced good designs. This further illustrates that following a good design process would lead to a design of good quality.

- 37 % of MEEN 446 students are in Poor Design Process – Poor Design Quality: This point raises the issue that there are still some students who despite having been taught the design process, are not applying it to the design task. Possible reasons are given in the previous paragraph.

Table 10: Comparison Between the Use of the Design Process and the Resulting Design Quality for Students from MEEN 445 and MEEN 446 Groups into Four Categories

<table>
<tr><td colspan="7">MEEN 445 only: 64 reports.
Design Quality Mean = 2.36; Std. Dev = 1.06</td></tr>
<tr><td colspan="2" rowspan="2">Design Quality
Design Process</td><td colspan="2">Poor</td><td></td><td colspan="2">Good</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td rowspan="2">Poor</td><td>1</td><td colspan="2" rowspan="2">39 reports
61 %</td><td rowspan="2"></td><td colspan="2" rowspan="2">7 reports
11 %</td></tr>
<tr><td>2</td></tr>
<tr><td></td><td>3</td><td colspan="2"></td><td></td><td colspan="2"></td></tr>
<tr><td rowspan="2">Good</td><td>4</td><td colspan="2" rowspan="2">0 reports
0 %</td><td rowspan="2"></td><td colspan="2" rowspan="2">0 reports
0 %</td></tr>
<tr><td>5</td></tr>
</table>

<table>
<tr><td colspan="7">MEEN 446 only: 84 reports.
Design Quality Mean = 2.86; Std. Dev = 1.10
Correlation Coefficient = 0.76</td></tr>
<tr><td colspan="2" rowspan="2">Design Quality
Design Process</td><td colspan="2">Poor</td><td></td><td colspan="2">Good</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td rowspan="2">Poor</td><td>1</td><td colspan="2" rowspan="2">31 reports
37 %</td><td rowspan="2"></td><td colspan="2" rowspan="2">3 reports
3 %</td></tr>
<tr><td>2</td></tr>
<tr><td></td><td>3</td><td colspan="2"></td><td></td><td colspan="2"></td></tr>
<tr><td rowspan="2">Good</td><td>4</td><td colspan="2" rowspan="2">0 reports
0 %</td><td rowspan="2"></td><td colspan="2" rowspan="2">18 reports
22 %</td></tr>
<tr><td>5</td></tr>
</table>

Table 11: Comparison Between the Use of the Design Process and the Resulting Variety in the Proposed Solutions

MEEN 445 and MEEN 446 Combined						
Score for Design Process		**Score for Variety**			**Total**	**%**
		Poor		Good		
		1	**2**	**3**		
Poor	**1**	19	36	8	**63**	43%
	2	6	19	15	**40**	27%
	3	-	13	8	**21**	14%
	4	-	8	8	**16**	11%
Good	**5**	-	1	7	**8**	5%
	Total	**25**	**77**	**46**	**148**	100%
		17%	52%	31%	100%	
Correlation Coefficient between Design Process and Variety =						0.44

Table 11 shows the number of reports corresponding to a particular pairing of scores for Design Process and Variety. The correlation coefficient between these two assessment categories was found to be 0.44. While still significant, this correlation is not as strong as the correlation found previously for the data in Table 6 between Design Process and Design Quality. This result, and the almost total absence of reports that scored well on Design Process while scoring poorly on Design Variety (shown by shaded area in Table 11), does indicate that effective usage of the design methodology leads to a greater variety in the proposed conceptual solutions. Table 12 shows the comparison between Design Process and Variety, when the data set previously presented in Table 11 is partitioned into MEEN 445 and MEEN 446 subsets. Analyzing the data, the MEEN 445 subset has a mean score of 2.05 with a standard deviation of 0.76, while the MEEN 446 subset has a mean score of 2.21 with a standard deviation of 0.60. The statistical correlation between Design Process and Variety for the MEEN 446 subset gives a result of 0.57, indicating a large relationship (refer Table 7) [40, 41].

Table 12: Comparison of the Results for Following the Design Process and Resulting Variety for Students from the MEEN 445 and MEEN 446 Subsets

MEEN 445 only						
Score for Design Process		**Score for Variety**			**Total**	**%**
		Poor		Good		
		1	**2**	**3**		
Poor	**1**	13	20	8	41	64%
	2	4	4	9	17	27%
	3	-	3	3	6	9%
	4	-	-	-	0	0%
Good	**5**	-	-	-	0	0%
	Total	17	27	20	64	100%
		27%	42%	31%	100%	
					Variety Mean =	2.05
					Standard Deviation =	0.76

MEEN 446 only						
Score for Design Process		**Score for Variety**			**Total**	**%**
		Poor		Good		
		1	**2**	**3**		
Poor	**1**	6	16	-	22	26%
	2	2	15	6	23	27%
	3	-	10	5	15	18%
	4	-	8	8	16	19%
Good	**5**	-	1	7	8	10%
	Total	8	50	26	84	100%
		9%	60%	31%	100%	
					Variety Mean =	2.21
					Standard Deviation =	0.60
					Correlation Coefficient =	0.57

From Table 12 some of the results that are inferred from the data analysis are:

- For MEEN 445 subset, the distribution of the scores for Variety shows that 27% of the students scored 1 for Variety, 42% scored 2, and 31% scored 3.

- In contrast, of the students in MEEN 446 subset, 10% scored 1, 59% scored 2, and 31% scored 3 for Variety.
- The trend towards a higher score for a MEEN 446 student is significant, with 90% of the students scoring 2 or higher for Variety in the MEEN 446 subset as compared to only 73% of the students in the MEEN 445 subset.
- More importantly in the MEEN 446 subset, zero students had a poor variety score (score of 1) when they had a good score on the Design Process (score of 4 and above).

This above data shows that following the design methodology increases the probability of developing an innovative solution in addition to one that is of measurably higher quality.

The score for Variety was based on the number of conceptually different solutions that students developed and communicated. In this case, the challenge to design a toy for a blind child restricted the students to design for the remaining senses. Since, there are four remaining senses - hearing, touch, smell and taste. The students could potentially develop at least four conceptually different solutions. Taste would not normally be acceptable in a toy. This leaves only three senses and three fairly obvious conceptual categories. So, in retrospect, this design challenge was a poor choice to determine the measure for innovation based on conceptual difference in the solutions. In spite of the possibility to develop multiple conceptually different solutions, some interesting points that are raised based on the analysis of data are:

- 52% of the students in the combined group came up with only two conceptually different solutions.
- 60% of the MEEN 446 group, who are familiar with the idea of conceptual difference, came up with only two conceptually different solutions.
- 10% of the students in MEEN 446, who had a good score on the Design Process (Score of 4 and 5), came up with only two conceptually different solutions.

A possible reason for the above large set of students in the MEEN 446 group not showing more than two conceptually different solutions could be due to lack of understanding of the meaning of conceptually different. This provides feedback to the instructors in the class and emphasizes that a better job needs to be done in teaching the students.

An issue of potential concern was the objectivity, consistency, and possible bias of the evaluator. Recall that the plan was for a second, independent evaluator to assess some fraction (1/6) of the graded reports. These reports were randomly selected from the combined group. The outcome of this exercise showed a positive correlation of 0.58 between the results from the two evaluators, indicating that the objectivity, consistency, and possible bias of the primary evaluator were not issues for concern in this instance.

During the course of the evaluation, some general observations were made on the tendencies of the students. Those who did not follow the design methodology tended to be vague and non-specific in their designs. They jumped directly into solutions, and the multiple solutions are usually variants on one idea. Those who followed the design methodology were able to identify key issues earlier. These included: the ability of a blind child to locate the toy; translated the age group into the proper weight and size requirements for the toy. They were also able to effectively develop their concepts into viable configurations.

Both sets of students were able to recognize the need for the toy to be educational, fun and a contributor to child development. They were able to identify that they were limited to the four non-visual sensory perceptions of smell, touch, taste and sound. The predominant senses were those of touch and sound, and sense of taste usually was discarded for reasons of safety. Incorporation of Braille for identification and touch purposes was common. Typically the solutions proposed were modifications of the toys that are currently on the market or those that the student had played with and enjoyed.

The solutions could be broadly divided into four categories:

- Physical development
- Mental development
- Language and mathematical skills
- Musical skills

The common solutions that were proposed were Braille Rubik's Cube, texture block shapes, Braille electronic story books, Braille electronic keyboards, audio and touch sensory memory games, jigsaw puzzles, 'Simon says' toys, electronic computers, balls with audio sounds, target practice, piano and drum kits, stuffed and regular dolls with texture and audio capabilities.

There were also some innovative toys that incorporated taste and smell. For example, a modified lollipop that could record sound and vibrate the recording back into the mouth while the user is sucking a lollipop. Based on the feedback, most of the students enjoyed the opportunity to work on this design challenge.

7.4 DISCUSSION

In summary, the goal of the study was to test whether following a design process would lead to the development of better quality designs. This is evidenced by the following results:

1. The statistical correlation coefficient between Design Process and Design Quality for the whole group was 0.69 and for the MEEN 446 subset was 0.76. This number is significant and indicates a very large correlation (refer Table 7).

2. The statistical analysis of variance test on the mean values of the scores for Design Quality between the MEEN 445 and MEEN 446 subsets showed significant difference ($p<0.01$). This value indicates that the difference in the means between the two subsets is significant 99% of the time and is not caused by chance. Hence, an average student in the MEEN 446 subset would have a superior design quality as compared to an average student in the MEEN 445 subset.
3. 0 % of MEEN 446 students who showed Good Design Process had Poor Design Quality. This number is striking as it indicates that following the design process properly would not yield any poor quality designs.
4. 22 % of MEEN 446 students who showed Good Design Process had Good Design Quality. This number is twice that of the MEEN 445 students who having Poor Design process showed Good Design Quality. This further illustrates that following a good design process would lead to a design of good quality.

The relationship between following the design process and the resulting innovation evidenced by the measure of Variety although hampered by the choice of the design challenge still showed some significant results. These are:

1. The correlation coefficient between Design Process and Variety for the whole group was 0.44, which indicates a moderate relationship. For the MEEN 446 subset the correlation coefficient between Design Process and Variety was 0.57, indicating a major relationship (refer Table 7).
2. 90% of the students in the MEEN 446 subset scored 2 or higher for Variety as compared to only 73% of the students in the MEEN 445 subset. There is a significant trend towards a higher score for a MEEN 446 student.
3. More importantly in the MEEN 446 subset, zero students had a poor variety score (score of 1) when they had a good score on the Design Process (score of 4 and above).

Those who followed the methodology were able to identify the needs and address the key issues early in the design, and develop different concepts into effective embodiments leading to designs of superior quality. The results indicate that following the design methodology described here increases the probability of simultaneously developing an innovative solution and a design that is superior in quality.

Other results although not related to the goal of the study but are pertinent to the pedagogical issues and are gleamed from the analysis, are:

1. 53% of the MEEN 446 students scored poorly in the Design Process irrespective of the score they received on the Design Quality. This number is significant and really needs to be addressed as the MEEN 446 subset is considered to have understood the design process from the previous semester.
2. 37% of the MEEN 446 students who scored poorly in the Design Process also scored poorly in the Design Quality. This further adds to the above point indicating that either the student has difficulty in comprehending the subject or is apathetic, or it could be that the quality of instruction needs to be improved.

8 CONCLUSIONS

The contribution of this dissertation is to improve efficiency and effectiveness of the design process at a philosophical level where it emphasizes the importance of the design philosophy of Abstraction, Critical Parameter Identification and Questioning to the IIDE design methodology. The designer has to become adept at using this philosophy in order to be effective and innovative in the design process. This pedagogical basis of the methodology is so fundamental that it could be taught to students at the sophomore or junior level before they learn the design methodology in their senior years. This would ensure that a student is comfortable with the habits of thought and learning espoused by this design philosophy. Further it would enable students to access their knowledge base with greater insight and clarity of thought when called upon to do so in design.

In the Need Analysis Stage, there was a need for a method to enable and facilitate the development of the function structure. Since most of the design tasks are based on existing designs or are variations on existing designs, the Object Function Method was selected. In the Conceptual Design Stage, the differences in the Concept-Configuration model and Parameter Analysis Model are illustrated. Some of the key points emphasized by the Concept-Configuration model in order to be innovative and effective are (1) Proper critical parameter identification, (2) Oscillation between the Concept and Configuration Spaces, and (3) Positive communication between Concept-Configuration-Evaluation phases. The key to effective and efficient concept searching is the identification of the principal function and the critical parameter associated with the function that is used as the basis for searching the concepts. The Concept Search Techniques together with the implementation method shown enables the designer to search for concepts within the Concept-Configuration model effectively. The Object Function Method and the Concept Search Techniques while emphasizing the spirit of the IIDE philosophy also enhances the IIDE design methodology.

Finally, a study was conducted to investigate the relationship between how well the design methodology was followed and the quality of the resulting design solutions produced. Previous to this study, the assessment of the effectiveness of a design process in improving the quality and level of innovation in the designs that the students produced were largely subjective. There are inherent difficulties with conducting comparative experiments of this kind on live subjects (students) where a ‘clean’, ‘unpolluted’ reference group cannot be assembled. So, a statistical approach was taken to test for “evidence” of the effectiveness of method in improving design skills. The results indicate that following the design methodology described here increases the probability of simultaneously developing more innovative solutions and designs of superior quality.

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