

**MATERIAL AND PROCESSES SELECTION IN CONCEPTUAL
DESIGN**

A Thesis

by

KARTHIKEYAN KRISHNAKUMAR

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

MASTER OF SCIENCE

December 2003

Major Subject: Mechanical Engineering

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ABSTRACT

Material and Processes Selection in Conceptual Design. (December 2003)

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Materials and manufacturing processes are an integral part of the design of a product. The need to combine materials and manufacturing processes selection during the early stages of the design has previously been realized. The work that generally attracts the most attention is by M.F. Ashby. This methodology, like others, concentrates on materials and manufacturing processes selection after the conceptual design is completed and before moving into embodiment design.

The disadvantage of waiting until the conceptual design is completed to address materials and manufacturing processes is that the designer cannot search for conceptual solutions when dealing with issues relating to the materials and manufacturing processes domains. By not considering these issues early on in the design process, the scope for innovation is reduced and this results in the designer being fixated on the configuration at hand. It is well recognized that this is not the best way to address a design challenge and an even worse approach to innovation.

The basic framework for which enhancements and improvements are suggested is the design methodology practiced and taught by the members of the Institute for Innovation and Design in Engineering (IIDE) at Texas A&M University. Conceptual design is very much a part of the IIDE design process; but the current format concentrates on functional parameters and how to search for conceptual solutions for these, and does not highlight materials and manufacturing issues in the preliminary design stages where it could be most helpful.

The work documented in this thesis is an attempt to ensure that there is no disconnect between function oriented design and the materials and manufacturing processes that are applicable to that design. The core of the thesis is to incorporate a thought process which will help the designer during conceptual design phase to:

1. Consciously question if there materials and manufacturing issues;
2. Identify critical parameters in both of these domains; and
3. Search for conceptual solutions to these identified critical parameters.

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CHAPTER I

INTRODUCTION

1.1 OVERVIEW

This thesis attempts to enhance the design methodology developed by the Institute for Innovation and Design in Engineering (IIDE) at Texas A&M University [1]. In engineering, a design methodology is a procedure for working through the sequential stages in the design of technical systems [2]. These enhancements are achieved by paying special attention to those critical parameters that lie in the materials and manufacturing processes domains during the conceptual design phase. The goal of the thesis is to ensure consideration of materials and manufacturing process issues as an integral part of the concept-configuration looping phase of the IIDE Design Process. Achieving this goal will enable the designer to uncover and address the critical parameters associated with materials and manufacturing processes in a timely manner, and help develop conceptual solutions for these critical needs.

The proposed approach uses an established methodology [3] for selection of materials and manufacturing processes as a tool during conceptual design. This selection process for both materials and manufacturing processes was proposed by Ashby [3] and is well-suited to the needs of the designer at the conceptual design stage. The advantages of considering materials and manufacturing issues during conceptual design, as against doing these selections at the conclusion of conceptual design, are:

- i. If there are compromises made during selection of materials and/or manufacturing processes, and these compromises result in, or introduce, new critical parameters, conceptual solutions to these critical parameters can be pursued.

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

- ii. If there are critical parameters in the materials and manufacturing process domains associated with the configuration being developed, then the designer can identify these and develop conceptual solutions as needed. Alternatively, the designer may decide that the critical parameters cannot be satisfied, discard the concept, and search for new concepts that are not governed by the same materials and manufacturing process related critical parameter.

This helps to move the decisions on materials and manufacturing processes to the formative stages of the design process, and in turn, enables the designer to explore conceptual solutions that take into account not just the critical parameters from the functional domain, but also those from the materials and manufacturing process domains. This is the single most important enhancement offered by the proposed approach.

1.2 THE ENGINEERING DESIGN PROCESS

The IIDE Design Process is a systematic approach that can assist all designers, but especially inexperienced designers, to create innovative solutions to a “Need.” The IIDE Design Process is taught to students as a part of the mechanical engineering senior design courses at Texas A&M University. The students then practice its implementation in the design projects that are undertaken as a part of the course.

The process:

- i. Helps the designer identify, “What must be done?” to create a ‘design’ that will satisfy a ‘need’.
- ii. Guides the designer through procedures for performing each of the design tasks.
- iii. Provides evaluation procedures to judge how well the process has been implemented and how well the design satisfies the ‘need’ during each stage of the design.

1.3 WHY DURING CONCEPTUAL DESIGN?

Traditionally material and manufacturing process selections are done at the detail design stage. At this stage the design is generally fully laid out and some part or component drawings have already been created. It also means that critical issues related to materials and manufacturing processes are often not identified until this phase, forcing the designer to make compromises to overcome these critical issues. The later in the design process the designer uncovers such issues, especially those critical to the success of the design, the less flexibility the designer has to accommodate and incorporate the required changes into the design. The consequence is acceptance of a modified design which may be non-optimal because of compromises driven by delivery dates, lead times, and associated costs.

In the author's opinion, the detail design stage is too late a point in the product development cycle to identify the constraints imposed by materials and manufacturing processes and to go back and redesign the product. Clearly the need is to ensure the discovery of the critical design parameters associated with materials and manufacturing processes issues during the early, formative stages (conceptual stages) of the design process. This is where innovation and discovery occur, and where high-level decisions on solutions, concepts, and embodiments are first made. At this stage of a design, the leverage of good choices is high because they get magnified throughout the later, more resource-intensive, stages of the design.

1.4 DESIGN FOR MANUFACTURING (DFM)

Design for manufacturing is often defined as "The process of proactively designing products to: (1) optimize all the manufacturing functions - fabrication, assembly, test, procurement, shipping, delivery, service, and repair; and (2) assure the best cost, quality,

reliability, regulatory compliance, safety, time-to-market, and customer satisfaction” [4]. This means all these issues have to be addressed as early as possible in the design process so that the design makes a smooth transition from the design phase to the manufacturing phase.

1.5 WHY MATERIALS AND MANUFACTURING PROCESSES TOGETHER?

Design for Manufacturing, as defined above, does not take materials into consideration. This is unfortunate because there is a close relationship between materials and manufacturing processes, analogous to the relationship between design and materials. Materials and manufacturing process issues are inextricably coupled through the design. A designer cannot make decisions on one without constraining the other. So the designer should make decisions on material and manufacturing process issues as early as possible and should do so during the formative stages of the design in order to identify the constraints on these decisions and due to these decisions.

1.6 ORGANIZATION OF THIS THESIS

Chapter II of this thesis gives an overview of the IIDE Design Process and an insight into the concept-configuration looping procedure, which is where the enhancements to the process are being proposed.

Chapter III introduces Materials and Manufacturing Processes Selection. It gives the problem statement for this thesis; lays out a logic path designed to ensure critical parameter identification in the materials and manufacturing process domains; shows how this logic path can be used during the concept-configuration looping procedure to result

in a modified concept-configuration looping procedure; provides examples to show how the logic path works.

Chapter IV discusses guidelines for materials and manufacturing processes selection that are derived from Ashby [3].

Chapter V gives a Case Study which illustrates the application of the proposed enhancements.

Finally, Chapter VI gives the Recommendations and Conclusions that are drawn and lists some of the areas for future work that can be done to improve the IIDE Design process.

CHAPTER II

BACKGROUND – THE IIDE DESIGN PROCESS

This chapter summarizes the Institute for Innovation and Design in Engineering (IIDE) Design Process. This is based on the author's interpretation of the IIDE Design Process, and on research and knowledge gained from a research paper on the IIDE Design Process [1], and various books on design methodologies [2,5,6,7].

2.1 THE IIDE DESIGN PROCESS

An outline of the IIDE Design Process is shown in Fig. 1. The process consists of 4 main stages, namely:

- 1) Need Analysis [1,2].
- 2) Conceptual Design [1,2,5,7].
- 3) Embodiment Design [1,2].
- 4) Detailed Design & Product Creation [1,2].

2.1.1 Need Analysis

The need analysis stage of the IIDE Design Process is where the designer defines the given problem in a technically precise, yet abstract, manner that does not unintentionally box the designer into a solution set. Being “technically precise” means: (1) that the problem should be defined in an unambiguous and scientific manner; and (2) that the designer should be able to quantify the need by attaching units to it. Being “abstract” means that the designer should not point to a solution domain while defining the problem in a scientific manner.

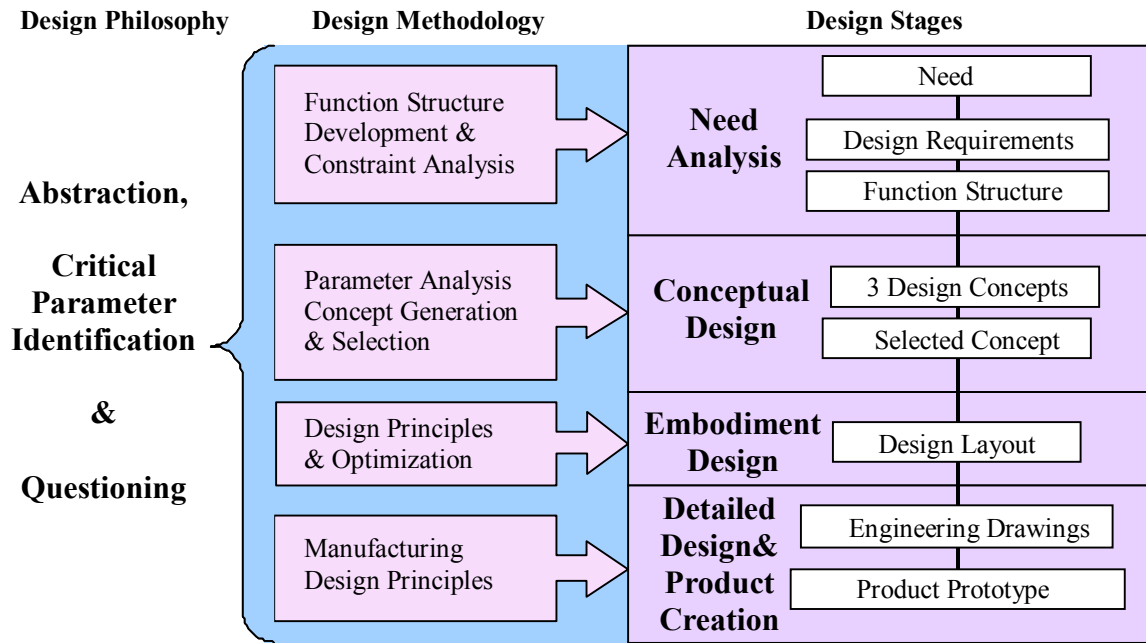


Fig. 1. Overview of the IIDE Design Process [1]

The three skills that are required to perform the whole design activity, but especially the need analysis and the conceptual design tasks are:

- i. *Abstraction*: This is the process by which a perceived need is progressively transformed, from a colloquially expressed statement into a functionally precise definition that identifies the real design task in technically fundamental terms. This enables a designer to identify the core or the essence of the problem by increasing the insight that the designer has into the problem [1].
- ii. *Critical Parameter Identification*: This is the process of identifying the critical or the key issue for the design need, i.e., the designer identifies the parameter that would “make-or-break” the design. The success of any design is in identifying those parameters critical to the design need and developing solutions to satisfy them. Hence, it is absolutely essential for the designer to identify the true critical parameter.

- iii. *Questioning*: The designer is asked to systematically question every word and connotation of the functions, and the constraints, for unbiased precision. This guides and enables the designer to find out more about the problem. Specifically, it enables the designer to identify what he/she needs to know but *does not yet know*, in order to complete a design that will best satisfy all the critical parameters and solution independent needs.

A procedure suitable for abstraction of the need statement from a more colloquial statement is [1, 2]:

- i. Omit requirements that have no direct relationship to the design problem.
- ii. Express quantitative needs in the form of qualitative needs, i.e., identify what function needs to be performed to achieve the quantitative need.
- iii. Question and eliminate perceived and fictitious constraints.
- iv. Increase the technical conciseness of the need statement.

The goal of need analysis is to help the designer better understand the problem, identify the critical parameters involved and define the problem in engineering or scientific terms, and enable innovation. This is achieved through abstraction, critical parameter identification, and questioning as described above.

The outputs of the need analysis stage are:

- i. A Need Statement – The Design Need.
- ii. A set of Design Requirements.
- iii. A solution independent Function Structure – functional requirements, and the associated constraint requirements and design parameters.

Each of these is detailed and explained further in the sections that follow.

Need Statement

The design task, as posed by the customer, is studied very carefully and the functional requirements, the non-functional requirements (like cost, operating conditions, etc.), and the constraint requirements are identified. The designer then identifies the core function that the design must perform in order to satisfy the basic requirement of the design. This

is called the “Primary Function.” The designer also identifies the “Primary Constraint”, which either puts a well-reasoned limit on the technological space in which solution sets can be sought and/or estimates the magnitude of the design parameter by which the suitability of any solution will be judged. These two components are then assembled into a technically precise sentence that is called the “Need Statement.” This need statement is usually in the form of an active noun-verb pair that expresses, in precise technical terms, the core need for the whole design. It answers the question of what the design must absolutely do, to what, for what, and/or with what. The final need statement captures exactly what the design must perform, and is, simultaneously, technically precise and yet most general. This is achieved by questioning every word of the need statement for scientific accuracy, ambiguity and necessity.

The methodology for arriving at a need statement can be illustrated by considering the example “Design the brakes for a car.”

The customer need given to the designer is: “Design a system to stop a car.” This is the result of the actions that the design should perform and not what actions the design/system should perform. This does not help the designer because it is in colloquial terms. Also this does not identify the constraint, or the critical issue that limits the solution set. Hence the ‘primary function’ for this case is the core function that the design must perform in order to satisfy the requirement, which is ‘to stop a car’. The ‘primary constraint’ sets limits on the solution domain that can be used to satisfy the primary function.

The first iteration would be to quantify the customer need. The need statement would now read something like, “Design a system to stop a car which is traveling at 60 miles/hr within 300 feet.” The Critical Parameter (CP) here is “Distance traveled before the car stops.”

The next step would be to make the quantitative need statement qualitative. The design must reduce the velocity of the car from 60 miles/hr to “zero” miles/hr, i.e., decelerate the car. The deceleration should be such that the car stops within 300 feet, i.e., at a required spatial rate. Therefore the need statement now reads, “Design a system that

will reduce the velocity of the car at a required rate.” Here the CP is “magnitude of deceleration.”

Now the designer questions the need statement: “Does my design have to decelerate the car?” The answer is “Yes”, but this is the result of the action performed by the design and not what the system must do in order to satisfy the design need. So the designer asks, “What should my design do to reduce the velocity?” The design has to remove or dissipate the translational kinetic energy of the car. Now the need statement reads, “Design a system that will dissipate the translational kinetic energy of the car at a required rate.” The associated CP is “rate of dissipation of kinetic energy.”

Again the designer questions what “dissipate” means. The word ‘dissipate’ implies a solution set wherein the kinetic energy is removed from the system and dumped into a sink, i.e., not utilized or stored. But, before the energy can be ‘dissipated’ it must be transformed, i.e., changed into another form of energy by doing work. Recognition of the need for transformation brings the realization that the energy can either be stored or dissipated and does not necessarily have to be thrown away. Now the need statement reads, “Design a system that will transform the translational kinetic energy of the car at a required rate.” The CP here is the “rate of transformation of kinetic energy.”

Now the designer asks the question, “What limits the rate of transformation of the kinetic energy of the car?” The three things that could affect the rate of transformation are:

- i. The maximum rate that is physiologically safe for the occupants of the vehicle.
- ii. The need to maintain the directional stability and the associated dynamics of the suspension system of the car.
- iii. The traction characteristics of the road-tire interface.

So the rate of transformation should be such that the driver does not lose control over the car or be injured when braking hard.

The designer now identifies “highest acceptable rate of transformation” as the constraint that sets the limit on the magnitude of the rate of transformation. “Acceptable” is interpreted here as the rate at which the driver does not lose control over the car. The final need statement now reads, “Design a system that will transform the translational kinetic energy of the car at the highest acceptable rate.”

This process of iterative abstraction, critical parameter identification, and questioning is summarized in Fig. 2.

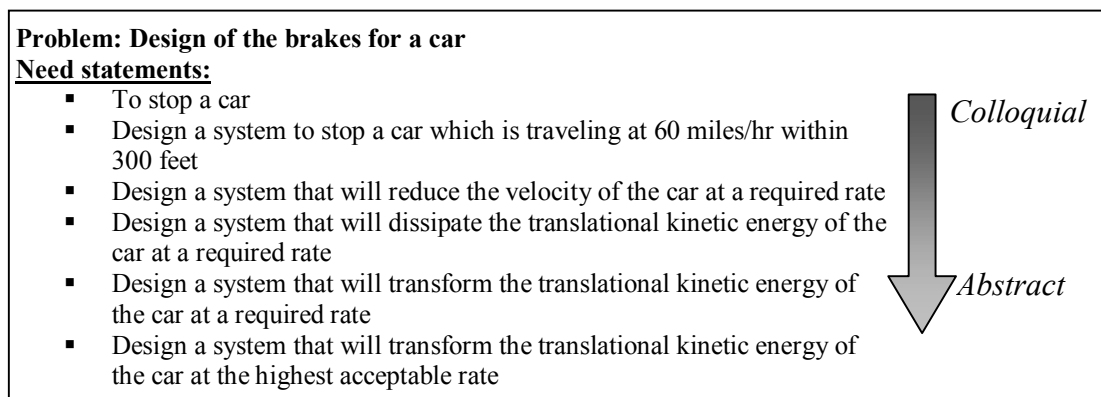


Fig. 2. Abstraction of the Need Statement for the Design of the Brakes for a Car [1]

The goal of the need statement is to very quickly focus the attention of the designer on the core function that the design must perform, while alerting the designer to the overriding constraint that will set bounds on the solution domain.

Design Requirements

The designer establishes the design requirements using the functional requirements, the non-functional requirements, and the constraint requirements. Design requirements must be attributes of the design that are quantifiable so that the designer, after performing the

design task, can check and verify if the design does indeed satisfy the functional requirements. “Quantifiable” means that units and numbers can be attached to the design requirements. These often look very different from the original “specifications” given by the customer. The original “specifications” given by the customer generally include a qualitative list of non-functional requirements and constraints on the design rather than design requirements. For example, the customer specifies requirements using comparative values or terms such as cheaper, safer, lighter, better, more, faster, smaller, less, little, etc. The functional requirements are used as the first level of evaluation criteria for choosing possible conceptual solution sets.

Function Structure

The function structure is represented in the form of a hierarchical flowchart in which the task defined by the need statement is first broken down into solution-independent functions called higher-level Functional Requirements (FRs), e.g., FR1, FR2. These are then broken down further into sub-functions or lower-level functional requirements, e.g., FR1.1, FR1.2, etc. When there are only a finite number of solution domains that can satisfy a functional requirement, the designer represents them in the form of Functional Alternatives (FAs), e.g., FA 2.1.1, FA 2.1.2, etc., as illustrated schematically in Fig. 3. Each of the FRs in the function structure is a need in itself and hence an active noun-verb pair. By satisfying each of these lower-level needs, which have been derived from the overarching need expressed in the need statement, the designer is equipped to efficiently develop a design which satisfies the overall need.

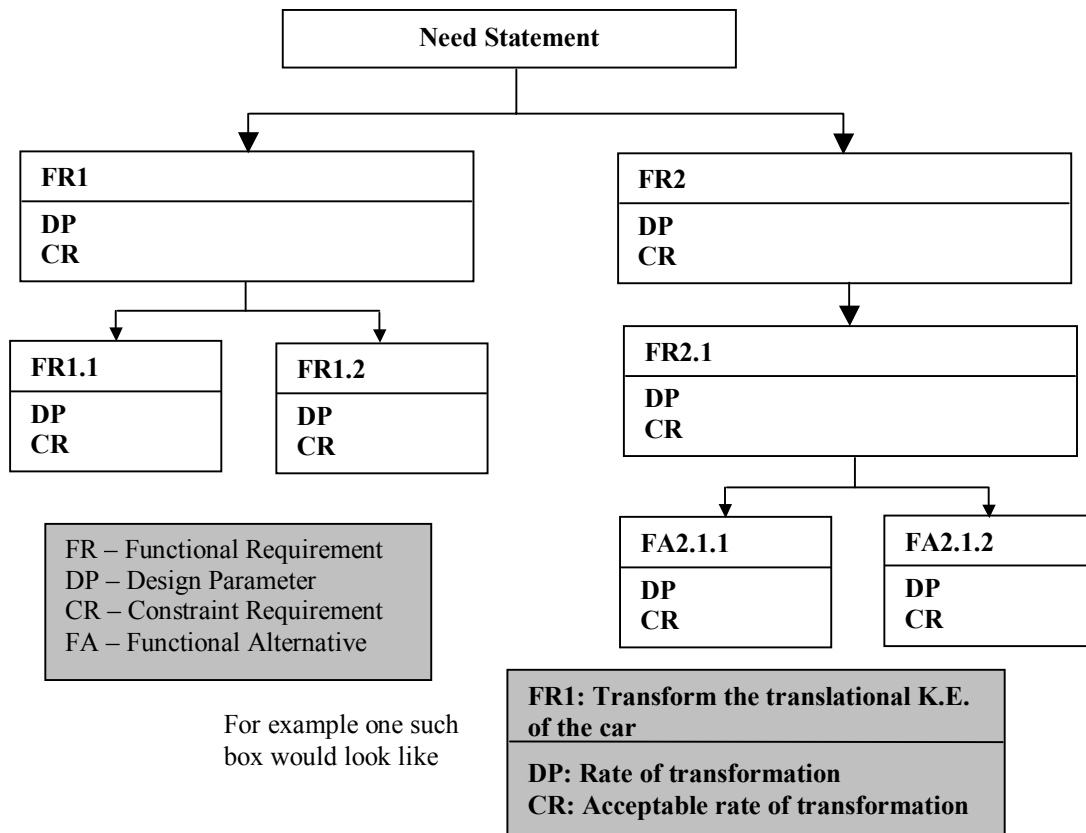


Fig. 3. Example of a Function Structure

The three main goals of the function structure are:

- i. To classify the need into functions that *must* be performed by any solution to the design need.
- ii. To serve as an effective tool for breaking down the design task into smaller parts (FRs), each of which is solution independent. The designer is also encouraged to keep these FRs uncoupled, i.e., independent from each other, so that the designer can optimize the solution to each individual FR without affecting any of the others. This is termed independence of functions and is described below [8].
- iii. To help the designer stay solution independent and to keep the solution domains open, thus enabling innovation at every subsidiary functional level.

The purpose of developing a function structure is to establish a solution independent framework for meeting the design need. The nature of the function structure is such that when moving down the function structure, from the need statement to the first-level sub-functions and then to the second-level sub-functions, in a hierarchical order, the questions answered are “When?” and “How?” Similarly if we move up, starting with the lowest-level function and go to the need statement, the question that is answered is “Why.”

Each of the functional requirements (FRs) defines what any solution to the design task *must* perform. Associated with each FR is a Constraint Requirement (CR), and a Design Parameter (DP). Design parameters (DPs) are scientific variables that characterize the respective FR, i.e., the designer designs to this parameter. A design parameter can be a single parameter (e.g., rate of energy transformation, viscosity, temperature, etc.) or a dimensional or dimensionless group of parameters (e.g., Reynolds number, strength/weight ratio, etc.). It is preferred that a design parameter have units. By satisfying the quantification of the design parameter a designer can verify that the design satisfies the functional requirement. As stated before, every FR also has a CR associated with it. The CR sets the magnitude of the DP, or the conditions under which the functional requirements should be satisfied. In most cases the CR quantifies, and sets the acceptable range, on the value of the associated DP.

Independence of Functions [8]: The designer should check for coupling or independence of the functions that are at the lowest level. This means that the designer should check if the performance of one function affects or alters the performance of another function. Independence of functions allows one functional requirement to be satisfied without altering or influencing another. The preferred way of checking for independence of FRs is to check if each of them has a different DP [8]. If two FRs have the same DP they are likely to be coupled, though this need not always be the case.

An example for such an exception can be illustrated by considering the design of the brakes for a car. Consider the functions: (1) transform the kinetic energy of the car; and (2) transfer the kinetic energy of the car. The two functions have the same design

parameter of 'rate of energy transformation', but the functions are independent. The rate at which the transformation should take place depends on the maximum acceptable rate as defined before. The rate at which the energy transfer should take place depends on the solution domain, although the sum of the energy transferred must be equal to the energy transformed. For example, if the energy is to be stored then the rate of energy transfer depends on the rate at which the energy can be stored.

Coupling of functions is usually the cause of design conflicts. If the conceptual solution to one of the coupled functions is realized, then the conceptual solution for the other function will depend on the existing conceptual solution. This will create difficulties for the designer because it usually forces the designer to make non-optimal compromises. These compromises limit the degree of optimization that can be achieved for each of the two FRs.

Progress in moving to the lower levels in the function structure ceases when it is no longer possible to identify sub-functions that are solution independent. The designer is encouraged to stop because further development of the function structure will be solution specific and cause fixation on a particular solution set. It is seldom possible to remain solution independent below the third-level sub-functions. Functional alternatives as stated before are used to indicate the existence of a small and finite number of solution domains. Each functional alternative then becomes the head of its own hierarchy of FRs, which may be carried further as solution independent functions within the identified solution set.

2.1.2 Conceptual Design

The IIDE Design Process views conceptual design as that key stage of the design process where the designer searches for fundamental scientific principles, laws, effects, or constitutive relations that can be exploited through a suitable embodiment and can subsequently be developed into a design that satisfies the need. This is where the designer looks at basic concepts to satisfy the design need. This, in turn, helps in creating different, innovative, and more effective embodiments that meet the need. This

approach is preferable to taking existing embodiments and modifying them to fit into the new design. Looking at fundamental scientific principles to solve the problem rather than modifying existing configurational solutions, avoids fixation on the part of the designer and helps him/her to be innovative. Conceptual design is much more than mere “Brain Storming for ideas.” It is a systematic search by the designer for useable scientific principles. The goal of conceptual design is to generate at least three, conceptually-different and implementable, conceptual design layouts.

Conceptual design in the IIDE Design Process consists of movement between three domains/spaces: Concept Space, Configuration Space and Evaluation. This is illustrated in Fig. 4.

- i. Concept space is where creative and innovative concepts, based on scientific principles, are generated. These concepts can be further developed to satisfy the design need.
- ii. Configuration space is where an embodiment for the idea generated in the concept space is realized.
- iii. Evaluation is an important intermediate stage when moving in either direction between the concept and configuration space. It helps in identifying the key issues involved and in ensuring development of a viable embodiment for the proposed concept.

The action of moving from the concept space to the configuration space is termed “Particularization.” The action of moving from the configuration space back to the concept space is termed “Generalization.” The designer moves back and forth between these domains using a procedure termed concept-configuration looping. The reason for the designer to move back into concept space to solve the issues discovered in the configuration developed is because it helps the designer to think out of the box and find innovative solutions to the issue. This is one more reason why conceptual solutions to critical issues are preferred to configurational changes.

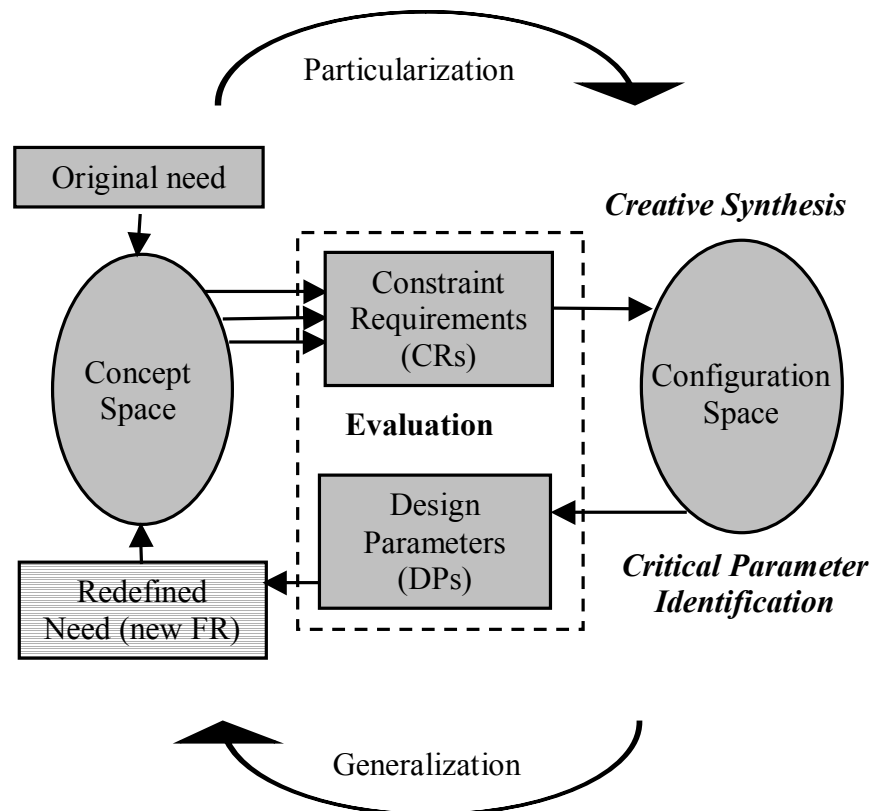


Fig. 4. Concept-Configuration Looping Procedure for Concept Evaluation [2,5]

The success of the designer in creating a good conceptual design depends on three skills that are very important for creating an effective design. These are:

- i. Possessing the knowledge and skill necessary to identify concepts or scientific principles, and think conceptually, i.e., scientifically, in the “concept space.”
- ii. The ability to synthesize configurations that can embody the concepts generated in the concept space, i.e., the ability to think of different conceptual configurations, for each of the concepts discovered, in the “configuration space.”
- iii. The ability to identify the critical parameter for the developed configuration, and to abstract from this critical parameter the redefined need which is used to search for conceptual solutions.

In this manner the designer is encouraged to come up with three conceptually-different and configurationally-feasible conceptual design layouts, each of which can provide a potential solution to the design need. These concepts must be different from each other at a fundamental level, i.e., the underlying fundamental or scientific principle must be different for each of these three concepts. If the underlying principle is the same then, in reality, the so-called “concepts” are just configurational variations of the same concept. One way of checking to see if the concepts are fundamentally different is to check if the critical parameters are different for each of the configurations developed. If the critical parameters are the same, then it is very likely that the solutions are configurational variations of a single concept. This challenge of coming up with three different conceptual solutions forces the designer to consciously search for different scientific principles that can be exploited to satisfy the design need. This forces the designer to think “out of the box” and maximizes the potential for innovation.

The viability of the concepts generated in the concept space can be checked using a methodology termed “Parameter Analysis” [5]. This methodology has been expanded and incorporated into the IIDE Design Process as the “Concept-Configuration Looping” procedure. This was illustrated in Fig. 4 and is explained in more detail below.

Concept-Configuration Looping Procedure

The process of developing a viable conceptual solution starts by bringing an “original need” into the “concept space.” This original need is usually one of the critical lowest-level FRs, the associated design parameter, and the constraint requirement that defines the magnitude of what is to be done with the design parameter. The designer now asks the question: “What fundamental scientific principle can I use to address this particular FR.” This helps the designer to discover concepts that may be capable of forming the basis for a solution to the design need. Before proceeding to the configuration space, each potential concept is checked to see if it satisfies the CRs. If a concept cannot satisfy the CR, then the concept is discarded and the designer goes back into the concept space and searches for a different concept.

If the concept is capable of theoretically satisfying the CRs, the designer then thinks of embodiments that can exploit this concept to satisfy the need. This thinking helps the designer to go from the concept space to the configuration space. The designer is encouraged to think of all the different possible configurations for the same concept. This process of developing different configurations for the same concept is termed “Creative Synthesis.”

Each configuration is then evaluated against the design requirements that are applicable for the particular function. The designer first identifies the critical parameter that needs to be satisfied for a configuration to work. The designer asks the question, “What is the most critical issue in the configuration, that I have developed, that limits its use in a potential design solution based on this concept?” This is the critical parameter for that particular configuration. The identification of the critical parameter is done in the configuration space. The identified critical parameter is then generalized, i.e., the designer formulates a “new need statement” to address the critical parameter. This is termed the “redefined need.” The redefined need is similar to the need statement for the design, in that it is a technically precise, yet solution-independent statement. This redefined need is then taken into the concept space to identify one or more concepts. One of these concepts is incorporated into the original embodiment to address the “redefined need.” This process continues through numerous iterations until a viable conceptual solution is developed.

It is a general guideline that, if a concept survives at least three well-executed concept-configuration loops, then there is a very good possibility that it can be developed into a competitive solution to the design need. Once a viable solution has been reached, the designer is asked to divorce from this conceptual solution, go back to the original need that was first brought into the concept-configuration looping procedure, search for another conceptually-different solution, and then go through the same process as with the first concept. This process is repeated until the designer has three, fully developed, and viable conceptual design solutions.

Let us again consider the example of the design of the brakes for a car. When the designer brings the critical lowest-level FR, “Transform the translational kinetic energy of the car”, into the concept space to search for concepts, one of the concepts that can be identified is “Air Drag.” The DP for the FR in question is the rate at which energy needs to be transformed and the CR is the required rate of transformation, i.e., the highest acceptable rate of transformation. Now, the concept of air drag is evaluated against the CR, to check if the concept satisfies the required rate at which the energy needs to be transformed. The answer is that the concept does indeed have the potential of transforming the kinetic energy at the required rate. The designer now tries to embody the concept. One of the embodiments for air drag is a flat plate. The designer then identifies the critical parameter for the configuration, which will be “the area of the plate normal to the flow.” The designer abstracts, from the critical parameter, the need to “maximize the area that is normal to the flow” and searches for concepts. A conceptual solution to this would be a parachute. An order of magnitude calculation shows that the area required to achieve the required rate of transformation is very large. The successful embodiment of this concept is also limited by the space requirements for deploying the parachute and the need to achieve repetitive braking. These do not satisfy the constraint requirements. Hence the concept is discarded and the designer looks for new concepts that could be developed into potential solutions to satisfy the need.

Continuing with the discussion on the design of the brakes for a car. The designer identifies the concept of ‘Coulomb friction’ for the FR, “transform the translational kinetic energy of the car.” The designer evaluates this concept to check if it can fundamentally satisfy the CRs by doing an order of magnitude calculation and finds that the concept has the potential of satisfying the design need. The designer then proceeds to the configuration space to develop a configuration that uses this concept. One of the possible configurations is: “Two surfaces rubbing against each other where the kinetic energy is used to do work against the friction force between the two surfaces, thus producing heat energy.” The designer evaluates this concept with the design requirements that relate to the FR. This configuration has the potential of satisfying the

design need but the amount of heat generated causes temperatures at the interface of about 600°C. Hence, the designer identifies the critical parameter which needs to be satisfied for this configuration to succeed as the temperature at the interface of the two surfaces. This is now generalized to give the new re-defined need: “Maintain the interface below a critical temperature”, where the critical temperature is the temperature at which the two surfaces melt or lose integrity. The designer then moves back to the concept space to search for solutions to this re-defined need. Some of the possible conceptual solutions to this need are:

- i. Finding materials that can withstand the maximum temperature that might be reached.
- ii. Cooling the interfaces between the two surfaces, i.e., removing the heat from the interface.

The process of iterative movement between the concept and configuration spaces enables the designer to search for conceptual solutions to the problems identified in the configuration space, rather than fixing the design in the configuration space and trying to improve it there. As stated before, if an initial concept survives three well-executed concept-configuration loops, it is then very likely that the resulting embodiment can be developed into a viable, innovative and competitive solution to the design need. Note that a well-executed loop identifies the true critical parameter, not just *a* parameter, associated with the proposed embodiment. If, during one of the three loops, the designer is not able to satisfy the critical parameter, the concept is discarded and the designer returns to the concept space to search for another concept that does not have the same critical parameter as the previous one.

A fully-developed conceptual design layout is an assembly of conceptual solutions. Each of these conceptual solutions is chosen from the different conceptual solutions available for every lowest-level FR in the function structure. The designer develops such conceptual design layouts starting with the three fundamentally-different conceptual solutions corresponding to the critical lowest-level FR in the function

structure. A conceptual design layout is considered fully developed if all the lowest-level functions have been addressed.

Evaluation of the Concepts Developed

At this stage the designer has three viable conceptual design layouts. Any of these can be pursued to satisfy the design need. The task is to select one of these for further development during embodiment design and detail design. The tool used for evaluation of competing conceptual design layouts in the IIDE Design Process is a modification of an evaluation procedure developed by Pugh [7]. This tool helps the designer identify both the strengths and the weaknesses of each conceptual design layout with respect to the others. Having done that, the designer can overcome a weakness by:

- i. Going back into the concept stage; identifying the lower-level function that relates to the weakness; and replacing the existing conceptual solution for that functional requirement with another.
- ii. Trying to combine the benefits of two different conceptual design layouts and creating a hybrid conceptual design layout.

The designer uses the design requirements as the evaluation criteria to compare each of the conceptual design layouts in a relative sense. An evaluation matrix is created with these criteria. For example, Table 1 shows the evaluation matrix for support bearings for a shaft. The designer chooses the hydrodynamic bearing as the datum since it is the most widely used type of bearing for this application. The other types are then compared relative to the hydrodynamic bearing on the various evaluation criteria and a “+” for “better than”, “S” for “same as”, and “-” for “worse than” is assigned. The sum of the evaluations of each concept is shown at the bottom of the table. Note that no relative weights or levels of importance are assigned to any of the evaluation criteria.

Table 1: Concept Evaluation for Different Kinds of Bearings [7]

Criteria	Hydro-dynamic	Rolling element	Hydro-static	Magnetic
Speed limit	D A T U M	S	S	+
Freedom from vibration		S	+	+
Power loss		+	S	+
Life		S	+	+
Initial cost		+	-	-
Lubrication cost		+	-	+
Total +'s		3 +	2 +	5 +
Total S's		3 S	2 S	0 S
Total -'s		0 -	2 -	1 -
+ ⇒ Better than; S ⇒ Same as; - ⇒ Worse than				

The process described above is an example of a general process that can be applied to evaluate conceptual design layouts for any design. This evaluation helps the designer identify at a glance:

- i. The conceptual design layout that best satisfies the design requirements.
- ii. The weaknesses in a particular conceptual design layout relative to the others.

In the first case, the designer can proceed with the chosen conceptual design layout or, in the second case, can return to conceptual design phase to improve the concept as explained before.

The designer is encouraged not to assign weights to the different evaluation criteria at this stage, since personal bias might influence the evaluation. Prioritizing or

arranging the evaluation criteria /design requirements in the hierarchical manner shown below is preferred to assigning weights:

- i. Functional Requirements.
- ii. Non-Functional Requirements.
 - a. Safety / Ethics: Operator safety, end-user safety, environmental safety, etc.
 - b. Cost: Set-up cost, raw material cost, production cost, quality cost, etc.
 - c. Other non-functional requirements: Time-to-market, lead-time to set-up production, lead-time to get raw material, etc.

When comparing two conceptual design layouts, prioritizing the evaluation criteria in this manner minimizes the possibility of choosing a conceptual design that does a better job of satisfying the non-functional requirements but does not do as well when it comes to satisfying the functional requirements.

2.1.3 Embodiment Design

Embodiment design is the stage where the chosen conceptual design layout is taken in as the input and the final design layout is the resulting output. The embodiment design stage can be further divided into two stages: synthesis and analysis [6]. During synthesis, an embodiment for the conceptual design layout is created. This embodiment is a more detailed physical representation of the conceptual design layout that better spells out the details of the interfaces in the design. The designer is encouraged to follow the ‘Seven Design Principles’ of the IIDE Design Process derived from the design principles detailed by Pahl and Beitz [2], while creating the embodiment. This embodiment is then taken into the analysis stage where it is analyzed to check what can go wrong with the embodiment. This feedback is carried to the synthesis stage where the designer modifies the embodiment to overcome the predicted failure mode. Now the modified design is again checked for failure, and modified again if necessary. This process is repeated until all possible failure modes have been eliminated. Fig. 5 shows a simple schematic diagram of the process described above.

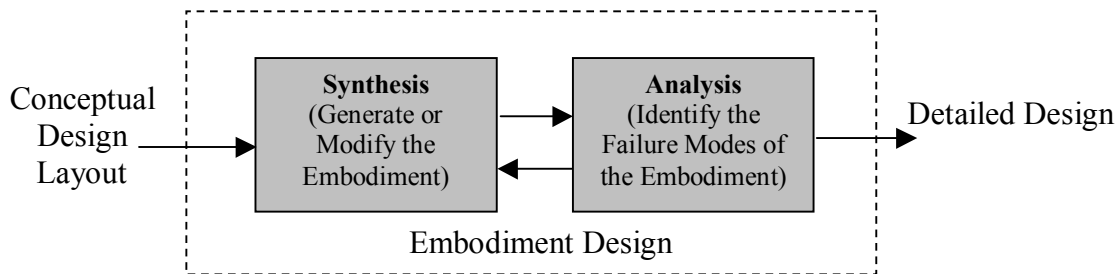


Fig. 5. Schematic Representation of Embodiment Design

The resulting design layout, which is the output of this stage, gives the shape and arrangement of the various components of the design, and the details of the interfaces between them. The design requirements and the interface specifications must be clearly specified at this stage to avoid ambiguity during detail design. Embodiment design is a labor-intensive stage. It is therefore critical that, before the designer starts doing embodiment design, the concept that has been chosen for embodiment design, not only satisfies the functional requirements, but also the non-functional requirements. If the conceptual design needs modification later, most of the work done in the embodiment design stage will be wasted.

The result of embodiment design is only one of the many possible embodiments for a particular conceptual design layout. Ensuring the best possible embodiment is therefore both desirable and necessary. The designer can check the generic quality of the embodiment using the ‘Seven Design Principles’ [2]. Violation of any one of these principles highlights a fundamental weakness in the embodiment that has been developed.

Seven Design Principles

- a. *Separate functions*: This means that the functions that the design must perform should be independent of one another, and not coupled. In other words, performing one function must not affect, or hinder, the performance of the other.

The designer is encouraged to follow this principle right from the development of the function structure. The designer encounters a coupled function when there is not a one-to-one mapping between the FRs and the DPs [8]. The designer can solve this problem by separating the functions in time or in space. The advantages of separation of functions are:

- i. It reduces product development time since the optimization of the different functions is easier.
 - ii. It helps design teams to work independently of one another because interfacing is easier, and the interface specifications are better spelled out.
 - iii. It improves product quality and performance since the optimization of one function does not adversely impact the quality and performance of the other.
- b. *Provide a direct & short transmission path*: The designer studies the path of transfer of energy, materials, information, forces and moments. The path of flow of all of these should be direct with particular attention to transfer across interfaces. The advantage of this is that it simplifies loading and there is efficient and effective usage of material. The principle should be applied particularly if rigid components need to be designed for transfer of forces and moments [2].
- c. *Constrain only to the required degree, i.e., do not over-constrain*: The designer is encouraged to constrain the design only to the required degree. Over constraining has a direct coupling with tolerances. The more constrained a design, the tighter the tolerances required. An over-constrained design usually has reduced life, increased cost, longer time-to-market, and can be very difficult to manufacture, assemble, and maintain.
- d. *Minimize gradients / Match impedances*: The designer should take care that there are no sudden changes in stiffness, or resistance to the flow of force, or energy. This can be achieved by incorporating one, or all, of the following:
- i. Matching deformations.
 - ii. Providing functional symmetry.

iii. Providing physical symmetry.

As this principle is always followed by nature to achieve a state of equilibrium, it would be beneficial to incorporate this in all designs. The goal of the designer is to minimize the gradients and to match the impedances.

- e. *Provide functional symmetry / Balance forces and moments internally:* The forces, moments, and deflections associated with the design should be balanced by creating symmetry in the design. Symmetry can be obtained functionally or physically. Creating symmetry between functions can eliminate undesirable functions. However, asymmetry by design can be utilized in certain situations for advantage. For example, by designing the various connections in a computer asymmetrically, it is ensured that the user can connect the different cables in *only* one way – the right way.
- f. *Design for self-help:* The overall effect is made up of two effects; an initial effect and a supplementary effect. The initial effect triggers the physical process required to perform the required function but is insufficient on its own to achieve the desired result. The supplementary effect performs the actual function. A good example of this would be self-sealing covers for pressure vessel applications.
- g. *Design to fail-safe:* The principle of fail-safe allows the occurrence of a failure of the design to perform a function but ensures that there are no catastrophic consequences because of the failure. This means that in a system that is designed to fail-safe, failure of any component to perform its function will not cause serious damage to the entire system or its surroundings. Any failure in a system that is designed to fail-safe will not result in:
- i. Serious damage to the entire system, causing shutdown.
 - ii. Injury to personnel operating the system.
 - iii. Catastrophic effects on the environment in which the system operates.

2.1.4 Detailed Design and Product Creation

At the output of the embodiment design stage, the designer already has a functionally performing layout of a design which satisfies the design need. The detailed design stage of the IIIDE Design Process concentrates on the specifics of each component and on how they interact with other components in the design. This involves creating:

- i. The detail or production drawings for the design and for the individual components of the design. (Drawings are the single, most important means of communication between the design engineer and the manufacturing engineer).
- ii. The assembly procedures and manufacturing layout instructions for the components so that they can be manufactured and assembled.
- iii. The test procedures and quality control measures that need to be followed in order to meet the required quality standards before the design is released into the market.

The above information, i.e., the drawings, assembly procedures, etc., will help the production engineer in manufacturing and assembly of the product. Since the manufacturer is going to infer all the information from the output of this stage, representing the design correctly and completely through drawings and descriptions is as important as the design itself.

At the end of detailed design and before the design is sent to manufacturing, the designer is encouraged to check for the following [2]:

- i. Observance of in-house standards.
- ii. Accuracy of dimensions and tolerances.
- iii. Essential production documents.
- iv. Ease of acquisition of standard parts.

If the designer has failed to consider any of the above factors, the detail design is considered incomplete. The designer has to address all these issues before forwarding the design for production.

2.1.5 Prototyping or Product Creation

Prototyping is the final stage where a trial or model of the design is built before it is sent to production. This is done to verify if the design performs all the required functions. The development of CAD/CAM and simulation software now provides the designer with tools through which 3-D models of the various components can be created and assembled to see how the various components interact. This helps the designer in identifying design flaws, if any, and correcting them. The goal of a good design process is to minimize, and if possible eliminate, ‘development’ during prototyping. In other words, prototyping should be a verification activity not a design phase.

2.2 SUMMARY

In this chapter we have discussed in detail the IIDE Design Process. The IIDE Design Process is an established design methodology and can help any designer but especially a novice designer to be innovative. The IIDE Design Process is based on the philosophy of three basic and necessary skills of the designer namely, abstraction, critical parameter identification, and questioning. The IIDE design process helps the designer create innovative solutions to any design challenge by providing an effective and efficient framework for the designer to perform the three actions mentioned above during every stage of the design namely, need analysis, conceptual design, embodiment design and during detailed design.

Let us quickly review these stages of the design process:

Need Analysis: During need analysis the designer must be careful to remain solution independent. The goal is to create a solution independent framework for the design, which the designer can exploit during the conceptual design stage.

Conceptual Design: The core of conceptual design is the concept-configuration looping procedure. Unlike other conceptual design procedures, this helps the designer identify

concepts, check their feasibility, and helps the designer develop a configuration that can be a potential solution to the design need. The designer is encouraged to perform at least three concept-configuration loops for any concept. This is because it is a general rule of thumb that if a concept survives three well executed concept-configuration loops then the resulting conceptual design layout is more often than not a feasible and competitive solution to the design need. Encouraging the designer to come up with three conceptually different solutions helps the designer to think out of the box and thus fosters innovation. The last step of the conceptual design stage is to select the best conceptual design layout for further development during the embodiment design stage. The selection procedure helps the designer to compare the different conceptual design layouts and identify the weaknesses relative to each other. The key to the selection procedure is that it further helps the designer to develop a new hybrid concept during the selection procedure by overcoming the negatives of one conceptual design layout using another.

Embodiment Design: During this stage the selected conceptual design layout is further developed using the seven design principles described earlier in this chapter.

Detailed Design: This is when the designer creates production drawings, selects suitable materials and manufacturing processes, and attends to the all the small details of the design.

The last two stages are the more labor-intensive stages of the design process. The design gets more and more rigid as it progresses through these stages. At this point changes that need to be made have huge ripple effects throughout the design. This is why the IIDE Design process encourages the designer to spend time and effort on the formative and innovative stages of the design namely need analysis and conceptual design.

There is however one weakness in the IIDE Design Process. This is the consideration of materials and manufacturing processes, which influence the feasibility of the design to a great extent, are not considered until the detailed design stage. Further chapters address this need to consider materials and manufacturing processes during the formative stages of the design, i.e., during conceptual design.

The conceptual design stage of the IIDE Design Process described in this chapter considers only one aspect of the design, which is to satisfy the functional requirements of the design. The basic design philosophy of the IIDE Design Process is to help the designer better understand the design problem, and help the designer discover early on in the design process the critical parameters that need to be addressed in order to satisfy the design need. There is no doubt that satisfying the functional requirements of the design problem takes precedence over all other non-functional requirements. However, the critical parameters that can “make-or-break” the design may result from the non-functional domain, primarily from the materials and/or the manufacturing processes domains. The probability of the designer not discovering these critical parameters is high since the process does not guide a designer to consciously consider such issues. A solution to this need is to consider materials and manufacturing process during the formative stages of the design, and to help the designer identify critical parameters in both these domains as proposed in the following chapter.

CHAPTER III

IDENTIFYING MATERIALS AND MANUFACTURING PROCESSES-RELATED CRITICAL PARAMETERS DURING CONCEPTUAL DESIGN

3.1 CURRENT IDE CONCEPT-CONFIGURATION LOOPING PROCEDURE

More often than not, the “critical parameter identification” that is part of the concept-configuration looping procedure described previously in Chapter II, only identifies functionally-critical parameters. This is because the designer is working with the functional requirements and tends to think functionally. However, there are non-functional requirements such as materials, manufacturing processes, on-time delivery, procurement, production, etc., that may become critical parameters for the design. The current concept-configuration looping procedure does not help the designer to readily identify these.

The goal of this thesis is to enhance the current concept-configuration looping procedure in ways that will help designers identify, and address critical parameters that occur in the domains of materials and manufacturing processes at the appropriate stage. It does so by introducing a modified concept-configuration looping procedure, which is detailed and discussed in this chapter. The objective of the modified concept-configuration looping procedure is to help the designer recognize the parameters that could affect performance as a result of the selected candidate materials and manufacturing processes. This will be achieved by identifying constraints within these domains and determining whether any one of the constraints could become the critical parameter for that configuration being considered. This materials/processes-related critical parameter must also be addressed, along with the functional critical parameter, if

the design need is to be met. By identifying and addressing both the functional and the materials/processes-related critical parameters together, and by doing so at the time when the formative conceptual design decisions are being made, the design process can be raised to the next level by being more comprehensive and better able to address the design task at hand.

3.2 WHY IS THE SELECTION OF MATERIALS AND MANUFACTURING PROCESSES NECESSARY DURING THE FORMATIVE STAGES OF THE DESIGN?

Traditionally, material selection occurs in the embodiment design stage, i.e., after the conceptual solution to the design need has been chosen. Ashby [3] points out that choosing materials and processes during the conceptual stage of the design leads to more optimal design solutions but he has no systematic method for enabling a designer to do so. Many designers select materials during conceptual design, but this often occurs unconsciously, without the discipline associated with a methodology. A methodology ensures that this step is not overlooked. It also enables experienced designers to effectively impart their design skills to inexperienced designers under their supervision. At the same time, a methodology provides a framework that can guide all designers, but especially an inexperienced designer, to better address the design task.

For a few designers, materials and manufacturing process selection is a conscious activity every time, for some others it is a conscious activity only some of the time. But very often, this activity is an intuitive one. An observation made by Otto and Wood [9] is that a conscious effort to address material selection during conceptual design occurs when:

- i. There is a previous history of problems related to choosing materials or processes for that particular product.
- ii. The product has evolved over a long time and the design is relatively mature.

- iii. The main need or constraint is to reduce the cost of the product, to extend the operating range of the product, or to optimize its performance.

An example of an evolved product in categories two and three mentioned above is the development of a disposable camera [9]. The manufacturer's requirement was to design a camera that produced satisfactory results and yet was so affordable that it could be disposable. The need statement for the camera would have read something like, "Design a reliable camera that will not have a retail price of more than \$7."

During critical parameter identification, the critical parameter for embodying the concept of a disposable camera would have been 'Cost', and the redefined need would have been: "Design a low cost camera suitable for mass production so as to make its utility override its life." The outcome was that:

- i. Suitable materials and manufacturing processes were chosen.
- ii. The design was tailored to exploit the 'Cost' advantages of these materials and processes [9].

Use of this extreme approach is not generally applicable, and may be useful only when designing certain classes of products that have evolved over a period of time or for consumables that are produced for a mass market. However, the underlying design philosophy of integrating materials and processes during conceptual design is a powerful one and should be encouraged for the betterment of any design methodology. This thesis attempts to generalize the philosophy of considering materials and manufacturing processes early on in the design process, into a viable design methodology. It is achieved by adapting a thought process of consciously considering materials and manufacturing processes in the formative stages of the design, in conjunction with the material and process selection methodology detailed by Ashby [3]. This is the basis for the proposed modifications to the IIDE Design Process that are detailed and explained further in the next section.

3.3 MODIFIED CONCEPT-CONFIGURATION LOOPING PROCEDURE

Consider the concept-configuration looping procedure of the IIDE Design Process described in Chapter II of this thesis. A block diagram version of this concept-configuration looping procedure is shown in Fig. 6. For the design to proceed any further, the critical parameter that is identified in the configuration space (Box 6) must be either eliminated, or a solution to satisfy this parameter must be found. It is a “make-or-break” issue for that specific embodiment of the concept under development. If not correctly identified, the execution of the design, as previewed in chapter II, will not be possible. Such a critical parameter, if not correctly identified early in the concept design stage may later become a “showstopper” for the design, force the designer to make non-optimal compromises during the later stages, or result in a design that does not meet its performance expectations. It is the author’s contention that often, the critical parameters identified by the process illustrated in Fig. 6 are functional in nature, and the critical parameters associated with materials and manufacturing processes remain undiscovered until later stages in the design processes. This leads to an inferior final product.

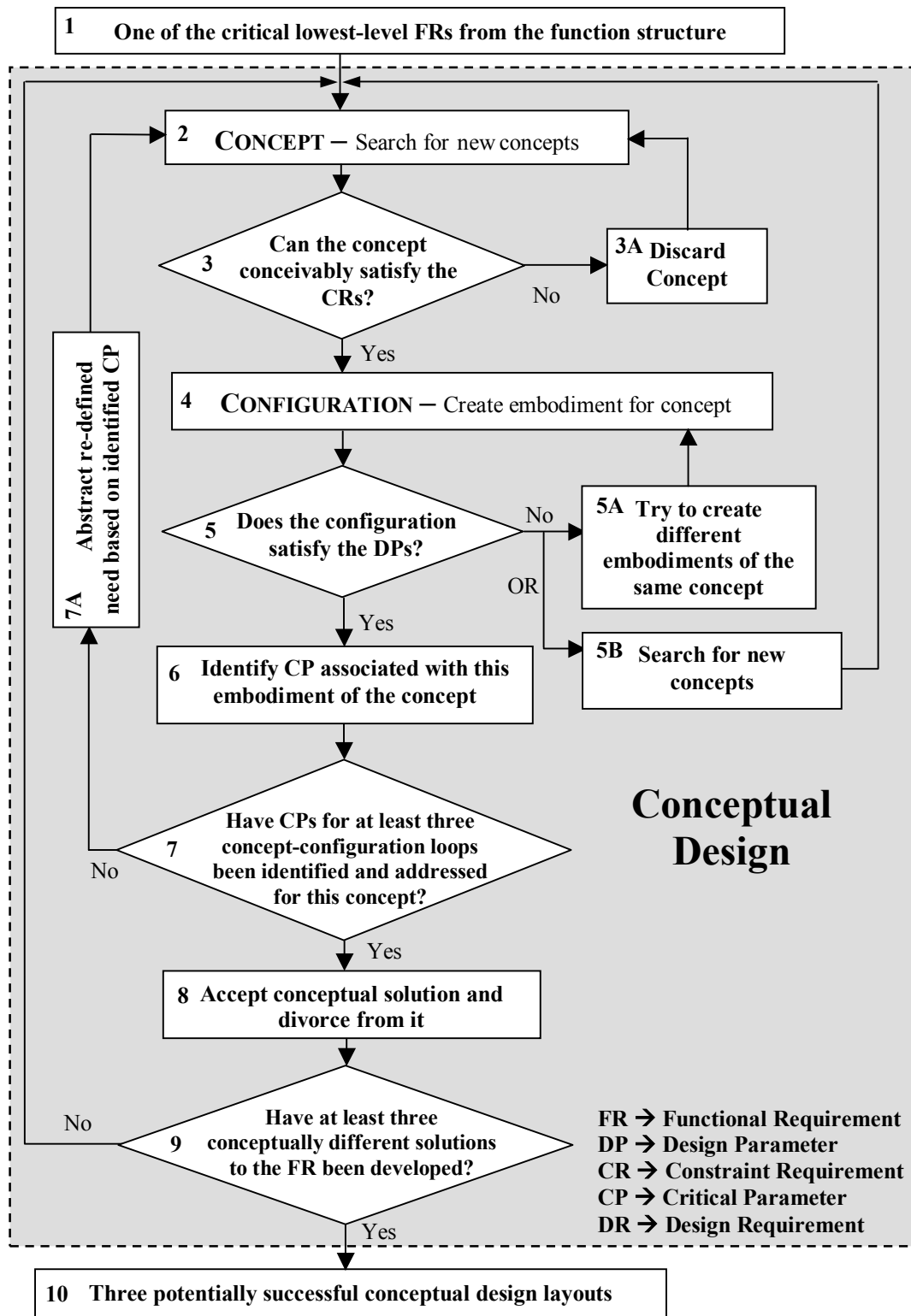


Fig. 6. Concept-Configuration Looping Procedure as Currently Followed in the IIDE Design Process

The drawbacks of such late discoveries of critical parameters related to the materials and manufacturing processes domains are:

- i. The designer has to redesign the part from the beginning, i.e., start with a new concept that does not have the same materials/process-related critical parameter.
- ii. The designer is forced to make configurational changes to the embodiment, which results in non-optimal solutions.
- iii. The designer is forced to make compromises that could have been avoided.
- iv. The designer wastes time, and money, in developing a concept that cannot satisfy the design requirements.

The author suggests that, while analyzing the embodiment to identify the functional critical parameter, the designer should consciously question whether materials and manufacturing process issues could potentially become critical parameters. If this is the case, the designer can follow the methodology proposed in this thesis to avoid the pitfalls discussed above.

In the discussion that follows, the materials selected and the manufacturing processes by which these materials will be processed, formed, or treated to give the final design, are considered together. The materials/processes-related critical parameter may arise in either one of these domains, or two critical parameters may arise from both domains simultaneously. They should then be considered sequentially, with the materials issues addressed first. Either way, the logic path given in Fig. 7 below can be used to develop conceptual solutions to these critical materials and manufacturing process related issues.

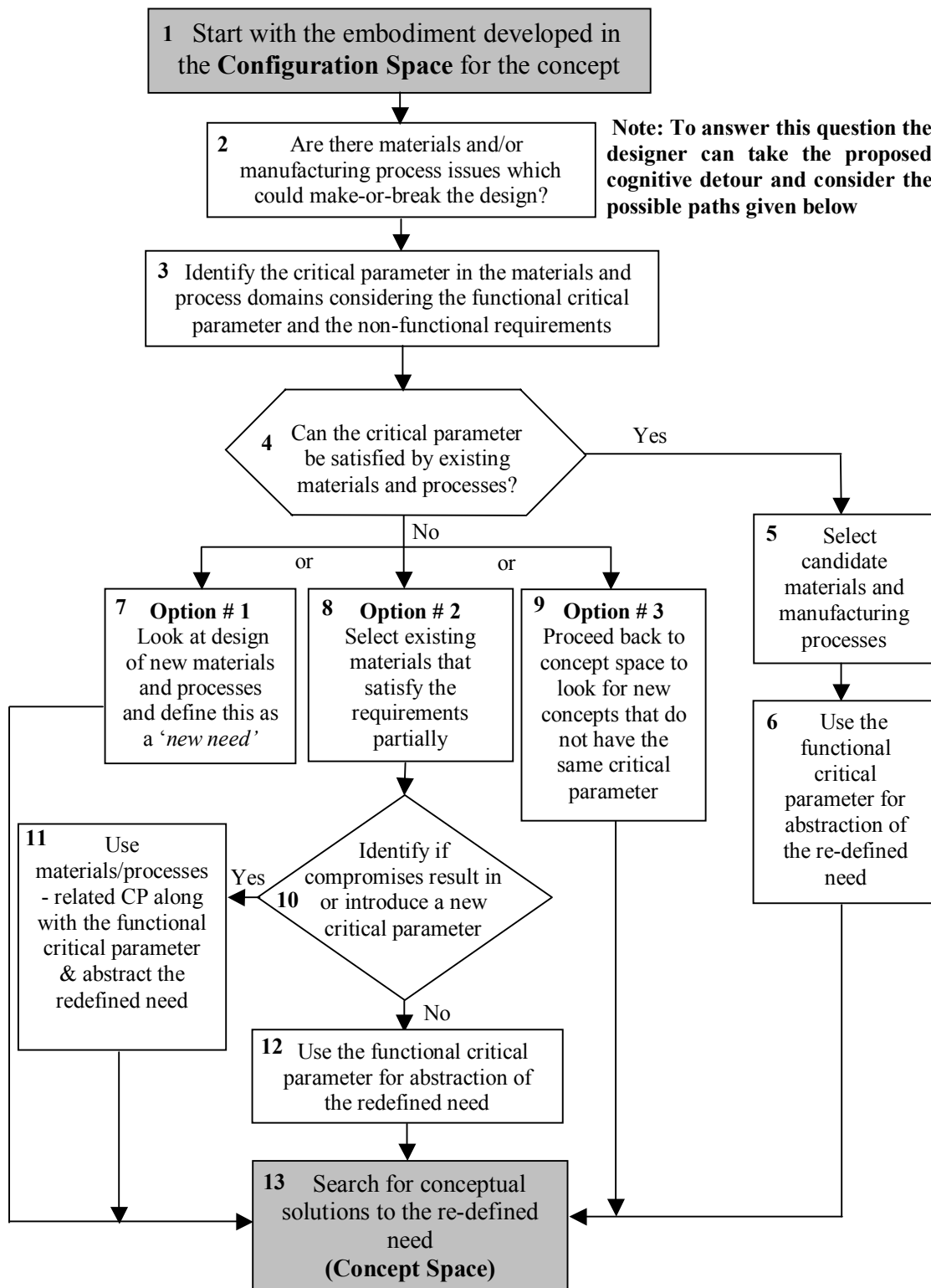


Fig. 7. Logic Path for the Modified Concept-Configuration Looping Procedure for Identification of Materials/Processes-Related Critical Parameter

There are five possible logic paths that the designer can take in Fig. 7. They are:

Path # 1: $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 13$: When the designer is able to find a group of candidate materials and manufacturing processes that meet the requirements of the design.

Path # 2: $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 7 \rightarrow 13$: When the designer decides to make innovations in the materials and/or manufacturing processes domains to meet the design need.

Path # 3: $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 8 \rightarrow 10 \rightarrow 11 \rightarrow 13$: When the designer identifies that the compromises made during the materials and/or manufacturing processes selection result in, or introduce, a materials/processes-related critical parameter, the designer uses this critical parameter, along with the previously identified functional critical parameter, to abstract the redefined need.

Path # 4: $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 8 \rightarrow 10 \rightarrow 12 \rightarrow 13$: When the compromises made during the materials and/or manufacturing processes selection do not introduce any new constraints or critical parameters, the designer uses only the previously identified functional critical parameter to abstract the redefined need.

Path # 5: $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 9 \rightarrow 13$: When the materials/processes-related critical parameter becomes a showstopper, the designer decides to discard the concept under consideration and searches for new concepts to develop to satisfy the original need.

Each of the *five* logic paths shown in Fig. 7 ensure that the critical materials and/or manufacturing processes issues are not overlooked during the concept-configuration looping procedure. In the following discussion, “critical parameter”, refers to the “materials/processes-related critical parameter”, unless noted otherwise.

The logic path starts with checking the embodiment developed for the concept in the configuration space by questioning: “Are there material or manufacturing process issues which could make-or-break the design?”(Box 2). Prompting the designer to consciously ask this question is the most important recommendation of this thesis. In order to answer this question, the designer has to understand the materials and

manufacturing process related issues, which leads the designer to take the proposed cognitive detour. The cognitive detour helps the designer to switch from a functional track to an implementation/realization track. The question may be: “Can this functional embodiment of the concept be implemented with existing/available materials and created with existing/available manufacturing processes?” This helps the designer to switch from searching for functional critical parameters to searching for critical parameters in the materials and manufacturing processes domains (Box 3). In order to do this the designer must be able to clearly understand the material requirements of the design and be able to identify the related material properties. These CPs may result from either the functional critical parameter, or from non-functional requirements.

Having identified the critical parameter, the designer asks the question, “Can the critical parameter be satisfied by existing materials and processes?” (Box 4). The answer to this question is most often, “I don’t know.” In such cases the designer follows the path for “No.”

If materials and/or manufacturing processes can be selected that meet the critical parameter requirements, the designer takes Path #1. The selection is made using the methodology proposed by Ashby [3] (Box 5).

Once materials and manufacturing processes have been selected that satisfy the materials/processes-related critical parameter, the functional critical parameter identified previously is used for abstraction of the re-defined need (Box 6). This re-defined need is taken back into the concept space, to search for conceptual solutions that will satisfy this newly discovered need with respect to this stage in the embodiment of the original concept, hence improving the conceptual solution (Box 13).

If there are no materials and/or manufacturing processes that satisfy the requirements, then the designer has three options:

Option #1, Box 7: If the designer realizes that the materials/processes-related critical parameter cannot be satisfied in the materials and/or manufacturing processes domains, innovations can be made in materials and/or manufacturing

processes that can form the basis of a completely novel design or design concept. In this case the designer takes Path # 2. In other words, instead of discarding the concept, the designer can abstract and define a “new” design need that relates directly to the materials/processes-related critical parameter (Box 7). This new need is now considered as a new design problem and the designer searches for conceptual solutions to the new need in the concept space (Box 13). The result of such concept searches may be developed into an innovative design solution in the materials and/or manufacturing processes domains.

Option #2, Box 8: The designer has the option of partially satisfying the requirements, by choosing a group of materials and/or processes that partially satisfy the requirements (Box 8). Then the designer identifies if the compromises made during the selection have introduced, or resulted in, a new materials/processes-related critical parameter (Box 10). The compromises made during the selection may result in a critical parameter in the functional domain, in the materials domain, or in the manufacturing processes domain. Alternatively a new critical parameter that was not part of the original configuration may be introduced in any of the three domains. For example, by choosing steel coated with ceramic as a material to satisfy the temperature requirements on the materials for the brakes of a car, the designer introduces a new critical parameter, namely, the difference in the coefficients of thermal expansion of the steel and the ceramic coating. If a critical materials/processes-related parameter is identified, then the designer takes Path # 3 where the designer uses this critical parameter, alongwith the functional critical parameter identified previously, to obtain the redefined need (Box 11). This ensures that conceptual solutions to any material and/or process issues are adequately pursued. If there are no new critical parameters identified, the designer takes Path # 4 where he/she proceeds to use the functional critical parameter to abstract the redefined need (Box 12). This need is then taken into the concept domain to search for conceptual solutions (Box 13).

Option #3, Box 9: If the designer realizes that the materials/processes-related critical parameter is a showstopper, and a satisfactory conceptual solution cannot be found, the designer discards the concept and proceeds to search for new concepts. In this case, the designer takes Path # 5, which takes the designer back to concept space, where the designer starts with the original need and searches for conceptual solutions that do not have the same materials/processes-related critical parameter (Box 13). This ensures that, if there are critical issues associated with the materials and/or manufacturing processes domains that could become showstoppers for that concept, the designer quickly discards the concept without wasting time and effort in further developing a concept that cannot be properly realized.

If, as is often the case, these critical parameters persist as required Design Parameters (DPs), the designer is left with one of two options: return to Option#1 (Box 7) to design a new material (an engineered material), or relax the constraint requirement on the need, i.e., accept a compromise on the performance requirements of the design.

The cognitive detour that is proposed in this thesis starts by consciously questioning the configuration that has been developed. The next step is materials/processes-related critical parameter identification, followed by abstraction of a redefined need from the materials/processes-related critical parameter that has been identified. The final step is to move back to the concept space to satisfy this redefined need. This cognitive detour is still based on the basic design philosophy of questioning, critical parameter identification, abstraction. It simultaneously enables innovation by helping the designer seek for conceptual solutions to the abstracted need. The primary benefit is that the proposed sequence reduces the likelihood of the designer not considering material and manufacturing process issues during the formative stages of the design, especially critical parameters that could become showstoppers for the design.

As stated before, the degree of success that can be achieved by following this approach is depends strongly on how well the designer can identify the materials/processes-related critical parameters associated with a given configuration.

Identification of the real critical parameter here is just as critical as in the previous discussion in Chapter II.

All of the different logic paths (Paths 1-5) shown in Fig. 7 start in the configuration space (Box 1) and end in the concept space (Box 13). Hence, these logic paths can be incorporated into the current concept-configuration looping procedure. As discussed before, materials and manufacturing process issues are coupled with functional issues and the critical materials/process parameter is just as important as the functional critical parameter. This is why these logic paths are given in parallel with the functional critical parameter identification process during the current concept-configuration looping procedure.

Incorporation of the logic paths (Fig. 7) into the existing concept-configuration looping procedure (Fig. 6), results in the modified concept-configuration looping procedure (Fig. 8). The shaded boxes highlight the modifications to the existing concept-configuration looping procedure. The modifications enable the designer to consciously question material and manufacturing process issues in parallel with the functional issues. The cognitive detour shown in Fig. 8 forces the designer to ask the question: “Are there materials and/or manufacturing process issues that could make-or-break the design?” The designer then follows the full logic path laid out in Fig. 7, but represented by a single box (Box 6B) in Fig. 8. This is why Box 6B is double-lined to indicate that it is not a single step, but a substitution for the whole logic path laid out in Fig. 7.

If a materials/processes-related critical parameter is identified by following the detour, then this critical parameter is used, alongwith the functional critical parameter, to abstract the re-defined need. The re-defined need is then used to search for concepts that will address not just the critical functional issues, but also the critical materials and manufacturing process issues. This helps the designer to methodically consider the critical issues in the materials and processes domains, identify critical parameters in both of these domains, and search for conceptual solutions to these critical parameters.

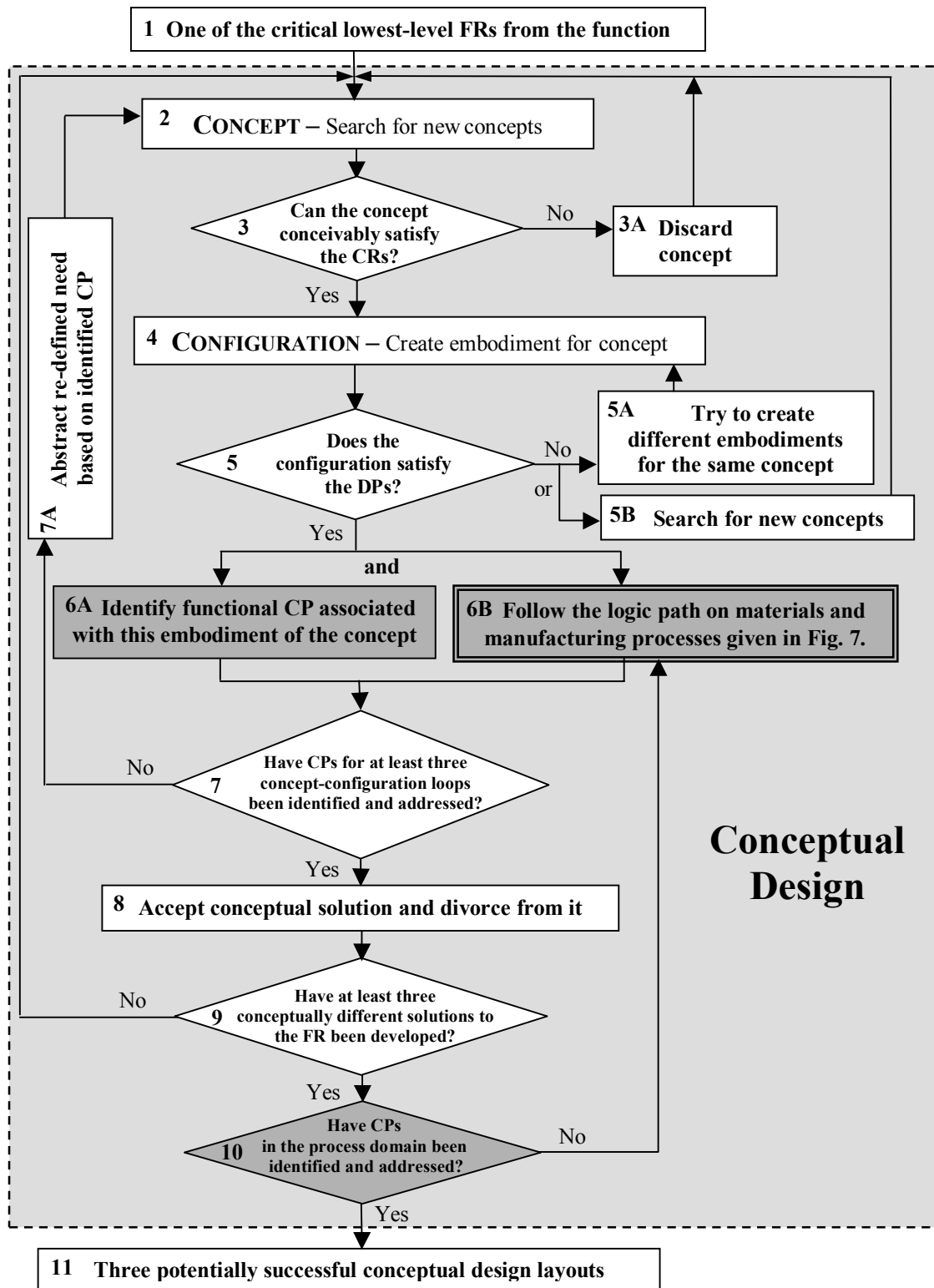


Fig. 8. Modified Concept-Configuration Looping Procedure to Address Materials and Manufacturing Processes-Related Critical Parameters

In addition to Box 6B, two other boxes have been shaded in Fig. 8. These are Boxes 6A and 10. The shading highlights the differences from Fig. 6. Box 6A represents the identification of the functional critical parameter. The box says “functional CP” rather than “CP” as it did in Fig. 6 to clearly distinguish that here the designer is to focus on the critical parameter in the functional domain. The other shaded box, Box 10 is a check to make sure that the designer has searched for critical parameters both in the materials and manufacturing processes domains and sought conceptual solutions to these issues before he/she proceeds to embodiment design.

3.4 EXAMPLE SHOWING HOW THE MATERIALS/PROCESSES-RELATED CRITICAL PARAMETER CAN ARISE FROM THE ASSOCIATED FUNCTIONAL CRITICAL PARAMETER

The modified concept-configuration looping procedure can be better understood by considering the example of the design of the brakes for a car. Continuing the discussion from the concept-configuration looping procedure discussed in Chapter II, let us start with the concept for transforming the kinetic energy of the car into heat through “Coulomb friction”, i.e., “dry friction.”

Concept (for transforming energy): Coulomb Friction – The translational kinetic energy can be transformed into heat by doing work against Coulomb friction.

Configuration: This requires two surfaces that are pressed together and rubbing against each other, with the “dry” friction between the two surfaces resisting the relative motion and thus doing work and producing heat. The kinetic energy of the car is used to do work against the friction force between the two surfaces. This work is converted into heat. Thus the kinetic energy of the car is converted into thermal energy. The source of the heat is at the interface between the two surfaces.

Critical Parameter Identification (Functional): The maximum permissible temperature at the interface is the critical issue from a functional standpoint.

Let us now take this example and walk through the modified concept-configuration looping procedure given in Fig. 8 and the logic path given in Fig. 7. During the modified concept-configuration looping procedure, after identifying the functional critical parameter (Box 6A; Fig. 8), the designer follows the logic path for materials and process considerations (Box 6B; Fig. 8). This leads the designer to the logic path shown in Fig. 7. The designer starts down this logic path by asking the question (Box 2; Fig. 7) - “Are there materials and/or manufacturing processes issues which could make-or-break the design?” In this case the materials issues certainly can. This is because the designer discovers that, while the temperature at the interface is not precisely known, the high required rates of kinetic energy transfer result in high rates of heat generation at the interface. The rate at which the heat is generated is higher than the rate at which this heat is removed from the interface. This causes the interface temperature to rise and the designer recognizes that this temperature will get progressively higher. The designer also recognizes that materials may not possess the required properties at these high temperatures and hence identifies that the availability of suitable materials can become a critical issue in this case.

The designer next proceeds to Box 3 in Fig. 7, where he/she tries to identify the materials related critical parameter. The maximum temperature that the interface should be allowed to reach depends on the maximum temperature that the materials in contact can withstand while still satisfying the other material requirements, such as high shear strength, high coefficient of friction and high coefficient of thermal conductivity. The designer identifies the desired combination of properties of the materials from the design requirements as detailed in the section below.

$$F = \mu N$$

where; F = friction force, N = normal force between the two surfaces, μ = co-efficient of friction between the two surfaces.

The aim of the designer is to maximize the friction force between the two surfaces in contact. The friction force is directly proportional to the normal force applied on the two surfaces and the coefficient of friction between the two surfaces. The relative motion between the surfaces and the friction force resisting this motion induce a high shear stress on both the materials in contact. Hence, both materials must have high shear strength at high temperatures.

The coefficient of friction for the pair of surfaces rubbing against each other should be high in order to maximize the friction force for a given normal force. It is also desired that the coefficient of friction be a constant over the operating temperature range. If the coefficient of friction changes, then in order to achieve a constant friction force the normal force (applied force) must change. Also the coefficient of friction is desired to be a constant because if it changes, for a constant applied force, either the car will decelerate too fast or decelerate too slowly. Specifically, if the coefficient of friction decreases with increased temperature, the normal force must increase in order to maintain a constant friction force. Oxidation of either of the two surfaces reduces both the coefficient of friction between the two materials, and the local shear strength at the surface. Hence, the materials should be resistant to oxidation.

The surfaces that are in contact are heated rapidly. At the same time there is non-uniform heating of both the surfaces in contact. These two effects combine to produce a thermal gradient. This is because the entire volume of each of the materials whose surfaces are in contact is not at the same temperature. This induces transient thermal stresses, which depend on the magnitude of the thermal gradient. Both the materials should be able to withstand these thermal stresses. Also non-uniform heating of the brakes may cause local warping of the contacting surfaces. To avoid warping and to maintain the flatness of the surfaces in contact, the heat being generated at the interface must be quickly distributed to the whole volume of both materials. Hence, the thermal diffusivity of both the materials should be high.

Even though resistance to wear is a desired property for both the materials in contact, the designer wants sacrificial wear to take place on the surface of the part that

can be most easily replaced. This is achieved by choosing two different materials one of which is the sacrificial material. The sacrificial material is called the brake lining. The designer ensures sacrificial wear of the brake lining, by choosing or formulating a material that has all of the previously mentioned properties, but a lower surface hardness than the non-sacrificial material.

Hence the materials used for the brakes are desired to have the following properties:

- i. High shear strength.
- ii. High coefficient of friction.
- iii. High coefficient of thermal conductivity.
- iv. High resistance to wear, but lower surface hardness than the non-sacrificial material.
- v. High resistance to oxidation.

All these properties are desired at the operating temperatures, which should be as high as possible. The critical material related parameter is the high shear strength at high temperature.

The designer next asks the question - "Can the critical parameter be satisfied by existing materials and processes?" (Box 4; Fig. 7) The designer discovers that materials cannot be selected to completely satisfy all the properties because the temperature at the interface is either indeterminate or not known. In other words, the answer to the question is "I don't know." In this case the designer is tempted to choose the path of "Yes" through Boxes 5 & 6 in Fig. 7 and perform materials and processes selection in the traditional deterministic way. In doing so, the designer would choose different materials that have the highest performance capability and then configure and size the rest of the design so that the interface temperature would not exceed their capability. The materials parameter would now clearly be the critical parameter for the design, and would dictate the path that the designer would take for the rest of the design.

However, with the answer to the question in Box 4 being “I don’t know” a designer is advised to not rely on the approach outlined above, but rather follow the “No” path to each of the other three options (Boxes 7, 8, & 9; Fig. 7). In most design problems the designer will face this dilemma for two reasons. The first reason is that the designer is in the very early stages of the design process where there are no predetermined desired values for the different material properties. The second reason is most design problems are solved in an iterative process of optimization of more than one material property, to satisfy the design need. Therefore, in this case, the designer should choose the path of selecting materials that partially meet the design requirements and explore the capabilities of combining materials through the technique of “Separation of Functions” (as explained in Chapter IV). This takes the designer to Box 8 in Fig. 7, where the designer selects materials that partially satisfy these requirements and prioritizes the list of candidate materials based on the shear strength of the materials at high temperature. The next step is Box 10 in Fig. 7, where the designer tries to identify if there are any constraints imposed on the design by the materials selection and whether any of these can become a critical parameter.

Let us assume that the brake lining material is either metallic or semi-metallic, e.g., graphite with finely powdered iron or copper and small amounts of inorganic filler. Heating of the material above its eutectoid temperature, followed by cooling it below the eutectoid temperature at a rate different from the rate at which it was originally manufactured, will change the microstructure of the material. This is undesirable because it changes the material properties. If the rate of cooling is faster than during manufacturing, the surface hardness of the brake lining will increase with use. The lining may cease to be sacrificial and cause excessive wear to the non-sacrificial parts. So, the interface temperature should be maintained below the eutectoid temperature for the sacrificial materials. This constraint on the interface temperature is the real critical parameter for the design and the design would be incomplete until this issue is addressed.

Since these newly unveiled constraints introduce a materials-related critical parameter, the designer moves to Box 11 in Fig. 7, where the materials-related critical parameter, “eutectoid temperature of the sacrificial materials”, alongwith the functional critical parameter, “maximum attainable interface temperature”, is used to abstract the redefined need. The redefined need may read, “Limit the interface temperature below the eutectoid temperature for the selected materials.” This now leads the designer into Box 13 in Fig. 7, which returns the designer to the concept space with a new redefined need. For this new need the primary function is, “limit the interface temperature”, and the associated constraint requirement is, “eutectoid temperature of the sacrificial material”, identified from the materials domain.

In summary, the above discussion on the example of the brakes for a car, shows that the proposed modifications to the existing concept-configuration looping procedure help the designer to consciously consider materials and manufacturing processes at an early stage during conceptual design, and helps the designer to identify the materials-related critical parameter. At this stage of the design, there have been no decisions made on the geometric configuration, but the designer is still able to identify the critical materials issues. The concept-configuration looping procedure, with the proposed modifications, clearly reduces the possibility of the designer failing to identify such issues, i.e., it minimizes the overlooking or late discovery of critical parameters that stem from the materials and/or manufacturing process domains, and which may become potential showstoppers.

In the above example the functional critical parameter was directly related to the critical materials parameter. The usefulness of the proposed modifications is further magnified in cases where the materials/processes-related critical parameter results from non-functional requirements. This is because the designer tends to think functionally at this stage of the design and the probability of the designer failing to identify and address critical parameters from non-functional requirements is quite high. This can have serious consequences downstream, when the materials/processes-related critical parameter can become a showstopper for the design at a later stage.

3.5 EXAMPLE SHOWING HOW THE MATERIALS/PROCESSES-RELATED CRITICAL PARAMETER CAN ARISE FROM THE NON-FUNCTIONAL REQUIREMENTS

As an example of a materials/processes-related critical parameter that lies in the non-functional domain, consider the design of a gate valve for fluid flow in oil wells under deep-hole conditions (very high pressures) and expected sour service.

Gate valves are on-off (open-close) devices. Gate valves never operate with the gate in an intermediate position. When closed, the gate seals against the high pressure, and the valve acts like a pressure vessel with pressure differentials of 10 – 20 Ksi. The valve must open against this pressure. When open, the valve must not offer any obstruction to the flow. When the gate is just beginning to open or when it is almost closed, the pressure difference through the orifice is high and the fluid velocities are consequently high. The resulting flow is a jet which is highly erosive. Also when the gate is closed, nearly-closed, or just about to open, the pressure difference between the gate and the valve-seat is high and the friction forces are large. The gate has to move rapidly to minimize the time during which erosion is most severe. For example consider the gate valve shown in Fig. 9, for a pressure of 10,000 psi and a pressurized area of the gate of 12.57 in², the force on the gate is 125,700 lb. The need statement for the design can be “Design a system that will prevent fluid flow while fully closed and contain the pressure.”

Consider the function “Contain pressure in the closed position.” The valve now acts like a pressure vessel and the region where the valve-seat joins the valve-body is exposed to the fluid and is subject to high stress. A designer following the current design methodology identifies the functional critical parameter as the very high principal stress at the base of the valve-seat. He/she will then proceed to abstract the redefined need using this critical parameter, and search for conceptual solutions to this redefined need.

The need will be for high strength alloys that can be heat treated to have high yield strength.

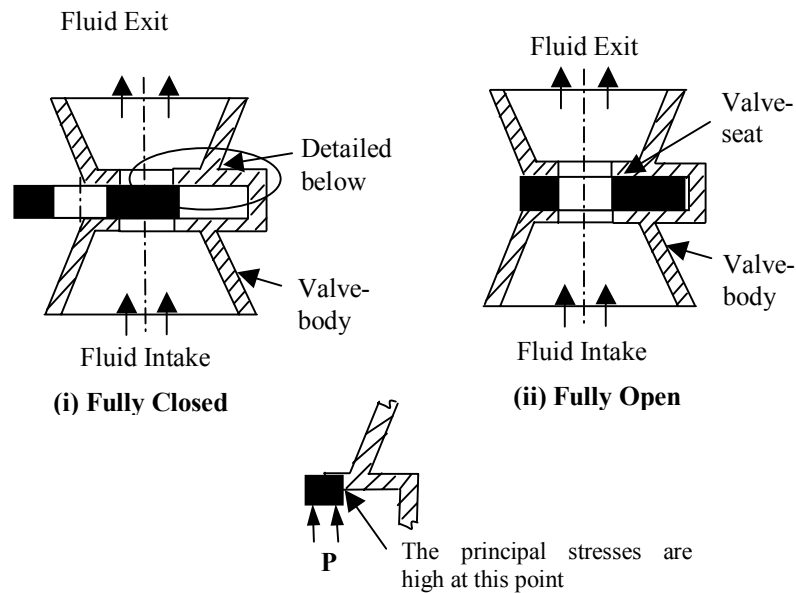


Fig. 9. Conceptual Sketch of a Gate Valve

When the designer completes a conceptual design, and tries to select materials that satisfy the design requirements, he/she will discover another critical parameter in the materials domain that results from the non-functional requirements, namely the sour environment. The production fluid contains hydrogen sulfide that induces Stress Corrosion Cracking (SCC) when a part is simultaneously subjected to high tensile stresses. The base of the valve-seat is exposed to the production fluid and is subject to high principal stress (tensile stress). Hence, the base of the valve-seat is susceptible to SCC.

To avoid SCC the designer has two options. One is to reduce the stresses involved below the threshold stress for SCC. The other is to choose a material that has a

yield strength below the threshold for SCC. The solution is often a combination of both of these options. The National Association of Corrosion Engineers (NACE) Standard (MR 0175), limits the maximum yield strength to which ferrous alloys can be heat treated when they are to be used under sour conditions. The standard also sets an upper limit on the maximum yield stress that the base of the valve-seat can be subjected to when the valve is in sour service.

The designer then identifies that the principal stress at the base of the valve-seat is not the real critical parameter. The real critical parameter in this case results from the possibility of SCC, for which the critical material property of yield strength has to be set at a lower value than would otherwise be the case. The critical parameter thus results from non-functional requirements and lies in the materials domain. Given that the non-functional requirements lead to a critical parameter in the materials domain and not in the functional domain, there is a high probability of the designer not discovering this critical materials issue if the designer followed the current IIDE Design Process.

In the above example, a designer following the modified concept-configuration looping procedure considers materials and manufacturing processes, and the functional requirements simultaneously. After identifying the functional critical parameter, “the principal stresses at the base of the valve-seat”, the designer considers materials and manufacturing processes (Box 6B; Fig. 8). This flags the designer to follow the logic path given in Fig. 7.

The designer starts by asking (Box2; Fig. 7) – “Are there materials and manufacturing process issues that could make-or-break the design?” In this case the answer is “I don’t know.” So, in order to answer the question the designer identifies (Box 3; Fig. 7) if there are critical materials and/or manufacturing process related issues that can make-or-break the design.

The designer considers the environmental conditions to identify the non-functional requirements imposed on the material and asks the question, “What is the issue with the environment that makes it hard to select a suitable material?” This ensures

that the selected materials will perform as required in the operating environment, which in this case is the production fluid. The presence of hydrogen sulfide as one of the components of the production fluid makes SCC a possible cause of failure for the design and the materials selected must be able to withstand SCC. Hence, the designer is able to identify the critical issue in the design as stress corrosion cracking (SCC) coupled with the high principal stresses.

In order to avoid SCC the designer has to select materials based on the NACE standard (MR 0175). The NACE standard restricts the yield strength of the material that can be used, especially for high alloy steels. The designer proceeds to the next step (Box 4, Fig. 7) and asks the question – “Can the critical parameter be satisfied by existing materials and/or processes?” Here again the answer may be “I don’t know.” In which case, the designer should take the path for, “No.” The designer considers his three options and chooses to satisfy the requirements partially, Option # 2 (Box 8, Fig. 7). The candidate materials are selected based on the desired properties in conjunction with the NACE standard. The designer then questions if there are any constraints that are imposed on the design. This brings the designer to Box 10 in Fig. 7. In this case, because of the possibility of SCC, the NACE standard imposes a restriction on the maximum yield strength of the materials that can be used. This constraint on the maximum yield strength becomes the materials-related critical parameter. The candidate materials that are finally chosen for the design are those materials that have high yield strengths as high as the maximum allowed by the NACE standard (MR 0175) and satisfying other properties like:

- i. High shear strength.
- ii. High tensile strength.
- iii. High resistance to corrosion from the production fluid.
- iv. High fracture toughness.
- v. Low coefficient of static friction between the valve and the valve seat.

Having identified the critical materials parameter, “maximum allowable yield strength as per MR 0175”, the designer proceeds to Box 11 in Fig. 7. The designer uses the functional critical parameter previously identified, “the principal stress at the base of the valve-seat”, and the critical materials parameter to abstract the redefined need. The redefined need could read, “Maintain the principal stress of the valve-seat below the maximum allowable yield strength of the materials chosen in compliance with MR 0175.” This redefined need is now taken into Box 13 in Fig. 7 for searching for conceptual solutions and the subsequent development of the configuration, which will not exceed the allowable principal stress anywhere in the body of the valve.

A quick review of this example shows that the logic path laid out in Fig. 7 helps the designer identify critical materials and/or process issues resulting from non-functional requirements. The proposed modification also helps the designer use this critical parameter to abstract the redefined need that can be used to search for conceptual solutions. This example further emphasizes the usefulness of the proposed modification in helping the designer gain insights into the materials and manufacturing process domains during conceptual design. These insights can be critical to the success of the design.

3.6 ADVANTAGES OF FOLLOWING THE PROPOSED METHODOLOGY

Following the proposed modifications to the concept-configuration looping procedure can help the designer make high level (conceptual) decisions regarding both materials selection and the corresponding manufacturing processes. These modifications encourage the designer to search for critical issues in both the materials domain as well as the manufacturing processes domain. They also help the designer seek conceptual solutions to critical issues in all three domains namely, design, materials, and manufacturing processes. The major advantages of incorporating the proposed modifications into the IIIDE Design Process are:

- i. The modifications help the designer to consciously consider materials and manufacturing process related issues during the formative stages of the design.
- ii. They encourage the designer to seek conceptual solutions to all of the critical parameters, i.e., if there are critical parameters in the material and manufacturing process domains, the designer consciously searches for conceptual solutions to these critical parameters. This would not necessarily happen when using the existing concept-configuration looping procedure.
- iii. They help the designer to consciously question material and manufacturing process requirements early in the design process, and thus help the designer revisit the requirements from the materials as well as the manufacturing processes standpoint.
- iv. They save a lot of time in product development and minimize the probability of a late discovery of materials/processes-related critical parameters which could force the designer to make compromises, or go back and re-design the part, or even worse, become a showstopper that prevents the design from being executed at all.

If there is a critical parameter in the materials domain, then the designer looks for solutions in:

- a. The manufacturing processes domain, to identify if there are processes that can impart the required properties to the selected candidate materials.
- b. The functional domain, to see what changes can be made to the geometry of the design.
- c. The materials domain, to see if innovation is possible by developing a new material that has the required properties.

Similarly, conceptual solutions to critical parameters in the process domain can be found in the following domains:

- a. The manufacturing processes domain, to identify if new processes can be developed to meet the requirements.

- b. The design domain, to see what changes can be made to the design itself to make it more suitable for use of the process.
- c. The materials domain, to see if there are materials that are more suited to the use of the manufacturing processes of choice.

Following the proposed modifications will enable the designer to select materials and manufacturing processes, identify the constraints in each domain, check if these constraints become critical parameters, and help the designer develop conceptual solutions to these constraints. This approach will reduce the product:

- i. Development time considerably, since the probability of redesign is reduced.
- ii. Evolution time can be reduced in some cases since the designer starts unbiased with the whole spectrum of materials and processes rather than using the predefined group of materials/processes that have been used traditionally. A prime example of this could be the body of a telephone. Plastics and the process of injection molding were developed in 1908 but they were not used to produce telephone bodies until the early 1980's [9].

3.7 SUMMARY

Chapter III discussed the following:

- i. The logic path for considering materials and manufacturing processes during conceptual design (Fig. 7)
- ii. How this logic path fits into the current concept-configuration looping procedure to give the modified concept-configuration looping procedure (Fig. 8)
- iii. Finally, a couple of examples to show the effectiveness of the proposed modifications in helping the designer identify materials and/or manufacturing related critical parameters. The first example shows how the critical materials related parameter can result from the previously identified functional critical

parameter, and the second one shows how the critical materials related parameter can result from non-functional requirements.

Chapter IV deals with the selection procedures for candidate materials and manufacturing processes. This chapter describes a selection procedure for both materials and manufacturing processes, which is derived from the selection procedure developed by Ashby [3]. He provides a methodology that considers two material properties simultaneously, but most often the designer faces a challenge of optimizing a group of materials properties. This chapter concentrates on choosing candidate materials based on a combination of material properties simultaneously, rather than looking for each individual property separately. The material must possess all these properties in order to be successfully satisfying the design requirements. It details a procedure that can be used to translate material requirements into candidate materials that are suitable for the design. The chapter also details a similar procedure for candidate manufacturing processes.

CHAPTER IV

MATERIALS AND MANUFACTURING PROCESSES SELECTION

Selection of the appropriate materials and/or manufacturing processes for a design is one of the key steps in the proposed modifications (Box 5, and Box 8 in Fig. 7). One of the challenges is to overcome the problem of the designer getting fixated with a particular family of materials and/or manufacturing processes. The probability of this happening is high when:

- i. The product being designed has evolved over a period of time.
- ii. A material/manufacturing process has been used historically for the given application.

Hence it is critical that while selecting both materials and manufacturing processes the designer not make unnecessary assumptions, that will box the designer into a certain class of materials or manufacturing processes. In this chapter a selection procedure has been developed to encourage innovation. This is done by applying the principles of questioning, critical parameter identification and abstraction to the materials and manufacturing processes selection procedure detailed by Ashby [3].

4.1 MATERIAL SELECTION

The three main stages, or domains, in the material selection process are shown in Fig. 10. The selection of materials as shown in Fig. 10 involves two major steps:

Step 1: Translates the material requirements of the design into the desired material properties (Requirements → Properties, Fig. 10).

Step 2: Finds the best match between the desired and the actual properties of different materials (Properties → Materials, Fig. 10).

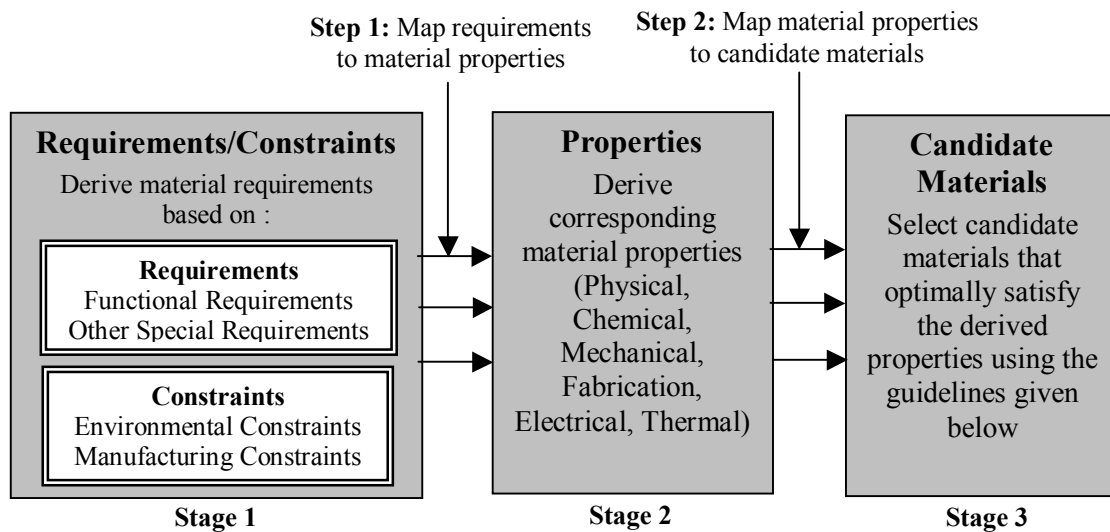


Fig. 10. Flowchart That Represents the Steps Involved in the Selection of Candidate Materials to Satisfy the Requirements of the Design

The first stage/domain in the material selection process is to derive a list of material requirements from the following factors. They are:

- i. *Functional Requirements:* The functions that a design must perform, as identified by a function structure and brought into conceptual design for concept search will enable the designer to define the requirements that the material must satisfy. For example, the functional requirements may require the material to have certain capabilities with respect to thermal conduction, yield strength, coefficient of friction, etc. Hence these requirements must be considered while selecting materials for the design.

Conflicting requirements in material properties may also be a reason for coupling between functions. Consider the example of the design of a cooking pan. One of the functions requires that the material have high thermal diffusivity, to conduct the heat from the stove to the food. Another function requires that the material be a good insulator, so that the user can safely handle the food. Hence there is a coupling between the functions of transfer heat from the stove to the

food and of allowing access to the user. This conflict in requirements is overcome by separating the functions in the material domain by choosing different materials for the pan and the handle.

- ii. *Environment*: The environment in which the design will operate or perform the required functions can restrict the scope of material choices. The materials need to satisfy these requirements irrespective of the solution domain to withstand the conditions they will be exposed to in the operating environment. For example, extreme temperature environments, corrosive environments, and prolonged exposure to radiation all lead to environment-imposed restrictions that become the primary criteria that need to be considered during material selection.
- iii. *Manufacturing Processes*: The geometry of the design influences both the manufacturing processes and the materials selected for the design. The influence of the geometry of the design on the materials selected for the design, although not apparent, is an important factor to consider during material selection. The geometry of the design influences the selection of manufacturing processes and the manufacturing processes in turn influences the selection of materials. For example, if the design is of a complicated shape/geometry, casting or injection molding would be a preferred manufacturing process. Hence the materials selected must be suitable for these processes. Therefore, the fabrication properties, required by the manufacturing processes influence the selection of materials and must be considered during candidate materials selection.
- iv. *Other Special Requirements*: The selection of materials can be influenced by some of the special attributes that the design must have and may be specified in the customer requirements. For example, the material could be required to be recyclable, biodegradable, non-toxic, appearance, finish, etc.

As mentioned above the designer will use all of the applicable factors listed above to derive the material requirements. Having discussed the factors or criteria that influence the material requirements, let us now identify some of the material properties, which is the next stage as shown in Fig. 10.

The designer must be aware of the assumptions that are made to define the material properties while translating the requirements into the relevant material properties. The designer is encouraged to question all the assumptions made to define the material properties and check if these are applicable to the particular design challenge. This is very important because, if the basic assumptions based on which a material properties are defined do not hold good for the design challenge undertaken, then the calculations based on the numerical values of these properties, that prove that the material is applicable to the design, are no longer valid. This implies that the material may no longer be suitable for the design.

It must be understood that materials are not classified by requirements but by material properties or attributes that they possess. These include:

- a) *Physical Properties*: Crystal structure, density, melting point, vapor pressure, viscosity, porosity, reflectivity, transparency.
- b) *Mechanical Properties*: Hardness, modulus of elasticity, poisson's ratio, yield strength, ultimate strength, fatigue strength, damping properties, cavitation, spalling, fracture toughness.
- c) *Thermal Properties*: Thermal conductivity, specific heat, coefficient of expansion, emissivity, absorptivity, melting point.
- d) *Chemical Properties*: Corrosion, oxidation, thermal stability, stress corrosion cracking, hydrogen embrittlement.
- e) *Electrical Properties*: Conductivity, dielectric constant, hysteresis.
- f) *Fabrication Properties*: These properties are related to how the material can be processed in order to obtain the final shape of the design or to obtain/retain the needed properties of the material. These properties of a material indicate what would be the best, or the easiest, way of fabricating the finished part from the raw materials. Examples of such properties are: castability, heat treatability, hardenability, formability, machinability, inspectability, and weldability.

After identifying the material properties that correspond to the material requirements identified (Step 1), the designer can proceed to selecting a group of candidate materials that satisfy these properties derived from the requirements (Step 2) by using the selection procedure described below (First Selection and Second Selection). The third stage is a set of candidate materials that satisfy the requirements of the design and is shown in Fig. 10. Having identified and defined the three stages clearly, let us discuss how to proceed from one domain to another. A method for proceeding from one stage to another and finding a list of candidate materials is described in the following paragraph.

4.1.1 Material Selection Guidelines

Step 1, as shown in Fig. 10, will be to translate the requirements into material properties. This involves identifying the material properties that relate to the material requirements. Similar to critical parameter identification, this depends on the skill of the designer and also his knowledge of the design. Consciously asking the designer to translate requirements into material properties will help the designer identify the requirements that he/she cannot readily translate into material properties. The designer can now research and identify the material properties that are related to these requirements. For example, if the material requirement is, “Material must be resistant to fracture”, the designer can identify that the material property that he/she should look for in order to satisfy this requirement is “Fracture toughness.”

Once the material properties that need to be satisfied have been identified the next step (Step 2) would be to select candidate materials that possess these material properties. The designer, when starting the search for suitable candidate materials, should start with an inclusive list of possible materials, and proceed to rapidly shorten the list by using only those criteria that are absolutely necessary. These criteria are the ones that the material must satisfy irrespective of the solution domain. This keeps options open and helps avoid fixation on one single material. The goal is to maximize the opportunity to come up with new material choices or material combinations.

Figure 11 shows the materials selection strategy proposed by Ashby [3] with a few modifications. The guidelines shown in Fig. 11 help the designer to:

- i. Consider the whole spectrum of available engineering materials at the beginning of the selection process.
- ii. Quickly focus attention on the materials that are applicable to the design using certain constraints, termed non-negotiable constraints (First Selection; Fig. 11). This is explained in detail in the next section.
- iii. Prioritize and optimize the list of materials using the Critical Material Performance Characteristic (CMPC) (Second selection; Fig. 11), which is a mathematical representation of all the material properties needed to satisfy the critical functional requirement and is explained in more detail in a subsequent section.

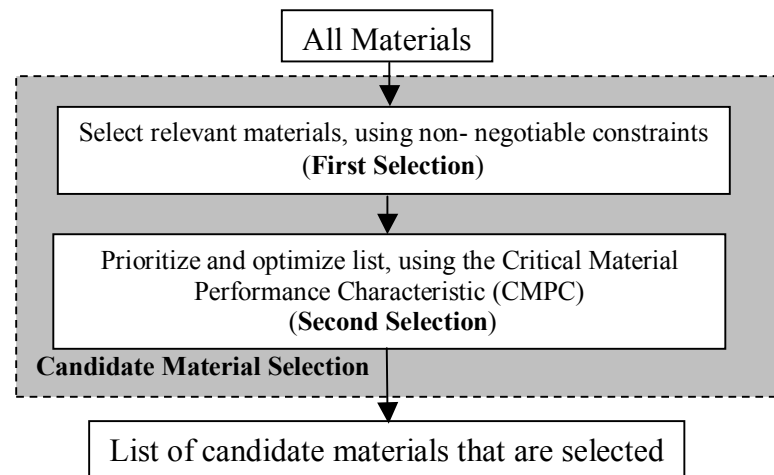


Fig. 11. Flowchart Shows the Two Stages in Candidate Material Selection as per M.F. Ashby [3]

The material selection process, i.e., the process of finding the best match between the desired properties and candidate materials, can be divided into two stages; first focusing the attention of the designer on a group of appropriate materials and then finding the best material from within this group. The procedure thus becomes:

- i. Choose material families that satisfy the non-negotiable constraints.

Optimize/prioritize the list of materials using the CMPC.

First Selection

This selection is based on material properties that are associated with certain constraint requirements that the material ***must*** satisfy in order to be applicable to the design. These constraint requirements, termed the non-negotiable constraint requirements by Ashby [3], have to be satisfied irrespective of the design solution. In other words, regardless of the solution domain, the material used in the design must satisfy these requirements, and hence possess the associated material properties. These requirements are derived from functional requirements, environmental constraints, manufacturing requirements, and any other special requirements as mentioned earlier. Then constraint requirements are translated into corresponding material properties which are used to select the materials. This selection helps the designer identify a subset of materials that satisfy the constraint requirements and, simultaneously, eliminate those materials that cannot do the job because one or more of their properties lie outside the limits of the constraint requirements. The advantage of using this method is that it narrows the attention of the designer to a subset of materials that is relevant to the design, provided the designer has identified the non-negotiable constraints correctly.

Since the first selection is to be made from the *entire* spectrum of available materials, an initial choice of one or more groups can be made from predefined families of engineering materials (e.g., ceramics, wood, aluminum alloys, steels, etc.), using material charts like the ones provided by Ashby [3]. These charts relate the variation of one material property with respect to another, for different materials/material families. By selecting a chart that corresponds to the required material property, the designer can

quickly focus on and select, groups of materials that possess the required property and hence, satisfy the constraint requirements. Appendix A shows an example of one such chart. This chart relates the variation in strength at temperature vs. temperature.

If the designer is not able to find a single family of materials that satisfies all the requirements, the designer has two possible options:

- i. Divide the material properties into surface properties and bulk properties and try to satisfy them separately and then combine the families of materials to achieve a viable solution. The logic path laid out in Fig. 12 uses the concept of “separation of functions” in the materials domain to help the designer separate the desired material properties into surface properties and bulk properties.
- ii. Revisit the requirements for the design and redefine the requirements to make them less stringent.

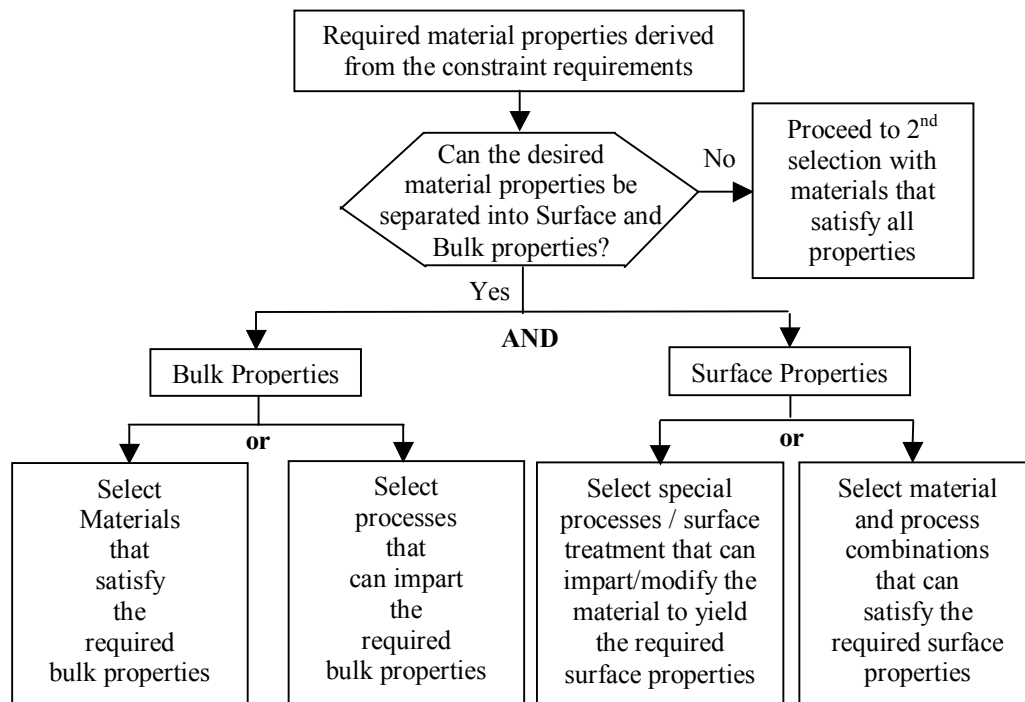


Fig. 12. Logic Path for Separation of Material Properties Into Surface and Bulk Properties

Consider the logic path laid out in Fig. 12. The separation of the material properties that are required to satisfy the constraint requirements starts with the designer asking the question, “Can the desired material properties be separated into surface properties and bulk properties?” If it is possible, the material properties are separated into surface and bulk properties. The designer then tries to satisfy the surface properties and the bulk properties separately by materials and/or manufacturing processes. For example, let us consider the design of a process chamber for etching of aluminum from silicon wafers. Two of the required material properties are a high resistance to reactive ions of chlorine (the process gas), and a high tensile strength so that the chamber does not collapse under vacuum. The resistance to chloride ions can be satisfied by choosing a less reactive metal like nickel, and the tensile strength can be achieved by choosing aluminum. The aluminum chamber can be nickel plated to meet the requirement of corrosion resistance. Therefore surface properties can be satisfied by coating, plating, or surface treating the base material which already satisfies the required bulk properties. This helps the designer to take a raw material, in this case aluminum, which possess all but one of the desired properties, in this case corrosion resistance, and satisfying that property by suitably choosing another material and/or manufacturing process. In this case nickel plating can be used. When as, in this case, a separate material is selected in order to satisfy a required surface property, care must be taken to:

- i. Select proper manufacturing processes for the application of the material chosen, to be able to successfully impart the required surface properties.
- ii. Consider the interface properties for the selected material combination, as one of these could result in, or introduce, a new critical parameter for the design.

The first selection helps the designer to identify the materials that can do the job, but does not help evaluate ‘how well’ they can do the job. This is done using the second selection step, in which the materials identified are ranked or prioritized. This step is described in greater detail below. The second selection, i.e., ranking of the candidate materials identified is performed using a mathematically-derived parameter called the

Critical Material Performance Characteristic (CMPC); this is similar to the material indices that are developed by Ashby [3].

Second Selection

The designer develops a mathematical representation in terms of the geometric parameters, and the material properties, for the critical, lowest-level function that the configuration must perform. The part of the mathematical representation that shows the influence of materials on the function is separated from the expression. This part of the expression is termed the Critical Material Performance Characteristic (CMPC) for that particular configuration. The CMPC shows the influence of material properties on the critical lowest-level function. Hence, to better satisfy the critical lowest-level function the designer should consider this parameter for choosing materials rather than any single material property at a time. The designer now looks for specific materials, within the previously identified family or families of materials, that would maximize the design performance by suitably choosing materials on the basis of the CMPC rather than on the basis of any single property at a time.

This can be better understood by looking at the material selection process for springs, as discussed by Ashby [3]. The primary function of a spring is to store energy and release the stored energy when required. Some of the configurations for a spring are: a cantilever beam; a leaf spring; a coil spring; and a torsion bar. The aim is to choose a material that would maximize the energy stored per unit volume for a given configuration.

The critical function that needs to be performed is to “maximize the energy stored in a given volume without yielding the material.” The design parameter is “amount of energy stored.”

The energy stored per unit volume (PE), is given by $PE = \frac{1}{2} (\sigma^2 / E)$, where E is the Young’s Modulus, and σ is the uniformly applied stress which must be kept below the yield strength σ_y . The equation shows the relationship between the two relevant

material properties and the function that needs to be performed. Hence, the CMPC for this function is σ_y^2 / E , where σ_y is yield strength. This means that the best choice of material for a spring would be to select a material that maximizes the $CMPC = \sigma_y^2 / E$.

This procedure described above is repeated every time the designer performs a concept-configuration loop. The function that needs to be performed by the design, identified by the need that is brought into concept search, is different each time, but is a part of, or more specifically an improvement to the original concept. Hence, each time through the concept-configuration looping procedure the CMPC will depend on the function that needs to be performed and the associated constraint requirement on that function. In traversing each loop, after the CMPC has been identified for the configuration being considered, the designer should start with the group of materials that have already been identified during the previous loop, if any, or with the group of materials from the first selection and narrow the list of materials down further using the appropriate CMPC.

Note that the “First Selection” step is performed only during the first concept-configuration loop. Once the material families that are applicable to the design have been determined, they do not change unless the material requirements themselves change during the design process. This can happen if the designer chooses to revisit the requirements and change them. Only then would the designer be required to perform the first selection again. Otherwise, during the second and subsequent loops, only the “Second Selection” needs to be performed. By following the first selection and the second selection during subsequent loops, the designer at the end of concept-configuration looping procedure will have a group of materials that meet the material requirements of the original need.

4.2 WHY DO WE NEED TO CONSIDER MANUFACTURING PROCESSES ALONG WITH MATERIALS?

After completing the materials selection phase, the designer must perform manufacturing processes selection during each of the concept-configuration loops. This will ensure that the designer selects the manufacturing processes that are most suitable for both the design and the selected candidate materials. Manufacturing processes and materials are inseparable just as much as design and materials are. Fig. 13 illustrates the coupling of constraints from one domain with another; from functional domain to materials domain, and from materials domain to manufacturing process domain, and vice-versa.

Design can be viewed as the process of finding the best match between the requirements, capabilities, and limitations of all three domains. The connection between the functional domain and the process domain of a design is not self-evident. To illustrate the connection let us consider the following example. Consider the task of designing a pressure vessel. Let us assume that one of the design requirements is that all joints in the pressure vessel must be 100% inspected. Inspection of the final product, i.e., the pressure vessel, implies that non-destructive techniques must be used. Let us assume that one of the the materials that satisfy all requirements of the design is titanium, and the process chosen for joining is welding. It would not be possible to inspect the welded joints 100% by non-destructive techniques. If other than meeting the criteria of 100% inspection, titanium and welding is the most suitable material and manufacturing process combination for the design, the designer may choose to design the welded joints in such a way that it is possible for 100% inspection of all the welds. This is an example of how the constraints from the process domain “Not possible to inspect welds 100%” can be transferred to the functional domain “design welded joints so that 100% inspection is possible.” It is clear that there is an interrelationship between the functional domain, the materials domain, and the manufacturing processes domain. Because of this

interrelationship between materials and manufacturing processes, it does not matter in which domain the designer starts the selection process, i.e., the designer can start in the materials domain or in the manufacturing processes domain, whichever is more convenient. The choice of the domain in which to start the selection process is being left to the designer.

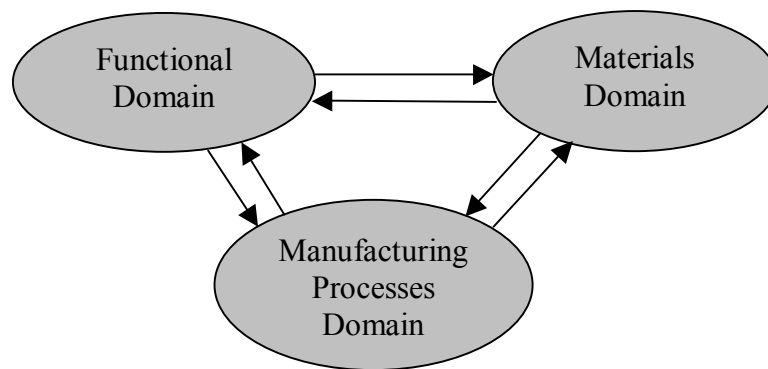


Fig. 13. Interrelationship Between Functional, Materials, and Processes Domains

An optimal solution to a design task can be reached by moving back and forth between the materials and manufacturing processes domains. However this is not an optimal way of obtaining the solution to any design challenge. Hence the need is to develop a methodology that focuses on reducing the number of iterations between the materials and manufacturing processes domains which improves the efficiency of the designer in addressing the design challenge. The designer can choose either domain as the starting point and still obtain an optimal solution, provided the designer properly identifies the critical parameters in both these domains and addresses them. For the purposes of this thesis, and to have a defined methodology, the materials domain has been selected as the starting point for the selection process. The candidate materials selection strategy and the methodology have already been detailed in the previous

section. The remainder of this chapter will concentrate on candidate manufacturing processes selection using an approach similar to that proposed by Ashby [3]. The factors that affect manufacturing process selection, and the guidelines to perform this are given in more detail below.

4.3 MANUFACTURING PROCESS SELECTION

Manufacturing process selection is usually viewed as the last step in the process of product evolution. For the purpose of this thesis, let us define manufacturing as the process of producing the required product and its components, starting with the raw materials and using processes such as forming, material removal, joining and finishing. Although manufacturing also includes assembly of the various components to give the final product, this thesis does not provide guidelines for choosing assembly procedures, but rather concentrates on attaining the required shapes and properties from raw materials.

The candidate manufacturing processes selection guidelines use a similar philosophy to that of materials selection guidelines, namely focusing, and then prioritizing and optimizing, based on the Critical Process Performance Characteristic (CPPC). The goal is to help the designer choose the process that best suits the requirements.

Similarly to the material selection strategy (Fig. 10), the process selection strategy is as follows:

- i. Translate the design requirements into process attributes.
- ii. Use these process attributes to filter the manufacturing processes and choose the manufacturing processes that are best suitable for the design.

4.3.1 Manufacturing Processes Selection Guidelines

The four major factors from which the process attributes are derived, are shown schematically in Fig. 14. These factors that influence the selection of manufacturing processes are given below:

- i. Geometry of the design.
- ii. Candidate materials selected.
- iii. Properties required of the material in the final configuration.
- iv. Production factors.

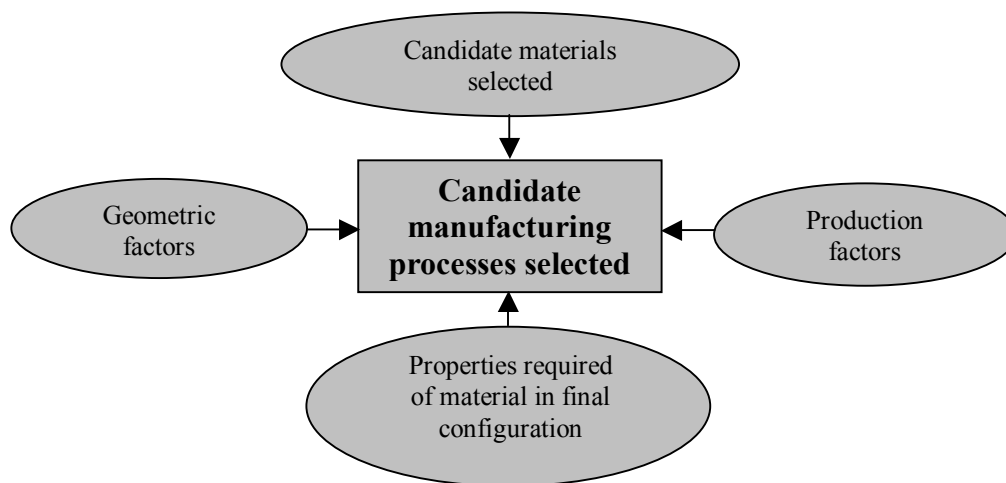


Fig. 14. Factors That Influence Candidate Manufacturing Process Selection

Geometry of the Design

At the beginning of the candidate manufacturing processes selection stage, the designer may not be able to make decisions on the geometry of the design. These geometric factors may, in turn, influence the candidate manufacturing processes selection. In cases where the designer is undecided on some of the factors given below, the designer can

omit these, and base the selection on those factors where more precise information is available. Inappropriately forcing consideration on any of these factors during candidate manufacturing processes selection could result in fixation on a particular configuration and/or manufacturing process. For example, consider the concept-configuration looping procedure for the design of the brakes for a car. While trying to develop a configuration for the concept of friction, the designer comes up with the configuration of two surfaces that are in contact and rubbing against each. At this stage the designer is not in a position to decide on the exact shape of the two surfaces that are in contact. Forcing the two surfaces to have a particular geometry will result in fixation.

The geometric factors that influence materials selection are:

- i. *Shape and Complexity of the Part:* Complexity is defined here as the presence of features such as undercuts, holes, threads, bosses, non-uniform wall thickness, and independent surfaces/planes. The presence of any and all of these features can cause a difficulty in manufacturing and/or require additional operations during manufacturing. For example, if the component has five independent surfaces, then the component will have to be indexed/located five times in order to perform the required machining operations on each surface. This increases the production time and also requires skilled labor to machine the part. Another approach would be to use special process such as electro-chemical machining, electrical discharge machining, etc. Yet another alternative could be to use casting, injection molding, or powder metallurgy. Hence, the shape of the part and its complexity may force the designer to choose a particular process. If this is the case the designer will have to choose a suitable material and/or may have to modify the geometry of the design to match up with for the chosen manufacturing process.
- ii. *Maximum Dimension (Size) and Wall Thickness:* The maximum dimension and the wall thickness are two factors that influence the selection of candidate manufacturing processes. The required wall thickness imposes restrictions on the shaping process that can be used to obtain the shape of the part. For example, if the wall thickness is high forging may not be a suitable manufacturing process. This is

because the forces required for forging are large and the material may not completely fill the die.

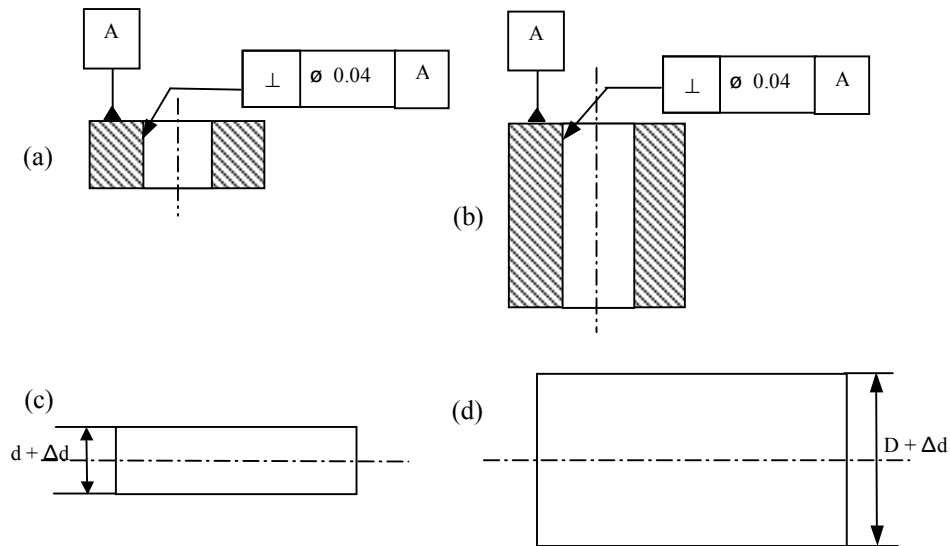
The maximum size (length, width, height) that can be handled by a process/machine is limited and is an important consideration when choosing a process. These process limitations may, in turn, impose, limitations on the size of parts that can be handled by the processes. For example, large parts are difficult to cast because the material may not flow properly into the mold and may not fill the mold completely. This may lead to defective parts. The designer can avoid this by casting the part in sections and joining them to attain the required final product.

- iii. *Tolerance and Surface Finish:* No process can produce a geometrically-perfect and dimensionally-perfect part every time. Manufacturing processes have a limitation on the tolerance and surface finish that can be achieved repeatedly. Hence some tolerance (ΔL), on a dimension (L), must be permitted in order to make it practical to manufacture. This type of tolerance is called dimensional tolerance. Similarly, some tolerance must be permitted on the desired shape of the part. This is called geometric tolerance. Examples of geometric tolerances are: the tolerance on the concentricity of a tube, the tolerance on the runout of a hole, and the tolerance on the flatness of a surface. The tighter the tolerance the more difficult it is to manufacture the part, and vice versa. The surface finish of a part indicates the measured roughness or smoothness of the surface. If there are two surfaces in contact, with relative motion between them then it is most likely that a surface finish requirement will be specified on both of the contact surfaces.

The design, in order to perform its functions satisfactorily, will have to maintain some tolerance and/or surface finish. Different processes have different limitations on the tolerances and the surface finishes that they can achieve. As a result, the tolerances specified for a particular design, both dimensional and geometric, along with the surface finish, are important criteria in the selection of suitable candidate manufacturing processes. There are certain special processes, like lapping, that can produce a tolerance of 5 μm over a diameter of one meter

with a surface roughness of about 0.08 Ra [3]. However, such processes are expensive, and should be avoided whenever possible.

The tolerance that can be maintained by a process varies with the nominal dimension for which the tolerance has to be maintained. Generally the larger the overall dimension, the more difficult it is to maintain a given tolerance. Dimension / Tolerance charts, like the one given by Ashby [3], can help the designer identify processes that are capable of maintaining the required tolerance over the given nominal dimension. In case the designer is unable to define specific values on the various tolerances, the designer can make a qualitative judgement on the range of



- (a) Easy to maintain required tolerance.
 (b) Same tolerance as (a) but more difficult to maintain because of the greater depth of the hole.
 (c) Required tolerance can be produced by turning on a lathe.
 (d) Same tolerance as (c) may not be achievable on a lathe because of the larger diameter.

Fig. 15. The Tolerance That Can Be Achieved Depends on the Nominal Dimension

tolerances that are acceptable. For example, radial drilling machines can produce a 4 in. diameter hole with a tolerance of 0.04 in. on the concentricity of the hole. However, if the design demands a tighter tolerance, it is better to choose a different process such as laser drilling. Fig. 15 illustrates the difficulty in maintaining a given tolerance, either geometric or dimensional, over a larger nominal dimension.

Candidate Materials Identified During the Material Selection Stage

Consider Fig. 13 which illustrates the interdependence between the materials and the manufacturing processes domains. This interdependence is caused by the fabrication properties of the candidate materials that have been identified during the material selection stage. The fabrication properties of a material govern the optimal way of processing the material to get the desired shape with the required precision. Hence, the designer should consider the fabrication properties of candidate materials already selected during the material selection stage. Some of the fabrication properties that need to be considered are: melting point, hardness, brittleness, and yield strength.

For example, if the candidate materials selected are brittle in nature then, forging is not a suitable candidate manufacturing process for the part. An alternative manufacturing process could be casting. Similarly the yield strength, and/or the hardness of the candidate materials selected, impose restrictions on the deformation processes that can be used. Consequently, if the material is most likely to be cast and then machined to obtain the final product, the designer can follow rules applicable to design for casting. This information is already available in design for manufacturing literature and will help the designer to improve the design and make it more suitable for casting.

As another example, the hardness of the material restricts the machining processes that can be used. If the hardness is more than $H_v = 3 \text{ GPa}$ (Approximately $R_c = 35$) then, the material cannot be machined using conventional machining methods [3]. Also, if the material has a very high melting point, and/or does not have very good flow properties, casting will not be the preferred way of processing the material.

There are non-conventional manufacturing processes that are not limited by physical properties such as the melting point or the hardness of the material, e.g., powder metallurgy, chemical vapor deposition (CVD), electro-forming, etc. The designer can specify their use, but must realize that these are special processes that have high set-up as well as operating costs, and should therefore be avoided unless absolutely necessary. If the designer realizes that there is no economical way to process the candidate materials into the required shape, then this becomes a critical constraint and the designer can either search for conceptual solutions in the materials domain or design a new process that will be capable of performing the required tasks. Alternatively the designer can go back and change the configuration to make it more compatible with a chosen process.

Properties Required of the Material in the Final Configuration

The goal of the designer is not just to attain the desired shape but also to attain the desired shape with the desired properties. There are instances where the process used may be capable of producing the required shape using the materials chosen, but the process may impart certain undesirable properties to the final configuration that may cause the design to fail. For example, consider the brazing together of two parts. Brazing has the limitation that the joint must be designed to operate in shear or compression but not in tension. Hence, even though the process can achieve the desired geometry and the materials chosen are compatible with the process, the properties desired for the final configuration may not be achieved. Therefore, the designer should always look at the effects on the final configuration of using a particular process. If there are undesirable properties introduced in the final configuration, these have to be overcome by another process, or the process itself has to be avoided.

Production Factors

Production factors are not related to the functionality of the design and are not relevant to the ability of a process to produce the component. However they influence the final selection of processes to a large extent. They may also become the primary reason for

not choosing a particular manufacturing process. This is because they directly relate to cost of manufacturing the design and hence the cost of the final product. For example, let us assume that two processes that both satisfy the material and the geometric requirements for a particular design are machining and die-casting. The final process chosen for manufacturing will depend on the production factors such as lot size, return on capital investment, and the total quantity, i.e., the total number of components, that need to be manufactured. If a component/part is complex in shape and the component/part is to be mass produced, then die-casting could be the preferred process. The number of parts produced could justify the associated high set-up cost. However, if the part in question were not going to be mass-produced, then machining would probably be a better choice. Depending on the manufacturing process chosen, the designer could change the design, if needed, to make the design better suit the process.

The preceding discussion of some of the most important factors that influence candidate manufacturing processes selection makes it is clear that the high-level decisions regarding manufacturing processes that are made during conceptual design can influence and even change the actual design of a part. The design changes that can make a design more effective and efficient, relative to the use of a particular manufacturing process, are available in the form of specific rules. For example, design for casting, design for machining, design for welding, etc. These rules are available in design for manufacturing literatures.

The final shape of a component/part is, more often than not, attained using more than one manufacturing process. These processes can be classified mainly into;

- a) Forming: Casting, forging, rolling, molding, powder methods.
- b) Material Removal: Turning, milling, planing, grinding.
- c) Joining: Welding, brazing, riveting.
- d) Finishing: Polishing, lapping, painting.

The goal of the designer is to attain the required shape, the required tolerances and surface finish, and the required properties, and do so in a minimum number of process steps, ideally one. However, achieving the goal in one step is not possible in

many cases. More usually, the material is first formed to the required shape. The required tolerances and surface finishes are then achieved by one or more additional processes.

So far we have discussed the candidate manufacturing selection process strategy, the factors that influence the selection of candidate materials, and the related process attributes. Let us now proceed to discuss how to use the process attributes derived from the requirements of the design to select candidate manufacturing process. Similar to materials selection, the designer must start with all the available manufacturing process and quickly focus on the ones that are applicable to the design, using only those process attributes that are absolutely necessary, i.e., without forcing consideration of any of the factors mentioned above. Once the set of applicable manufacturing processes are available the designer can then prioritize the list based on the total cost it will take to meet the critical requirements. Both these steps are explained in detail in the following section.

First Selection of Manufacturing Process

In order to select the candidate manufacturing processes, process charts that correlate two process attributes, one on each axis, can be used. An example of such a chart from Ashby [3] is given in Appendix B. If the chart indicates that two or more processes can provide the desired attributes, then it means that either of the processes can be used independently, or a combination of the different process can be used. The designer should first identify the non-negotiable constraints applicable to the design from a manufacturing point of view. These non-negotiable constraints will depend on the factors that have been discussed above. Once the constraints have been identified the designer transforms these constraints into process attributes. It must be noted that identifying the correct process attributes depends on the skill and the knowledge of the designer. The factors help the designer to look at some of the key issues and identify if there is some information that the designer must know but does not yet know so that the designer can do relevant research. The designer can then choose processes that satisfy all

these process attributes, or choose a set of processes that can be performed in sequence to satisfy them, thus satisfying the constraints.

Let us consider the example of two sealing surfaces for a valve. Assuming that the sealing surfaces are metallic and the shape to be circular, the designer may derive from the following non-negotiable constraints like tolerance and surface finish the following process attributes: Tolerance of 5 μm , surface finish of 40 Ra. Manufacturing process can be selected based on these process attributes.

Second Selection of Manufacturing Process

The critical parameter identified during the concept-configuration looping procedure could be process related. If this is the case, then the designer should choose/prioritize the manufacturing processes that best satisfies this critical parameter. Taking into account the total cost of satisfying the critical parameter, the designer could select the appropriate manufacturing process or manufacturing processes combination, which lead to the minimum total cost for executing the design. This total cost generally depends on the following factors:

- i. Set-up cost: includes equipment cost, development of infrastructure, installation of equipment, etc.
- ii. Operating cost: labor, number of shifts, overheads, supervision, etc.
- iii. The cost associated with the processing time.
- iv. Tooling cost.

For example, in the case of the sealing surfaces of a valve, the designer may identify during the concept-configuration looping that the manufacturing processes-related critical parameter as the tolerance on the sealing surface. The designer can take the processes that have already been identified during the first selection and prioritize them according to the total cost of satisfying this critical parameter. This will help the designer identify the most suitable and cost effective manufacturing process for the design.

4.4 SELECTION OF THE BEST MATERIAL AND MANUFACTURING PROCESS COMBINATION

The final selection of the optimal material and manufacturing process combinations for producing a design can be assisted by using a procedure similar to that followed for concept selection during the conceptual design phase. In this step, the designer forms a table that lists the evaluation criteria down one side, and the material-process combinations across the other. The candidate material-process combinations should be evaluated based on both functional and non-functional requirements in a hierarchical manner. The suggested hierarchy is:

- i. Functional requirements.
- ii. Safety / Ethics – operator safety, end-user safety, environmental safety, etc.
- iii. Cost – set-up cost, cost of raw material, production costs, quality cost, etc.
- iv. Other considerations – time to market, supplier reliability, supplier availability, etc.

Let us consider the example of the monolith that is used in the semiconductor industry. The functionality of the monolith demands that it hold high levels of vacuum. Since all the chambers mount onto the monolith it is absolutely important that there is not a leak in it. This means that the material and the manufacturing process chosen must be able to guarantee this high level of reliability. The material chosen is aluminum and the manufacturing process chosen is machining. This is because even though the monolith could be net cast and then machined, there was no guarantee that casting will be able to produce a leak free part every time. Hence evaluating the design in a hierarchical manner will help the designer choose the best suitable material and manufacturing process combination.

Since this is a relative assessment of the candidate combinations, any of the material-process combinations can be chosen as the datum and the other material-process combinations can be evaluated against it. The material and process combination that is presently used for the product can be chosen as the datum in those cases where the

product already exists. The designer should rate the other material-process combinations against the datum and assign either a '+' for better, '-' for worse, or an 'S' for equal for each of the evaluation criteria. Once all the criteria have been rated, all the '+'s, '-'s and 'S's should be summed. As in the concept selection phase, the designer can, and should, use the resulting table to identify where the weaknesses of a particular material-process combination lie. The designer can then try to overcome the identified weaknesses by combining the strengths of other materials and/or process to result in a new materials/processes combination. This will help the designer to choose the best material and process combination with respect to the overall requirements.

Table 2 is an illustration of a material and manufacturing process selection table that can be used to select the optimal material and manufacturing process combination. The table does not illustrate the selection process for any particular design but generically shows how the selection process works, and how the table should be used.

Table 2: Example of a Design Where Four Different Combinations of Materials and Manufacturing Processes Are Being Evaluated

Criteria	Material/Process Combination 1	Material/Process Combination 2	Material/Process Combination 3	Material/Process Combination 4
Tooling cost	D A T U M	S	S	–
In house execution capability		S	+	+
Environmental and operator safety		+	S	+
Raw material availability		S	+	+
Raw material cost		+	–	+
Total +'s		2 +	2 +	4 +
Total S's		3 S	2 S	0 S
Total –'s		0 –	1 –	1 –
+ ⇒ Better than; S ⇒ Same as; – ⇒ Worse than				

Using the table, the designer can compare material-process combinations and find out which of them best satisfies the requirements of the design. Similar to the recommendation made during the concept selection, if the designer identifies that a certain material-process combination has a negative rating for a particular criterion, then the designer should try to overcome this by exploring whether the negative originates in the materials domain or in the process domain. An effort should then be made to try to overcome the negative rating.

In the above example, Material/Process Combination 1 has been arbitrarily chosen as the datum. However, when the designer is performing an evaluation, he/she should pick the material/process combination currently being used, or is the benchmark,

in the market. If the design is completely new, and there are no existing designs that can be used as a benchmark, the designer should pick the material/process combination for which he/she best understands the evaluation criteria. For example, if the tooling costs are high, i.e., if the selected process needs a new production line to be set-up, or if new machines need to be bought, it increases the total cost for a particular material and process combination. This is a negative in the process domain. If this is the only negative for that material-process combination that is otherwise very desirable, the designer can try to overcome this by looking into outsourcing the manufacturing of that particular part or parts. So for example in Table 2 it would be best to choose Material/Process Combination 4, and look into outsourcing the part to an external supplier.

4.5 SUMMARY

Chapter IV gives an overview of the candidate materials and manufacturing processes selection procedure. This procedure is based on the selection process detailed by Ashby [3]. The selection process has been modified to make sure that it is consistent with the logic paths laid out in Fig. 7 and the modified concept-configuration looping procedure illustrated in Fig. 8. Hence, the proposed modifications help the designer identify “what” needs to be done and gives a method of “how” to do it. The chapter also gives a procedure for selecting the best suitable material-process combination for the design using a procedure similar to that of concept selection.

Chapter V is a case study that shows the application of the modified concept-configuration looping procedure to a design challenge. The case study presented is the design of a turbine blade for the initial stages of the gas turbine. It details; (i) the development of the need statement and the function structure for a turbine blade, (ii) a discussion on application the logic path (Fig. 7) for the turbine blade, (iii) discussion on the modified concept-configuration looping procedure for the turbine blade is given.

CHAPTER V

CASE STUDY TO ILLUSTRATE THE APPLICATION OF THE RECOMMENDED MODIFICATIONS

The recommended modifications improve the IIIDE Design Process by helping the designer gain better insights into the materials and the manufacturing processes related critical issues associated with the design task. This chapter discusses a case study that shows the application of the modified concept-configuration looping procedure detailed in Chapter III and how it could help the designer gain insights into the materials and manufacturing processes related issues relevant to the design of a turbine blade for a gas turbine.

5.1 PROBLEM STATEMENT AND BACKGROUND

Consider the design of a turbine blade for the initial stages of a gas turbine. The efficiency of the turbine depends, to a great extent, on the inlet temperature of the working fluid. The desire to increase the efficiency of the turbine forces the designer to design the turbine blades for higher and higher inlet temperatures. In other words, there is a constant need to design turbine blades that are capable of handling higher inlet temperatures of the working fluid. The inlet pressures are also high as the working fluid still has a lot of internal energy. Hence, the initial stages of a gas turbine are the high-temperature and high-pressure stages. This high temperature and high-pressure conditions will be considered as the operating conditions for the turbine blade. Also there are two sets of blades in a turbine: moving blades, and fixed blades. In this case study the design of the moving blades for a gas turbine will be discussed.

5.2 NEED ANALYSIS

Although this design challenge is a re-engineering effort, the discussion will be handled as it would be with any other engineering challenge, i.e., as if the designer were being asked to design a turbine blade for the first time. Since it is a re-engineering effort, it is clear to the designer that the end result of the embodiment for the design should be a turbine blade, which is to be attached to the rotor of the turbine.

Following the IIDE Design Process, a need analysis is performed to identify the primary function, the primary constraint, and the sub-functions that need to be performed in order to satisfy this primary function. The primary function of the turbine blade is to, “Transform the kinetic and the potential energy of a working fluid into mechanical energy.” The primary constraint that restricts the solution domain is the “high temperature” involved. Hence, the need statement would read, “Transform the kinetic energy and the potential energy of a high temperature working fluid into mechanical energy using a turbine blade.”

In order to perform the primary function, the two first-level functions that the blade must perform are:

- i. Withstand the combined stress.
- ii. Maintain its profile.

Let us consider the first function, “Withstand the combined stress.” The combined stress is a result of the stresses induced by the main force and the two moments that are acting on the blade. Namely:

- i. Centrifugal forces – Tension.
- ii. Bending.
- iii. Torsion.

“Withstand the combined stresses” means that the blade must not fail due to the combined stress induced by these forces and moments. Hence, the designer analyzes the modes of failure for the blade, and designs the blade to satisfy the most predominant

mode of failure, under the worst combination of stresses. Then the designer checks to see if the design performs satisfactorily for the other failure modes. The most common mode of failure for a turbine blade is fatigue fracture at the root of the blade. The failure occurs at the root of the blade because the largest principal stress (normal stress) is a maximum at this location. This stress results from the worst-case load, which is a combination of the tension, bending, and torsion, at the root of the blade.

Now consider the second function, “Maintain the profile of the blade.” The blade has to withstand both erosion and corrosion. Erosion of the blade is caused by a combination of:

- i. The high temperatures of the working fluid that soften the surface of the blade.
- ii. The high velocity of the working fluid that erodes the surface of the blade away.

Due to the high temperatures involved there is a certain amount of surface oxidation. This oxide layer forms a protective coating over the surface of the blade. Small amounts of vanadium, which frequently occur as impurities in the fuel, act as a flux in breaking down this oxide layer that forms on the surface. The combustion gasses then scour the blade and washes the layer away. A new oxide layer is formed which is consequently washed away. Hence, the erosion process is accelerated by the presence of vanadium in combustion gasses.

To make matters worse, the oxidation process is assisted by the high temperature. There will be oxidation of the blade but if a stable oxide layer forms on the surface then this layer prevents further oxidation.

All the information is represented in the form of the function structure for the turbine blade shown in Fig. 16. This now gives the designer a solution-independent framework for the design task.

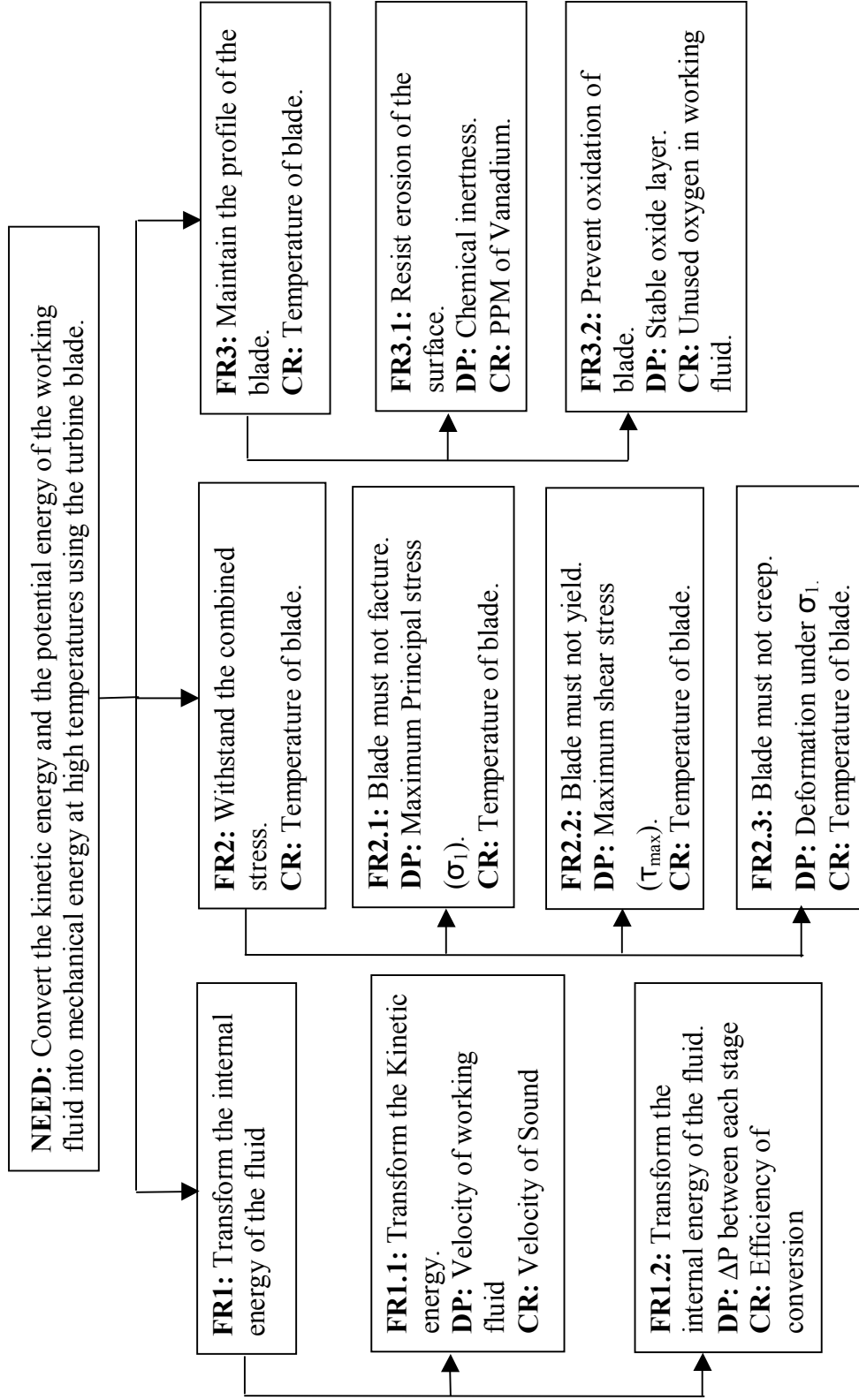


Fig. 16. Function Structure for the Design of a Turbine Blade

Once the need analysis is complete, the designer has identified what the design “must do” to satisfy the design need and has a solution independent framework that he/she can use to satisfy this need. The designer can now proceed to conceptual design and use the modified concept-configuration looping procedure with one of the critical lowest-level functional requirements from the function structure as the original need.

5.3 MODIFIED CONCEPT-CONFIGURATION LOOPING PROCEDURE

Consider the critical lowest-level function of the turbine blade, “Blade must not fracture”, as the original need brought into the modified concept-configuration looping procedure. The constraint requirement that the function must satisfy is the “temperature of the blade.” This is because the FR can be satisfied at lower temperatures without much difficulty, but the high temperature sets a limit on the solution domain, which makes it difficult to satisfy this FR. Hence, it is the constraint requirement for the design.

The configuration for the design is already known. It is a turbine blade. The designer can take the cognitive paths detailed in the modified concept-configuration looping procedure (Fig. 8), and the logic paths (Fig. 7) in Chapter III. The designer starts by considering functional and materials/processes simultaneously. The designer first identifies the functional critical parameter in Box 6A, Fig. 8. The functional critical parameter for the design is the principal stress at the root of the blade, because the principal stresses are responsible for causing fracture at the root of the blade. The designer then proceeds to Box 6B, which takes the design to the logic path detailed in Fig. 7.

The logic path for this critical lowest-level function for the turbine blade is as follows:

- a. The designer starts the logic path given in Fig. 7 by bringing the configuration, “turbine blade”, into Box 2 and asking the question - “Are there critical materials or

manufacturing process issues that could make-or-break the design?” In this case, the constraint requirement of the “high temperature of the working fluid” indicates that the materials chosen must withstand the temperature. This takes the designer to the next step, Box 3, where the designer tries to identify if there is a critical materials/processes issue.

- b. The designer identifies the materials/processes-related critical parameter by simultaneously considering the previously identified functional critical parameter, “principal stress at the root of the blade”, and the non-functional requirements. In this case the functional critical parameter and the environment “high temperature working fluid” result in the critical materials parameter “high temperature fracture toughness.” The reason for focusing on the fracture toughness at high temperature is that the properties of a material change with temperature, and this variation is not necessarily linear in nature. This means that it is not enough that the material selected for the turbine blade have a high fracture toughness. Rather what is needed is a high fracture toughness at the operating (high) inlet temperature.
- c. Before proceeding further, the designer has to identify the other requirements that candidate materials must satisfy. This prompts the designer to identify the requirements that the materials and processes must satisfy. The designer then translates these requirements into desired properties of the material. The desired properties of the material at the specified high operating temperatures are:
 - i. *Fracture Toughness*: The main mode of failure of the turbine blade is fatigue fracture and hence the materials should have high fracture toughness. (**High**)
 - ii. *Fatigue Life*: Since the predominant mode of failure is fatigue failure the material selected should have a high fatigue life. (**High**)
 - iii. *Crack Growth Rate*: The crack growth rate, after an initial crack is initiated or the material has an initial flaw, must be slow. (**Low**)
 - iv. *Fatigue Strength*: The material should also have high fatigue strength at the operating temperatures. (**High**)

- v. *Creep Deformation*: The creep deformation for the material must be low at the operating temperature. (**Low**)
 - vi. *Yield Strength*: The blade is subject to high tensile stress due to the centrifugal force. To prevent permanent deformation of the blade the material for the blade must have high yield strength. (**High**)
 - vii. *Formability*: The shape of the blade is a complex 3D aerodynamic shape which is based on the flow characteristics for maximum efficiency. Hence, the desired material characteristic is that it should be easily formed into complex shapes, and hence the formability of the material should be high for ease of manufacturing. (**High**)
- d. The next question asked is, “Can the critical parameter be satisfied by existing materials and processes?” The answer to the question is “I don’t know” and hence, the designer takes the route for “No.” The inlet temperature, as discussed in the problem statement, is considered the operating temperature of the blade. This is known to be high but the designer does not know the precise value of this temperature. Hence, the designer cannot satisfy all the required properties without knowledge of the inlet temperature. The inlet temperature is not a given because of the constant demand to increase the inlet temperature, in order to increase the overall efficiency of the turbine. The designer’s goal is to choose candidate materials that can satisfy all the requirements listed in section c, and to do so at the highest possible temperature. Since the designer takes that path for “No” the designer has three options: Box 7, Box 8, or Box 9 in Fig. 7.
- e. For this example, the **first** option, Box 7, is where the designer would try to solve the problem by designing new materials and/or processes. Ceramics can satisfactorily perform at the high operating temperatures and also satisfy the surface properties. However, they do not have the required fracture toughness. Hence, in the materials domain, the need would be to develop tough ceramics, or high strength ceramics. This calls for innovation in the materials domain.

Another option would be to satisfy the high temperature and surface requirements using ceramics, and substrate requirements of the required fracture strength by steel. The critical issue here would then be to develop a process to coat the substrate material with the ceramic. Basically, taking the first option could lead to developing one or more new processes to satisfy the design need.

The *second* option, Box 8, is to choose materials from existing list of materials that satisfy the requirements partially, check if the compromises made during the selection result in a critical parameter, and feed-back this critical parameter into concept space to search for conceptual solutions.

The *third* option is to discard the concept of a turbine blade and search for concepts that do not have the same critical parameter as “high temperature fracture toughness.” The third option, Box 9, would lead to a new need that would read, “Design a device that will produce power.” Solutions to this could be a fuel cell.

For further discussion let us consider the second option (Box 8). This means the designer is going to select materials that satisfy the requirements partially, and then check if any of the compromises impose new constraints on the design. If so the designer checks to see if one of these could become a critical parameter. This option is chosen because most of the design problems involve choosing an optimal material and manufacturing process as against developing or innovating in the domains of materials and/or manufacturing processes.

5.4 MATERIALS SELECTION FOR A TURBINE BLADE

5.4.1 First Selection

The first selection is based on the non-negotiable constraints that the material must satisfy. The designer identifies these constraints from the requirements for the design and derives the desired material properties for the turbine blade. These are:

Material Properties

- a. Fracture toughness: **High**
- b. Fatigue Life: **High**
- c. Fatigue strength: **High**
- d. Creep Deformation: **Low**
- e. Yield strength: **High**
- f. Formability: **Easily formable**

Some of the materials that satisfy these properties along with their fracture strength are given below:

- i. ***Aluminum 8090-T81***: 165 MPa $-m^{1/2}$, 150 ksi - in^{1/2}
- ii. ***AF1410 High Fracture-Toughness Steel***: 154 MPa $-m^{1/2}$, 140 ksi - in^{1/2}
- iii. ***Titanium Ti-8Al-1Mo-1V*** 151 MPa $-m^{1/2}$, 137 ksi - in^{1/2}
- iv. ***374 5 Titanium Beta III*** 176 MPa $-m^{1/2}$, 160 ksi - in^{1/2}
- v. ***6 Carpenter Pyrowear® 675 Stainless Steel***: 165 MPa $-m^{1/2}$, 150 ksi - in^{1/2}
- vi. ***7 Carpenter Pyrowear® 675 Stainless Steel***: 154 MPa $-m^{1/2}$, 140 ksi - in^{1/2}

5.4.2 Second Selection

The second selection, as discussed in Chapter IV, is based on the Critical Material Performance Characteristic (CMPC), which is identified by developing a mathematical relationship for the critical FR. This is done by first identifying the stresses that are induced in the blade by the tensile centrifugal force, and the moments acting, namely bending, and torsion. The stresses that are induced are:

- a. ***Centrifugal stress***: In gas turbines the operating speeds are typically of the order of 20,000 rpm, and hence the blades have high centrifugal forces acting on them. Consequently, there is a centrifugal tensile stress that acts on the blade, and is a maximum at the root of the blade.
- b. ***Bending Stress***: The bending stress that is induced in the blade is the bending stress due to the transmission of thrust from the working fluid to the rotor of the

turbine, through the blade. There is also an impulse transmitted each time the blade passes the passage between two stator blades. This causes a fluctuating bending stress on the blade. However, these fluctuations are small compared to the mean force that is acting on the blade and will not be addressed in this discussion. They must, however, be taken into account in the final design.

- c. *Thermal stress*: There is a constant heat input from the working fluid, and there exists a temperature gradient between the tip and root of the blade. This temperature gradient causes a variation in physical constants of the material used. The varying temperature also induces certain thermal stresses on the blade. For the purpose of this example, the thermal stress will not be considered in calculating the total stress at the root of the blade.

The blade must be able to withstand all of these stresses, and satisfy the critical function “Blade must not fracture.” The most predominant mode of fracture is, fatigue fracture. Since the operating temperatures are high, they cause the material to creep, which accelerates the rate of fatigue fracture. Creep deformation occurs over a period of time when a material is subjected to stress at high temperatures. In this example there is a possibility for the material of the blade to creep because the stresses are high and the temperature may be higher than 40% of the melting point of the material of the blade. Hence, the materials that need to be considered must have a resistance to creep, and fatigue fracture, at the operating temperature range.

The loads are a maximum at the root of the blade. Hence the combined stresses are also worst at the root of the blade. The bending forces (thrust) and the centrifugal forces contribute the most to the combined stresses the blade experiences. The stresses due to these forces are calculated at the root of the blade, and summed up.

The force exerted on the blade by the working fluid is not exactly tangential, and is given by [10,11]

$$F = \dot{m} \sqrt{(V_{t1} - V_{t2})^2 + (V_{a1} - V_{a2})^2}$$

where V_{a1} – Axial Velocity of working fluid at inlet.

V_{a2} – Tangential Velocity of working fluid at exit.

V_{t1} – Tangential Velocity of working fluid at inlet.

V_{t2} – Axial Velocity of working fluid at exit.

\dot{m} - is the mass flow rate of the working fluid.

The force exerted by the working fluid on the blades is equal to the rate of change of momentum of the working fluid between the inlet, and the exit of the blade. Knowing the mass flow, and the velocities of the working fluid, the designer can calculate this force.

Similarly, the centrifugal force on the blade can be calculated using the formula [11]:

$$F = \int_{r_1}^{r_2} \rho A \omega^2 r dr$$

where ρ – Density of the material of the blade.

A – Area of cross section.

ω – Angular velocity of the blade about the rotor axis.

r_1 – Radius from rotor axis to the root of the blade.

r_2 – Radius from the rotor axis to the tip of the blade.

The stresses induced by these two forces are calculated, and summed up to give the total stress (combined stress) at the root of the blade. The critical function that the blade needs to perform is, “Blade must not fracture.” Assuming tensile fracture of the blade, the designer can derive the equation for this.

$$K_{IC} = 1.2 \sigma_c \sqrt{\pi a_c}$$

Where K_{IC} – is the fracture toughness

a_c – is the critical crack length at which the fracture occurs

σ_c – is the critical stress applied remotely perpendicular to the crack plane

For ductile fracture to take place, the yield stress (σ_y) of the material must be high, and K_{IC} of the material must be high. For the critical crack length to be as long as possible, i.e., for the blade to be able to tolerate a longer crack without fracture the ratio of K_{IC} / σ_c must be high. Hence the Critical Material Performance Characteristic for the blade is

$$CMPC = K_{IC} / \sigma_c$$

Hence, after choosing materials with high fracture toughness and yield strength (first selection), the best-suited materials are those which maximize the CMPC (second selection). Having chosen the materials that best suit the design the designer proceeds to manufacturing process selection.

5.5 MANUFACTURING PROCESS SELECTION FOR A TURBINE BLADE

The materials that have been chosen have to be processed in a way that allows them to retain the properties that they possess, while attaining the desired shape. The geometric attributes of the design are: 3-D, complex, and an aerodynamic shape profile with tight tolerances. This is because the efficiency of the blade is related to its profile. There are no special surface requirements like surface finish at this stage of the design.

As stated before, the ideal solution would be to choose a one-step process that would be capable of producing a blade with the desired surface and bulk properties. However, in this case it is not possible, since there are no processes available that meet both sets of requirements. The designer could choose to innovate in the area of processes to design a process that can manufacture a turbine blade with the desired attributes in a single process step. For example, after consideration of the available processes, the desired bulk properties and the surface properties could be achieved by using precision

forging. This process limits the types of materials that can be used and hence all of the candidate materials may not be able to be processed by precision forging. An alternative would be to use forging to give an approximate bulk shape of the blade and then machining the final profile using Electro-Chemical Machining (ECM) or Electrical Discharge Machining (EDM).

5.6 ABSTRACTION OF THE REDEFINED NEED

Having identified the materials and the associated manufacturing processes, the designer proceeds to Box 10 of Fig. 7, to identify if there are any constraints imposed on the design that can become critical parameters. The highest temperature at which the given list of materials can operate is the temperature at which the blade has to be maintained. Therefore the constraint imposed is on the operating temperature of the blade. The next question is: “Does this become a critical parameter?” In this case, it certainly does. Therefore the designer proceeds to Box 11 and abstracts the redefined need. The redefined need for concept search would read, “Maintain temperature of the blade below T” (Where T is the highest temperature at which the given list of materials can operate). The designer proceeds to Box 13 with this redefined need to search for conceptual solutions.

One of the concepts that the designer may come up with could be to cool the blade. Then the designer can proceed to use the modified concept-configuration looping procedure for this concept. During the materials selection for this concept, the designer tries to identify the desired properties in order to effectively cool the blade. One of the properties that the designer would look for would be the thermal conductivity of the material of the blade.

Material Property:

- a. *Thermal Conductivity:* The blades are in continuous contact with high temperature fluid and there is continuous heat input into the blades. One of the solutions to this problem is to cool the blade. The blades should be cooled with maximum efficiency i.e., there should be effective heat transfer from the blade to a sink and the corresponding material property is the thermal conductivity of blade material. (***High***)

This property is now used to prioritize the already existing list of candidate materials from the first concept-configuration loop.

The discussion so far has walked the designer through the first modified concept-configuration loop for the example of the turbine blade. It can be clearly seen that the designer is able to identify the critical materials related parameter for the design challenge. It shows how the designer is able to satisfy the material requirements partially, how the materials selected impose a constraint on the design which is then used to abstract the redefined need for the second loop. Following the procedure detailed above during subsequent loops the designer will be able to identify the critical issues from the materials and/or manufacturing process domains and develop conceptual solutions to these issues.

5.7 SUMMARY

The case study details the execution of one modified concept-configuration loop and the abstraction of the redefined need from the resulting critical parameter. This procedure can be repeated for this redefined need and for subsequent critical parameters that result at the end of the loop. Let us quickly summarize the case study by considering the flowchart shown in Fig. 17.

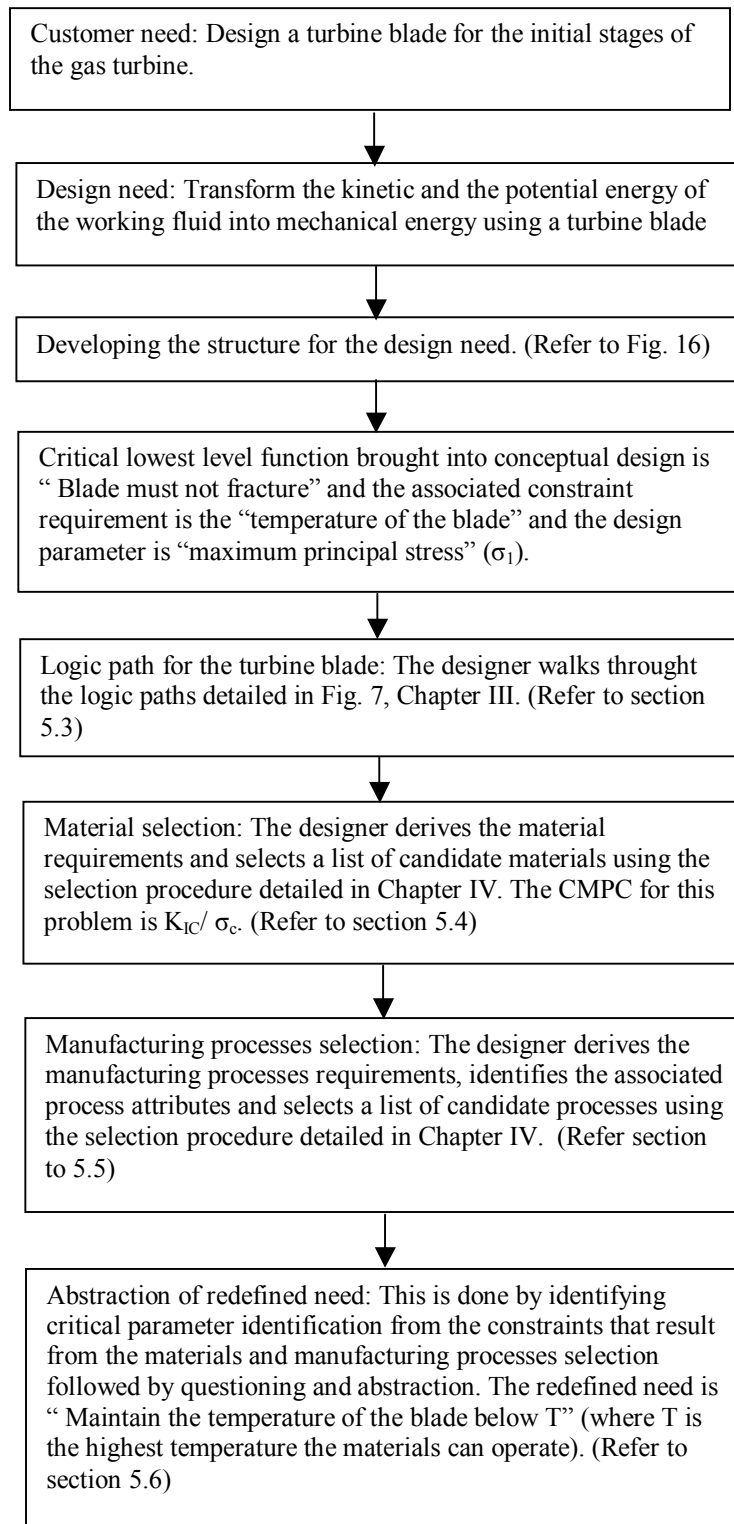


Fig. 17. Flowchart Representation of the Turbine Blade Example

The case study discussed above shows that, by following the modified concept-configuration looping procedure, the designer can better understand the critical material and manufacturing process issues, and search for conceptual solutions to these issues. In this case study the designer was able to identify that the materials-related critical parameter was the fracture toughness of the material at high temperatures. Following the logic paths given in Fig. 7, the designer discovers that the constraint imposed on the design that becomes a critical parameter as the “the highest temperature at which the list of materials can operate.” The designer then uses this critical parameter to abstract the redefined need. The redefined need is then taken back to concept space to search for conceptual solutions. This clearly shows that it opens up new domains, namely the materials domain and the manufacturing process domain, for innovation.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

In this thesis, the goal of identifying materials and manufacturing process issues associated with a design, during the formative stages of the design, has been approached like any other design challenge attacked using the IIDE Design Process. As in the IIDE Design Process, the first step is to identify the need statement for the thesis, which can be phrased as, “Modify the existing IIDE Design Process to consider materials and manufacturing process issues during the conceptual design phase.” The primary function defines what must be done, namely “Modify the existing IIDE Design Process to consider materials and manufacturing process issues” and the associated constraint requirement specifies when this must be done, namely “During conceptual design.”

After establishing the need, the stages in conceptual design of the IIDE Design Process where the changes need to be made was identified. The discussion in Chapter III shows that the best place to make the modifications is while carrying out concept-configuration looping. This discussion also shows the importance of identifying the critical parameters in the materials and the manufacturing process domains and searching for conceptual solutions to these critical parameters. These are issues that need to be addressed by any proposed solution to the need statement. Therefore this discussion that shows how and where the changes in conceptual design need to be made is detailed is analogous with developing a function structure, where a solution-independent framework for satisfying the need is formulated.

The basic philosophy of the IIDE Design Process is based on the principles of Questioning, Abstraction, Critical Parameter Identification, and Innovation. Innovation in design is enabled by developing a solution independent function structure and

following the three principles given above. These four principles have been practiced to at each stage of this work and are key to the success of this endeavor, as they are to the success of any design.

A design methodology must guide the designer to;

- i. Identify what needs to be done.
- ii. Details one or more methods of how to do it.
- iii. Means of assessing how well the need has been met.

So far we have discussed how this thesis helps the designer identify what needs to be done.

The answer to the question of how to address, or in other words the method to address, the identified need to include materials and manufacturing process issues is given by the logic path described in Fig. 7 of Chapter III. Incorporation of this logic path into the existing concept-configuration looping procedure detailed in Fig. 6 results in the modified concept-configuration looping procedure (Fig. 8).

It should be noted that Fig. 7 and Fig. 8 are themselves the outputs of a looping process similar to the concept-configuration looping procedure. During this looping process the existing logic path was taken and the following questions were asked.

- i. What can go wrong in the process?
- ii. What are the potential pitfalls for the designer?
- iii. What is the nature of the thought process followed by the designer?
- iv. What will the designer be tempted to do?
- v. Is there any room for misinterpretation?
- vi. What are the possible roadblocks that the designer may run into?
- vii. What are all the possible paths that the designer could take at each stage of the design? i.e., how can one ensure that the designer remains open to possibilities for innovation and does not become fixated on one approach?

By answering these questions while keeping the four basic principles in mind, and after numerous iterations, the resulting product was the logic path given in Fig. 7 and its incorporation into the concept-configuration looping procedure as laid out in Fig. 8.

Let us revisit the logic path given in Fig. 7, which is the core enhancement provided by this thesis. The single most important contribution to the IIDE Design process by this thesis would be to prompt the designer to consciously ask the question, “Are there materials and manufacturing process issues that could make-or-break the design?” This is the “concept” behind the thesis and is based on the principle of “Questioning.”

The next important contribution is in helping the designer identify critical parameters that lie in the material and manufacturing processes domains. This step involves the principles of both “Abstraction” and “Critical Parameter Identification.” Let us revisit the example of the brakes of the car. Simply saying that the materials must be able to withstand high temperatures, that the materials must be maintained below the critical temperature, or the interface temperature must be maintained below the temperature that the material can withstand, does not really help the designer. The example clearly shows how, by taking the functional critical parameter of “interface temperature”, the designer can follow the logic path and come up with the critical materials parameter, “eutectoid temperature of the material.” Now the designer can formulate a better re-defined need that clearly identifies the constraint on the design.

Finally the logic path helps the designer to search for conceptual solutions to the critical parameters identified, hence enabling innovation, which is also one of the core goals of the IIDE Design Process. In short, the logic path laid out is consistent with the design philosophy underlying the entire IIDE Design Process. The logic path that has been developed and detailed can, therefore, be compared to a conceptual design layout.

This logic path was then incorporated into the existing concept-configuration looping procedure to give a modified concept-configuration looping procedure. The modified concept-configuration looping procedure can be considered the embodiment

design on which detailed design was performed resulting in the procedure detailed in Fig. 8. Once again, it can be seen that the design philosophy behind the IIDE Design Process, and the existing IIDE Design Process itself have both been used to a great extent to develop the proposed modifications. It is therefore not surprising that the proposed modifications are fully compatible with the IIDE Design Process. This allows the proposed modifications to be naturally integrated into the existing process.

Having discussed the philosophy behind the proposed modifications, let us look at the advantages offered by the proposed modifications.

- i. The modifications help the designer better identify materials and manufacturing processes-related critical parameters and satisfy them before leaving the conceptual design phase. As a result when the designer leaves the conceptual design stage, the proposed design not only satisfies the prescribed functional requirements but also the materials and manufacturing process requirements associated with the design. Additionally, the designer has a list of candidate materials and manufacturing processes that are suitable for executing the design.
- ii. If there are any design changes that need to be made as a result of the materials and/or manufacturing processes-related critical parameters, these can be made at an early stage. These changes are conceptual in nature and addressing them during conceptual design is preferred over addressing them during or after detailed design.
- iii. Since the materials and manufacturing processes-related issues have already been addressed during the conceptual design stage, fewer iterations related to such issues should be needed during the later stages of the design. Also the modifications help the designer avoid any surprises in the materials domain and/or in the manufacturing process domain. Unanticipated issues can easily force a designer to make non-optimal compromises or even to discard a concept altogether.

- iv. The modifications provide a formal and systematic way of achieving the goal of addressing materials and manufacturing processes-related issues at an early stage of the design process, namely during conceptual design.

The proposed modifications are consistent with the philosophy of the IIDE Design Process and satisfy the need to address materials and manufacturing issues during conceptual design. The addition of the proposed modifications to the IIDE Design Process is therefore both appropriate and recommended.

6.2 FURTHER WORK

As stated before, a design methodology must help the designer identify what needs to be done, one or more methods of how to do it, and provide a procedure to check how well the need has been satisfied. This thesis addresses the first aspects only. Future work developing a procedure that will help the designer evaluate how well the materials/manufacturing processes detour has been executed. This could be in the form of design rules in the materials and manufacturing processes domains, analogous to the “Seven Design Principles” detailed by Pahl and Beitz [2] that are used to assess the quality of an embodiment in embodiment design and detailed design.

The proposed modifications can be validated further, fine-tuned, and enhanced by implementing the proposed changes in the IIDE Design Process. This validation could be attempted using a statistically valid group of students, i.e., one group of students could be used as a control group that uses the existing IIDE Design Process, whereas the other group could use the IIDE Design Process with the proposed modifications.

Another need that must be addressed by the IIDE Design Process is the inclusion of economic considerations into the design process. This thesis makes a start at including the fundamentals of Design for Manufacturing (DFM). The next step would be to try to

incorporate Design for “X” where “X” stands for “excellence” and hence includes manufacturing, assembly, cost, packaging, etc. In each case, the required modification could be incorporated during the conceptual design stage.

Finally, additional work can be done in developing a methodology that will help the designer develop a good function structure for a given design need. This could be done by using approaches similar to the “house of quality” from a functional point of view, thus using these established approaches that are used extensively in industry to identify the design parameters and their influence on the design.

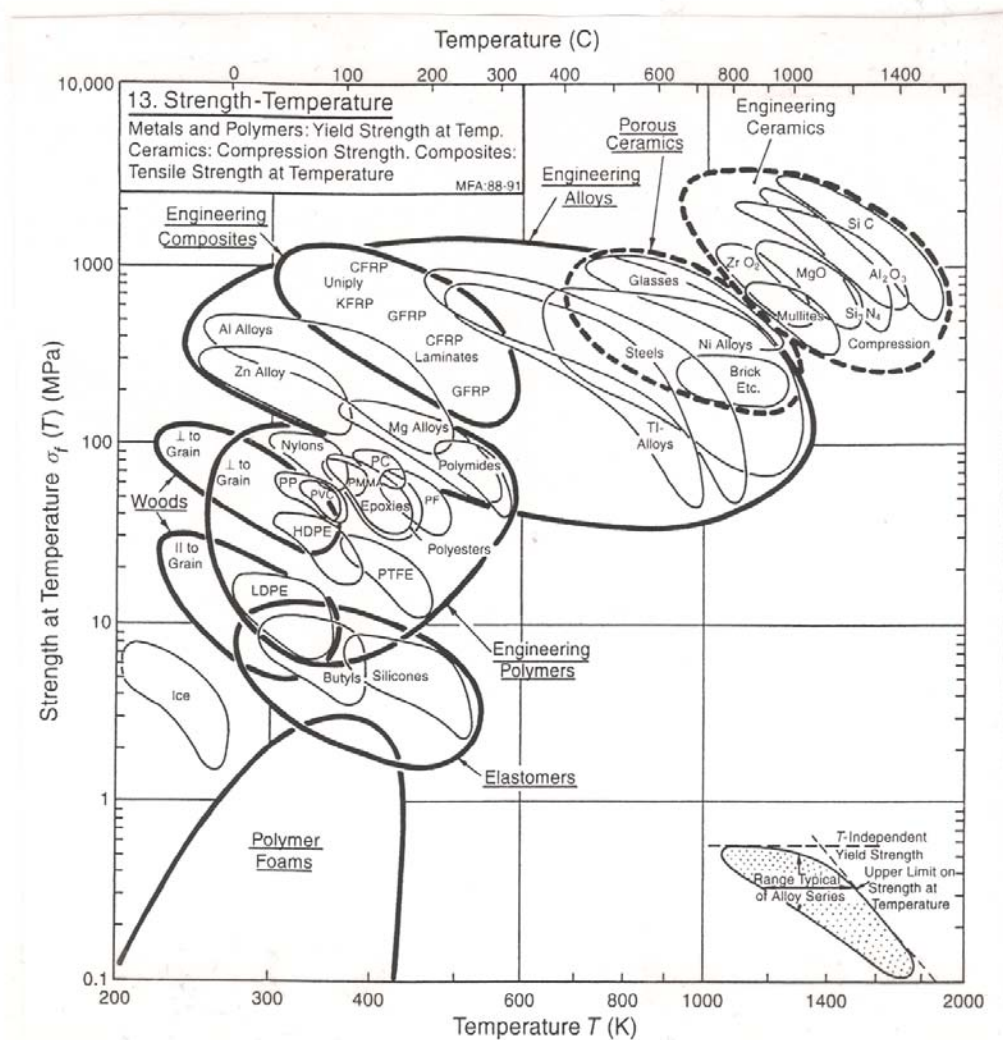
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APPENDIX A

AN EXAMPLE OF ASHBY'S MATERIAL SELECTION CHARTS

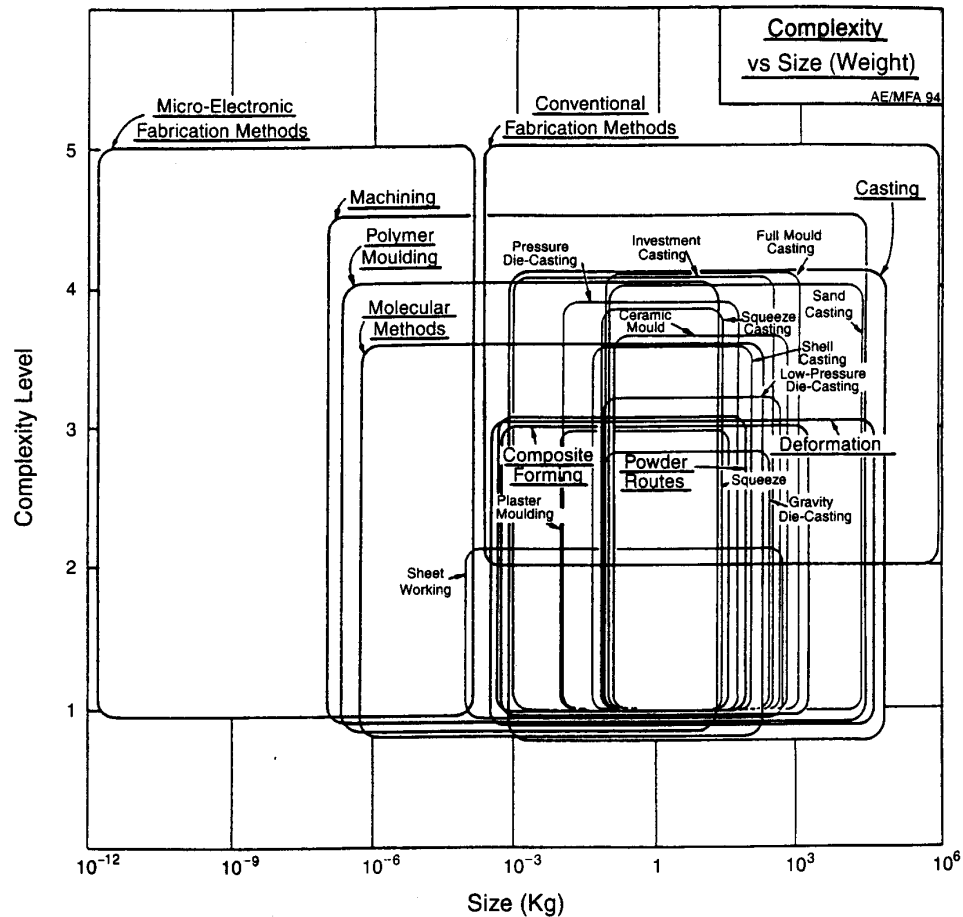
[3]



This plot shows the variation of strength, as defined in the top left hand corner of the chart, with temperature defined on the absolute scale (K). The yield strength is the stress required to produce a specified amount of plastic deformation. The tensile strength, or ultimate tensile strength (UTS), is the maximum stretching load that the material can withstand without failure divided by the original cross-sectional area of the specimen.

APPENDIX B

AN EXAMPLE OF ASHBY'S PROCESS SELECTION CHARTS [3]



The chart shows the variation of complexity, as defined in Chapter III, with respect to size. The range of operation for each process is shown by in the chart for various processes.

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