Session 2525

A Way of Doing Engineering Design

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Abstract

The ability to design is the distinguishing characteristic of an engineer. Yet, the process by which a design can be created most efficiently and with the highest degree of innovation is seldom taught at American Universities. Recent research at several universities and industries are increasing our understanding of both the engineering design process as well as effective means for teaching that process. These research findings have been combined and evolved into a cohesive design approach. At the core of this approach is a design philosophy based on good abstraction, good critical parameter identification, a methodology for questioning and a cognitive process of concept-configuration looping. This philosophy along with the design process is taught in the senior under-graduate design and graduate design courses at Texas A&M University. The students understand and experience the design philosophy and apply the design process on real world design projects provided by the industry. This paper describes the design philosophy and discusses its application in the various stages of the design process. It also discusses the methodologies involved in working through each of the stages of a design. The paper shows how the philosophy and the process enable the designer to design effectively, efficiently and still be innovative.

1. Introduction

Design is the culmination of knowledge in engineering and the distinguishing feature of a good engineer is the ability to design. Research at universities and industries have shown that engineering design is a process that can be developed and imparted to engineers [1-3]. These research findings have increased our understanding of both the design process as well as effective means for teaching that process. In that spirit, a design methodology was developed at the Institute for Innovation and Design in Engineering (IIDE), Texas A&M University. This methodology incorporated methods and techniques from various sources to form a cohesive approach to the design process. The core of this approach is the design philosophy based on abstraction, critical parameter identification, questioning and a cognitive process of concept-configuration looping. This philosophy along with the design process is taught in the senior under-graduate design and graduate design courses. The students understand and experience the design philosophy and apply the design process on real world design projects provided by the industry.

The framework for the design process is adapted from the widely accepted model of Pahl and Beitz [1]. The adaptations in the design process that were incorporated from various sources were - features in the development of function requirements from Pahl and Beitz [1] and Suh [4]. Concept generation techniques in addition to the brainstorming and other DELPHI techniques mentioned in Pahl and Beitz [1], were adapted from Altshuller's TRIZ [5] and Sickafus's USIT [6] methods. The design principles incorporated in the embodiment design were mainly from Pahl and Beitz [1] and

Suh [4]. The design methodology has evolved over the years based on feedback from students and further research [7-9].

The goal of the methodology is not only to teach the design process to the students but also instill in them the design philosophy that would enable them to perform design effectively and innovatively. This paper describes the design philosophy and discusses its application in the various stages of the design process.

2. Design Philosophy

The design philosophy is the essence of the IIDE design process. It consists of certain analytical skills that are applied throughout the design process in various stages. These skills are the ability to perform abstraction, identify critical parameters and the ability to question. These form the core of the methodology and enable the designer to be effective and innovative.

2.1 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 enables in identifying the core or the essence of the problem by increasing the designer's insight into the problem.

To understand the abstraction process, let us consider the task of designing a transportation canal to facilitate the movement of ships across a landmass. The need statement that describes the given problem 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 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 to cross the canal. For instance, the French tried to connect the Atlantic and Pacific oceans on the same basis as the Suez Canal, which had no gradients in the canal. Their failure can be ascribed to this falsely 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. So, "no gradient" placed an artificially restrictive and unnecessary constraint on the design. We can now question the earlier need statement and reword it as "connect two bodies of water". We then ask the question "Is the real need to connect two bodies of water?". The answer is "No." The real need is "to move ships from one side of a narrow land mass to the other side". This rephrasing of the need opened up 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 rise in elevation. This example illustrates the importance of abstraction in increasing the insight into the problem and expanding the solution space.

A general methodology for performing abstraction on a given problem statement is to:

- 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 various terms used in the need statement
    - 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? But 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"? By answering yes to all the above questions, a good abstraction has been performed. The ultimate goal of abstraction is to increase the insight into the problem and also increase the solution domain for innovative solutions.

Another example is provided to better illustrate the process of abstraction. The problem is to design the brakes of the car. Figure 1 shows the evolution of the need statement from a colloquially expressed form to a technically precise abstract form. The solution specific details are eliminated and the terms are made qualitative. By abstraction, the final need statement is technically precise, solution independent, general but not vague, and includes all possible solutions.

Problem: To design the brakes of the car

Need statements:
- To stop a car
- To reduce the speed of a car from 60mph to 0mph in less than 300 feet
- To decelerate the car at a controlled rate
- To dissipate the kinetic energy of the car at the required rate
- To transform the translational kinetic energy of the car at the highest acceptable rate

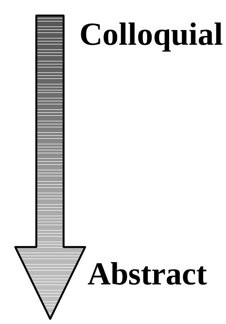

Figure 1: Abstraction on the need statement to design the brakes for a car.

2.2 Critical Parameter Identification.

Critical parameter identification is the systematic process by which a designer identifies the crucial "make-or-break" issues in the identified need. These issues can be physical/ natural/ chemical/mathematical concepts that are relevant to the need. The critical parameter identification and abstraction processes along with questioning go hand-in-hand.

To understand how to identify critical parameters, let us consider the previous example to design the brakes for 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 60mph to 0mph in less than 300 feet. The critical parameter here would 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 the disc and drum brakes, 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 one of the means of getting rid of the kinetic energy of the car. This realization results in a new statement "transform the translational kinetic energy of the car at a controlled rate". Since only the forward motion of the car is considered, the term translational better defines the transformation of the kinetic energy of the car. The critical parameter associated with this new statement is the "energy transformation rate". By identifying the critical parameter, the required information for solving the need can be identified. Hence, the "energy transformation rate" allows the designer to identify the total energy of the car and establish time limitations. By performing the energy transformation at a controlled rate, factors like the dynamics of the vehicle, safety of the passengers and the road conditions could be taken into account.

Evolution of the need	**Evolution of the critical parameter**
▪ To reduce the speed of a car from 60mph to 0mph in less than 300 feet	Stopping Distance
▪ To decelerate the car at a controlled rate	Deceleration
▪ To dissipate the kinetic energy of the car at the required rate	Energy dissipation rate
▪ To transform the translational kinetic energy of the car at the highest acceptable rate	Energy transformation rate

Figure 2: Evolution of the critical parameters for the brakes of a car.

The actions involved in identifying the critical parameters for the design are listed below,

- 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 the parameters for both the function and constraint. For example, transforming kinetic energy and the transformation rate.
- Develop relationships (constitutive) between variables that define the function – these could be equations or rule of thumb relations.
- Identify the consequences of failure to perform a 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.

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- Introduce quantification of the functions and constraints to establish the operating envelope or range.

The critical parameters often 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 determine the critical parameter. For instance, in the above example, at the tire and road interface the road conditions provide the limitations on the rate at which energy transformation can be achieved. The science of engineering is mostly about fields (three dimensional fields). The goal of nature is to minimize gradients or slopes of these fields. Therefore, critical parameters most often involve spatial or temporal gradients or slopes. From the above example, the “energy transformation rate” is an example of gradients. The magnitude or difficulty of the design task is often times set by rate. The goal of the designer would be to minimize the rate of changes.

2.3 Questioning

This is one of the key skills along with abstraction and critical parameter identification. The process of questioning goes hand-in-hand with abstraction and critical parameter identification, as it can be seen in the methodology for abstraction and critical parameter identification. For instance, in the previous example of the design for a canal, by questioning the constraint of “no gradient” we could determine whether it was a real constraint or artificially imposed. Similarly in the example for the brakes of the car, by questioning the need for “dissipation of kinetic energy” we identified that it was a part of “transformation of the kinetic energy” that included “storage of kinetic energy”. The process of questioning is a subtle yet powerful tool.

The designer, by questioning the needs and assumptions, makes a conscious effort to be innovative and not get fixated on certain ideas. Figure 3 shows the various questions in relation to the need. It consists of the five “W” s and the “H”. Along with the opposite questions of the “-not” the designer is able to explore the problem and gain insight to the need. The arrangement shown indicates that the questions of what, when, where, who and why enables effective gathering of information. The question of how encompasses all the other questions to answer the means with which their can be implemented.

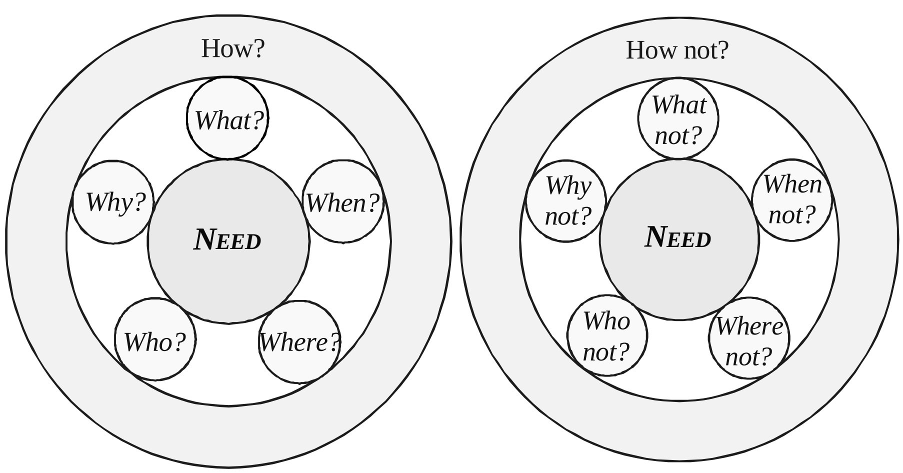

Figure 3: Schematic of the questions – five “W”s and one “H” along with the “-nots”.

3. IIDE Design Process

The IIDE engineering design process, as shown in Fig. 4, is a sequence of design activities, and it includes various methodologies and strategies that enhance the execution of each activity. The design process contains as its foundations the strategies of abstraction and critical parameter identification. These activities together with questioning form the essence of the design process.

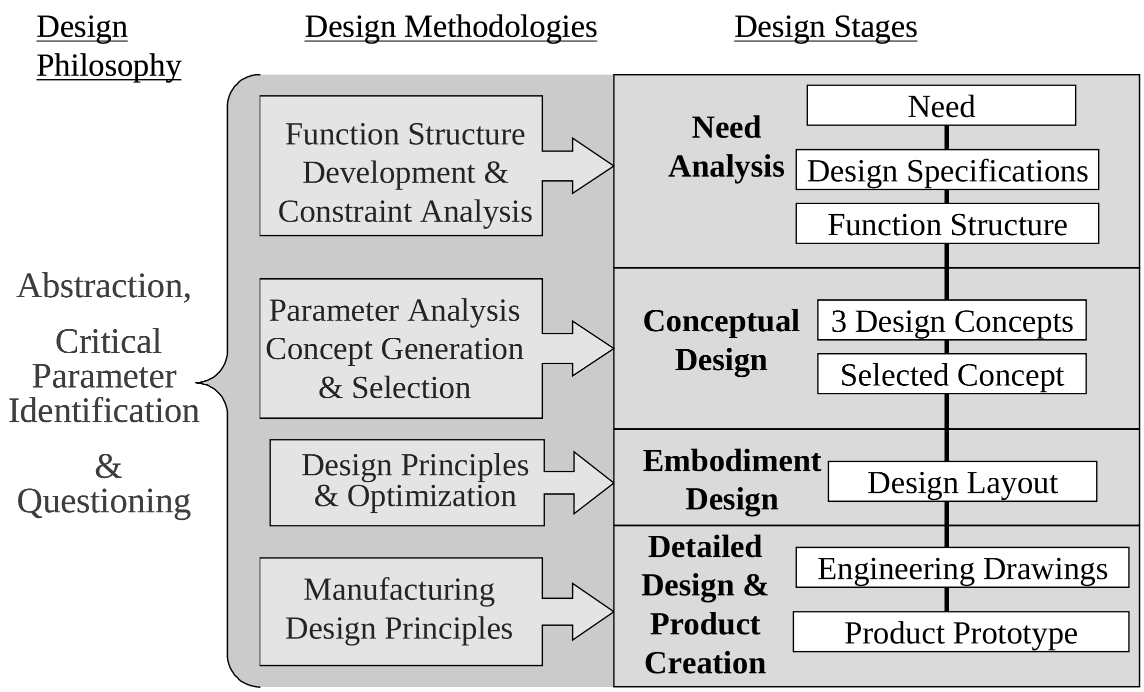

Figure 4: Overview of the IIDE design process.

The design process can be organized into four major stages, namely need analysis, conceptual design, embodiment design and detail design. The framework for the design process is adapted from the widely accepted model of Pahl and Beitz [1]. The various stages of the design are shown with the activities performed in each of these stages together with the outputs from these activities. The methodologies involved in performing the activities associated with the stages are listed along the stages. These methodologies provide the methods to perform the activities and to measure the goodness of the design by the quality of the outputs generated from these activities.

3.1 Need Analysis

In this stage of the design, the designer would extract the core of the problem from the 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 would in technically precise, yet abstract terms capture the fundamental issue of the problem. The designer would identify the various functional requirements (FRs) that would have to be performed to satisfy the need. In addition to the FRs the designer would have to identify various constraints and non-functional requirements

(NFRs) that have been imposed on the design. The NFRs could be cost, environmental and operating conditions within which the design has to be realized. Based on this, a *function structure* is developed which identifies the various functions and sub-functions that are to be performed by the design. The function structure is a list of all the functions that the design must perform to achieve the need. Based on the FRs and NFRs, the designer creates a list of *design specifications*. Thus, the understanding gained in this stage is reflected in the design requirements and it dictates the rest of the design process.

Care must be taken at this stage to maintain independence of the FRs, as coupled FRs would result in poor design and significantly increase the product development time and cost [1,4]. Also, the solution space is kept as large as possible without precluding any solutions by assumptions or perceived constraints. From the innovation perspective, the need analysis stage would lay the foundations for the design and determine the envelope for innovation.

3.2 Conceptual Design

This design stage involves searching for scientific principles and technologies that could potentially be used to satisfy the design need. These principles and technologies are abstracted to potential conceptual solutions for the need. The generated concept is developed into a reasonable configurable solution and is evaluated to satisfy the requirements. The iterative process through which a concept is fully developed or discarded is called the concept-configuration looping and is graphically shown in Fig. 5.

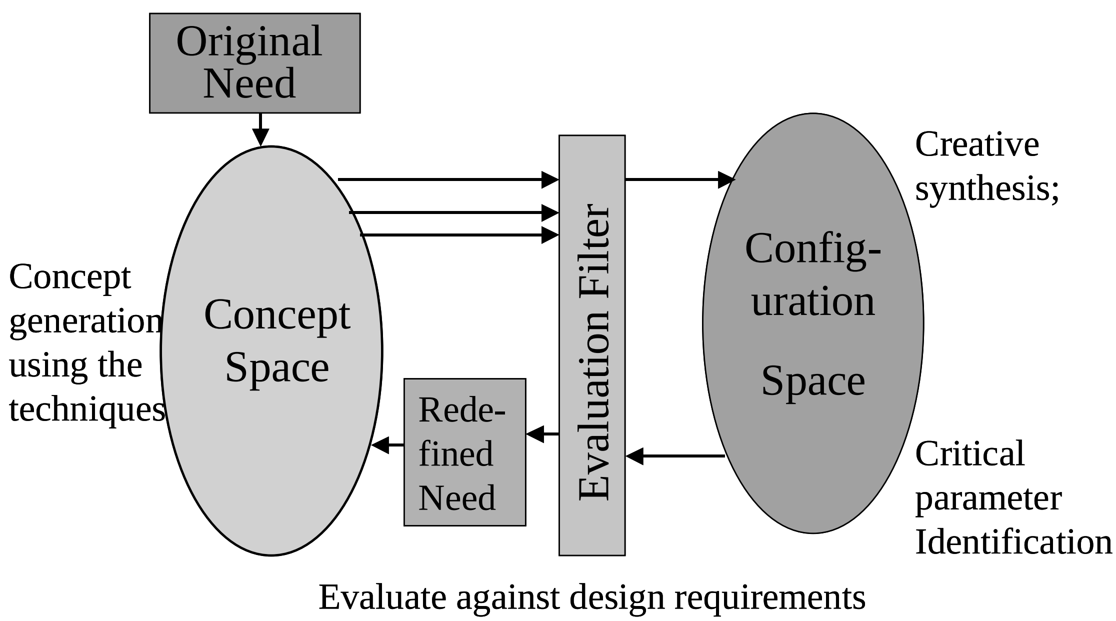

Figure 5: Concept-Configuration looping.

In the concept configuration looping there is a cognitive movement between the concept space and configuration space. The concept space represents the ideas or concepts to satisfy the original need. The configuration space would involve the embodiment of such ideas to provide form and structure. The evaluation would be done both on the concepts and the configurations so as to meet the design specifications. Usually the embodiment would have a critical weakness that would have to be addressed and this would represent the new redefined need for the concept space to generate ideas satisfying this need. This is an iterative process and would usually go through three to four loops before a concept is fully developed or rejected.

Typically, in this stage, three or more conceptually different competitive solutions are developed. Each of these are cycled through the concept-configuration looping shown in Fig. 5 to a stage where an objective evaluation of the concepts is possible. The output of the concept design stage is a viable conceptual design selected by the designer based on the evaluation. This is an important stage, as it would dictate the down stream of the design process. It would be difficult to correct any shortcomings of the conceptual design in the embodiment and detail design stages. Therefore, the success of the design process hinges on the outcome of this stage. The method of the concept-configuration looping and the principles behind it are explained in the concept-configuration section with examples.

3.3 Embodiment Design

In this stage, form and shape is given to the selected concept 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:

1. Separate functions (Avoid coupling)
2. Provide direct & short transmission paths
3. Constrain to required degree (Don't over-constrain)
4. Minimize gradients /Match impedances (Let Form Follow Function)
5. Provide functional symmetry / Balance forces and moments internally
6. Design for self-help
7. Design to fail-safe

The above principles could also be used to evaluate an existing design and suggest improvements in the design. Further, the design layout is optimized by balancing the demands of functionality, assemble-ability and manufacturability. If the design were highly coupled, the designer would have to resolve the conflicts between functional requirements. This would lead to compromises on the performance of the product.

3.4 Detail Design

In this stage, from the layout or assembly drawings, parts are drawn out and, material and manufacturing processes are specified. Further, the designer could perform detailed analysis of the design by computer simulation or prototype testing. The results would determine the performance of the design to meet the original specifications. At this stage, the design is in its final stages and any changes to the design would be impossible. The output of this stage would be the release of detailed drawings to a manufacturing facility.

4. Concept-Configuration Model

As the name suggests, the concept-configuration model consists of the concept and configuration spaces as shown in Fig. 5. The concept space comprises of ideas or concepts that are generated to satisfy the given need. The configuration space consists of implementing the concepts physically and giving them form and structure. A good design practice advocated by the methodology is to consciously move from one space to another. This enables the designer to be receptive for innovative solutions. This model recognizes that a good design is not based on one good idea, but a founded on series of good ideas.

The design process can be viewed as generating ideas in the concept space to solve a given need. The concept that satisfies the need is given shape or embodied in the configuration space. Then a key parameter in the embodiment is identified. This may be a weakness in the embodiment that creates conflict or will make it difficult for the embodiment to meet the quantified design requirements. This weakness becomes the new need to be solved. To solve this new need, concepts or ideas are again generated and so the process continues for a couple of iterations until it is discarded or the problem is solved. This form of iteration is called concept-configuration looping. This is based on the parameter analysis methodology developed by Jansson [9]. This methodology is comprised of three activities namely, parameter identification, creative synthesis and evaluation. The word parameter is used in a general way to describe any factor, concept or influence that is crucial in providing insight into a design task. The key parameters are not fixed during the design process. In creative synthesis, the designer would have to generate configurations to embody the key parameter. During creative synthesis several configurations may unfold that may not be attractive for further development. Only the viable solution is pursued for further synthesis. In evaluation, the designer compares the performance capabilities of the configuration to the desired capabilities. An objective evaluation allows the designer to identify good designs from a number of plausible but inferior designs. Thus, the designer can focus their effort on developing potentially good solutions and not waste time on developing mediocre design solutions. Further, the evaluation aids the designer in gaining new insights into the design task and identifies new parameters for the next parameter analysis. This process is better illustrated with the following example.

4.1 Example: Needle Count Design

The example is used to explain the design methodology, the various stages and the concept-configuration looping. It is not in detail but contains information that is pertinent to the task.

4.1.1 Background

A surgical needle package consists of eight needle-suture combinations wrapped in a foam package. During a medical operation, to prevent potential misplacement of needles in the human body the verification of the correct number of needles in the package is important. Therefore, it is imperative for the needle manufacturers to ensure that eight needles are present inside each package.

The manufacturing process flow for the combination is; the needle and the sutures are manufactured separately. They are wedged to make a needle-suture combination. The required number of such needle-sutures are packed in a foam package and sterilized at the end. Currently, the needle-suture combinations are manually counted and placed in the package. An operator prepares a package in 30 seconds. Typically, 15 operators work at any time.

The needles are extremely delicate and small. They are made from 420 steel, the length is 0.859 ± 0.0050 inches and the diameter is 0.0177 inches. The needles are curved to an angle of 160 degrees. A general schematic of the needle-suture combination is shown in Fig. 6. The suture is made from polyglactin – a polymer, the diameter is 0.006 – 0.010 inches, and the length ranges from 17.28 – 19.80 inches.

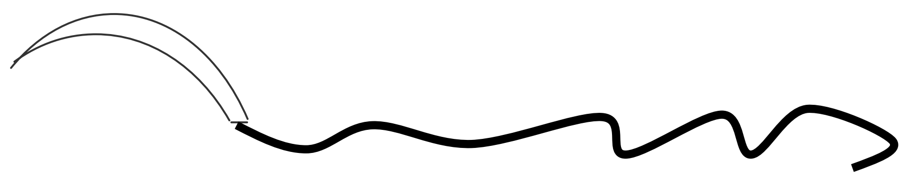

Figure 6: Schematic of the needle-suture combination.

4.1.2 Need Analysis

By performing abstraction and asking some questions we can gain insight into the problem.

- What is the purpose of the device/system and why is it required?
    - The purpose is to count the number of needles
    - To ensure correct number of needles (eight) are present in the package
- When is it 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 used?
    - In a manufacturing environment
- What constraints are imposed by the environment?
    - 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.

By performing abstraction, we can now develop a need statement for the design,

- 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.

The need statement went from being specific and constraining to a more abstract form that has expanded the scope of the design task. The function structure developed for the need statement is shown in Fig. 7. This identifies the various functional requirements that have been organized into structure so as to satisfy the given need.

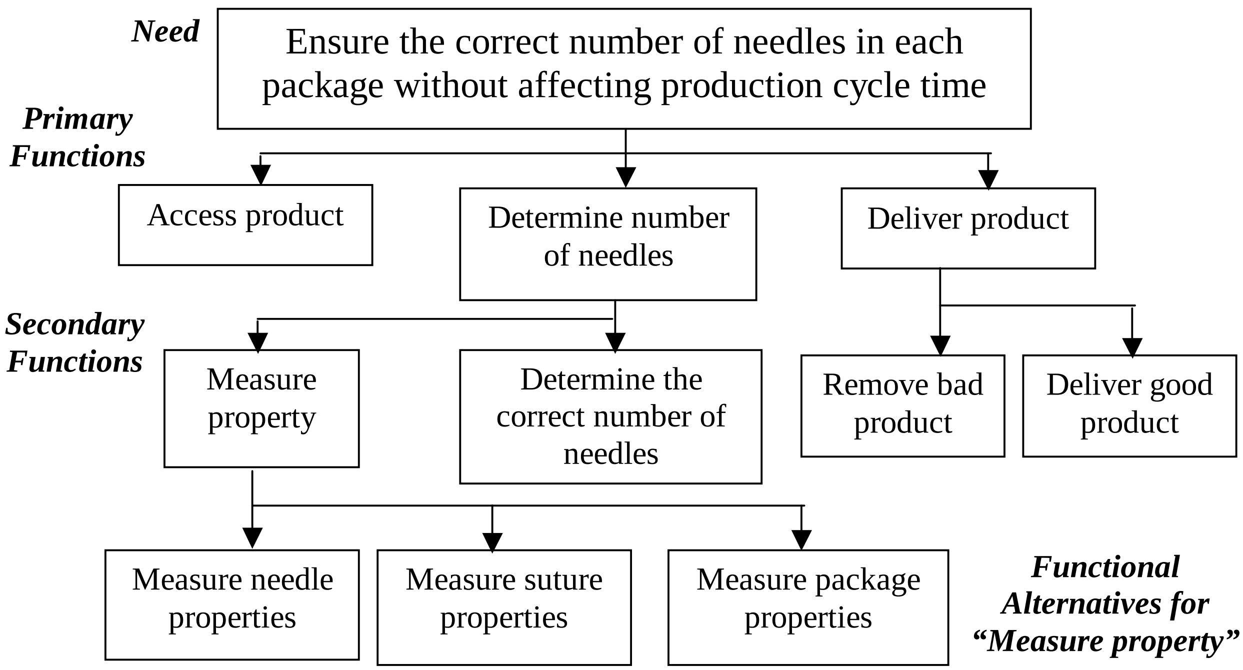

Figure 7: Function Structure for the needle count example.

By performing critical parameter identification, we have identified certain issues in the design that influence the design, they are,

- 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 does not give the desired discrimination
- Any of the needle properties should give the desired discrimination between 7, 8 and 9 needles

Hence, the critical function in the function structure for the design to work is "Ability to measure properties". The critical parameter is "Ability to measure properties *and provide the required discrimination between 7, 8 and 9 needles*"

4.1.3 Concept Generation

From the need analysis we have identified the critical function and the critical parameter involved in the design. The next step would be to generate concepts to satisfy the critical function and address the critical parameter.

The properties and the possible concepts for the needle-suture combination are –

- Needle (metallic)
  - Physical – weight, size and volume
  - Electrical
  - Magnetic
  - Capacitance
  - Thermal
- Suture (Polymer/natural fiber)
  - Physical – weight and size
- Foam Package (paper and foam)
  - Physical – weight, size and volume

Tight tolerances are difficult to maintain in the sutures and foam packages. Weighing the needle, suture and foam package combination is difficult, as discrimination between the needles is not possible. The option is to focus on the needle (metallic) alone as manufacturing tolerances can be maintained. Hence, the areas for identifying potential areas for concepts are only for the needle,

- Physical – cannot be done as the weights of suture and package come into play
- Electrical – possible
- Magnetic – possible
- Capacitance – possible
- Thermal – not possible as it may damage the needle

Hence, the possible conceptual solution domains are electromechanical, magnetic, capacitance and eddy-current solution.

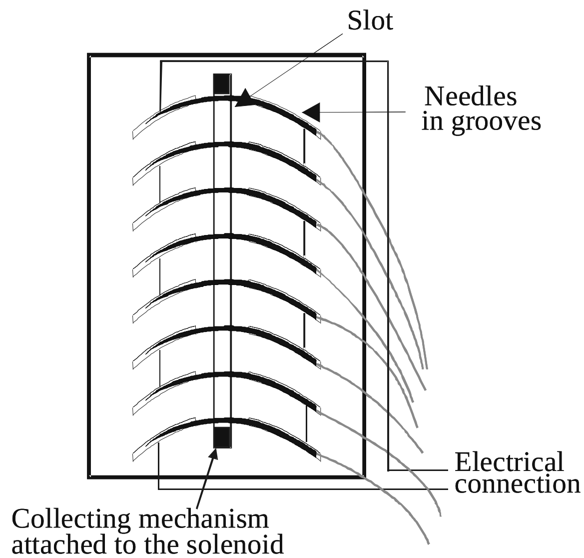

Figure 8: Electromechanical solution.

4.1.3.1 Electromechanical Solution

The needles are placed in grooves and establish electrical connection to the leads embedded in the grooves. Then a solenoid collects the needles into a bundle and the operator can then pack them. Figure 8 gives a schematic implementation of this solution.

The merits of this solution are that there is reliable needle count and calibration is not required. The drawbacks are there is physical contact with the needles, having potential to damage the needles. Also, since the needles considered are very small, there are difficult to handle and the cycle time would increase. Now, we divorce from this method and try the magnetic approach.

4.1.3.2 Magnetic Solution

Parameter analysis loop 1:
Parameter Identification (PI) -

- Measure the magnetic properties of the needle by weighing the package in the magnetic field.

Conceptual Solution (CS) -

- Measure the magnetic force on the needles.
- Weight = Gravitational pull on package + magnetic force on the needles

Evaluation (E) –

- The magnetic field increases the force exerted by the needles on the scale while not influencing that of the package or sutures. As a result, discrimination is better.
- The tolerance of the package still has significant impact.

Parameter analysis loop 2:

PI –

- Eliminate the influence of the package by measuring the magnetic attraction before packaging

CS –

- The operator places the needle-suture combination on the weight table

E –

- Discrimination is improved, but the suture tolerance still affects the variations and the measurement.

Parameter analysis loop 3:

PI –

- Eliminate the influence of the suture by subtracting its weight

CS –

- Weight the needle-suture combination twice. Once in the presence of magnetic field and other without the field.
- The difference between the two weighing would eliminate the weight of the suture.

E –

- Discrimination is better and this method can be used after packaging

- The drawback is – two weighing would increase the cycle time.

Parameter analysis loop 4: A question arises "Is there an another way to measure the magnetic force?"

PI –
- The magnetic force can also be measured by the force of attraction on the magnet

CS –
- The operator places the needle-suture combination on the table.
- The magnet is placed on the weighing scale. The arrangement is shown in Fig. 9.

E –
- This method can be used after packaging
- Experiments reveal that the needles become oriented in the magnetic field. This resulted in a loss of discrimination or needle damage if they are in the package.

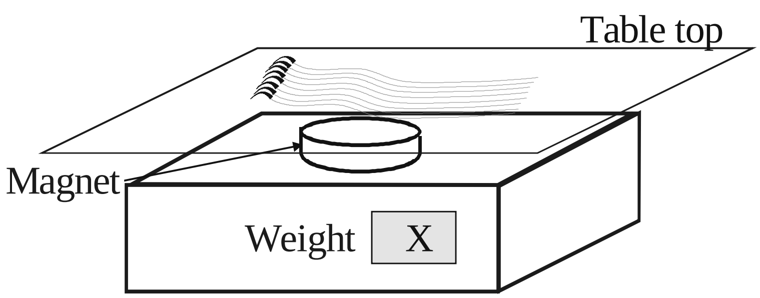

Figure 9: Schematic of the arrangement of the magnets and the needle-suture combination.

Parameter analysis loop 5:

PI –
- Eliminate the effect of the needle orientation by making the field uniform.

CS –
- A powerful uniform field can be created by using a powerful rare-earth magnet and placing the needles far away from the magnet.

E –
- This method provides reliable needle count.
- Could be implemented before or after the packaging
- It requires calibration and the needles would have to be demagnetized.

We can pursue the solution by using electromagnets or divorce from this solution to pursue other solutions like the capacitance and the eddy-current solution. But we shall stop here, as the intent of the above example was to illustrate the design philosophy and the concept-configuration looping.

5. Conclusion

This paper has sufficiently described the design philosophy and its application in the various stages of the design process by explanations and providing examples. The paper showed how the philosophy and the process enable the designer to design effectively and still be innovative.

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