A Framework for Conceptual Design Decision Support

By

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Abstract

The decisions made at the conceptual design stage are crucial to the overall success of the product as they affect all the downstream phases of the product life cycle, the user satisfaction of the product and the environment that the product is used and disposed of. The consequences due to these design decisions could therefore be good or problematic. Due to the lack of availability of knowledge and understanding about the complexity of such knowledge spanning these different areas, designers find it difficult to know the implications of their decisions made at the conceptual stage on the product's life cycle, the user of the product and the environment in which the product operates. Reviews of existing methodologies reveal that there is a need for a holistic view of knowledge in terms of the total context of the design problem under consideration to aid designers in their decision making at the conceptual design stage. This thesis addresses this problem by proposing, implementing and evaluating a computational framework for supporting decision making at the conceptual design stage.

The need for considering the implications of design decisions on other life cycle stages of the product and using the whole *context* of the design problem lead to the characterization and formalization of the *Design Context Knowledge* into different groups and context knowledge categories. This structuring facilitates the creation of feasible design solutions composed of what is called *Product Design Elements (PDEs) i.e. basic* elements as a functional means to constitute a conceptual product design solution. The proposed Function to PDE mapping model uses the aforesaid design context knowledge structured in different categories for reasoning and eliciting consequences, associated with selecting a particular design solution and determining its implications on the product's subsequent life cycle stages, user of the product and on the product itself. After developing a system architecture model based on the system requirements, the PROCONDES prototype system has been implemented for a sheet metal component design domain. An evaluation of PROCONDES performed by conducting a case study indicates the importance of design context knowledge in proactively supporting effective decision making during function to PDE mapping process (i.e. conceptual design stage) by generating timely potential (good and problematic) consequences. However, further work is required to improve the model and its implementation to fully explore the approach and use of PROCONDES for real-time design scenarios.

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1 Introduction

The development of a mechanical product undergoes a sequence of processes, which includes conceptual design, detailed design, design analysis, prototype making and testing, production process planning, manufacturing, inspection and assembly. The demand for high quality, on-time delivery, and low cost products with shorter design and manufacturing lead times for the dynamic global market is forcing companies to introduce new product and process design strategies. The main purpose of these design strategies is to reduce significantly the time required from the design concept stage to manufacture by applying a concurrent rather than a sequential approach to the various product and process design activities. The intent of concurrent engineering is to break the barrier between design and other product development processes especially manufacturing. Concurrent design (or concurrent engineering design) evaluates design from various product life-cycle aspects simultaneously, thereby producing a design with balanced functional performance, production cost and customer satisfaction.

The full realisation of this concurrent design approach is a challenging task, as it requires an in-depth understanding of the logic behind the designer's decision making process and the comprehensive models used in modern design practice. The design information generated at different concurrent activities in product and process design requires linking and mapping at right time with right contents in right format. The concurrent design methodology raises a major issue that needs to be addressed which relates to the provision of intelligent decision support for the design process. This involves identification of the required information to support the different design activities and the determination of adequate techniques for information selection and provision.

Engineering design is a process of generating a solution to produce products/artefacts, which satisfy requirements of the customer/market in the form of desired functionalities. However, there is currently no access to existing knowledge about the manufacturing environment as well as information about other downstream product development phases which could be used for decision making during the conceptual design process. The commitment to design decisions increases as the design process progresses and more design parameters of defining the design solution are introduced. These design decisions can have significant impact on product design and development as well as on the subsequent life cycle of the product [Borg et al., 2000]. Hence, there is a growing need for designers to consider these consequences and other downstream product related information during the initial stages of product design. Engineering designers mostly use a function focused approach in generating a solution to a given design problem [Cross, 1994] paying less attention to the implications of the generated design solutions/concepts on the later stages of the design, resulting in increased cost, poor quality of products and increased manufacturing lead times. Hence, there is a need to provide designers with tools to improve their designs by considering a range of product life cycle issues required to meet the functional requirements of the product. This assistance should be provided during the initial generation and evaluation of design solutions and not after they have been finalised.

Of all the different phases of the design process, the conceptual design stage is the most important phase of the design process, because the decisions made at this stage have a strong bearing on all the subsequent phases of the design and development process of a product. There is a need for a sound conceptual design, as a weak concept can never be turned into an optimum detailed design. The importance of conceptual design to the overall success of the product is crucial as once the conceptual design process has been completed, the majority of the product cost (i.e. as high as 70% of the product cost [Boothroyd et al., 2002]) and quality has been committed by selecting specific concepts/solutions. This also means that subsequent product life-cycle activities (i.e. manufacturing, assembly, use, recycle and disposal) have been implicitly determined by these solutions made at the conceptual design stage.

While experienced designers in a given application domain are usually able to create successful conceptual designs because of their in-depth knowledge and experience of the common design practices, customer expectations, and manufacturing processes, less experienced designers often require inputs from experienced designers to complement their knowledge. Ideally, a designer should be able to access necessary information related to design, customer requirements, manufacturing and other life phase constraints as well as life phase systems' costs during the design of a product in order to perform effective decision making. Even with recent advances in software technologies for engineering design and manufacturing, making sound decisions in the initial design phase is still difficult as it involves an understanding of unpredictable factors in manufacturability, quality, reliability, and serviceability [Ullman, 1997; Pahl and Beitz, 1996].

The solution space for conceptual design could be explored effectively and a best solution could be generated if the consequences caused by the design decisions on the subsequent product life cycle stages are fully considered at the conceptual design stage. These consequences can be incorporated at the conceptual design stage by using design information and knowledge obtained through understanding the important life cycle requirements of the product being designed for and the environment that the design process and the product will operate in. A good understanding of this design context is essential for successful design and any design support system should investigate as to how the design context knowledge and information can be used to provide effective support. Hence, it is essential to identify, understand the role and utilize design context knowledge in order to support the conceptual design stage. This thesis presents a framework to use this important and relevant information to provide proactive and intelligent design decision support through background reasoning of design context knowledge when solutions/concepts are generated to satisfy the functional requirements of the product.

1.1 Research Motivation, Aim, Objectives and Methodology

The lack of understanding of the impact that a poor design decision made during conceptual design, has on other life cycle phases and the non-availability of design background knowledge in current design practice are the primary difficulties that many researchers face. These difficulties are further compounded by the complex nature of design context knowledge surrounding design problems. The complex nature is exemplified by ill defined design problem specifications, incomplete specifications of design requirements, the magnitude of information that constitutes the design context knowledge at any design stage and the important role that the product life cycle related knowledge could play during conceptual design. All these present a clear case for a research problem, which needs to be addressed.

Seeking a more effective approach and desiring a comprehensive framework is the primary motivation that the author has to undertake this PhD research project. This motivation naturally leads to the following research aim definition and structured objectives of the project.

1.1.1 Research Aim and Objectives

The overall research aim is to understand the role that the design context knowledge can play in conceptual design and based on this understanding to derive a computational framework for supporting proactive decision-making during the function-based mechanical conceptual design. This support will be devised by proposing an approach of mapping potential design solutions to the desired functional requirements and evaluating them using design context knowledge.

To achieve the above aim, the following detailed specific objectives have been specified in this research:

- To examine the role of the decision-making process at the conceptual design stage and identify key aspects in conceptual design which are important from the perspective of decision making.

- To undertake a critical review of existing methods and associated frameworks and tools which support decision making at the conceptual design stage in order to identify their deficiencies/shortcomings.

- To understand the role of design context knowledge in conceptual design by clearly defining and structuring it into formalised groups and categories for supporting effective decision making.

- To propose and derive an approach to enable proactive and intelligent design support for decision making at the conceptual design stage in a function based mechanical artefact design.

- To evaluate and demonstrate the developed approach by implementing it in a prototype system and conduct a formal evaluation of the approach and the system.

- To suggest future research directions and research areas.

1.1.2 Research Methodology

The methodology developed in the CAD centre [Duffy and O'Donnell, 1999; Duffy, 1997], University of Strathclyde, Glasgow UK was adapted in this research work with slight modifications. While the main elements of the research methodology (Figure 1-1) are based on Zhang's [Zhang, 1998] thesis, the explanations for some of the phases are adapted from Lim's [Lim, 2002] thesis.

- ***Literature***: Literature review forms the backbone of any research process. In this research context, to define the design problem, literature review on the current approaches to decision making at the conceptual design synthesis stage including use of relevant computer based tools has been carried out.

- ***Design practice***: Design practice refers to the design reality. In this stage, some key elements from the design practice and literature are investigated to identify the design problem.

- ***Problem identification in computer support conceptual design***: The focus of this research is the development of a new approach for supporting decision making at the conceptual design synthesis stage of the design process.

- ***Research problem***: The research problem is concerned with addressing the "what" and "how" questions to support decision making at the conceptual design synthesis stage of a product.

- ***Solution***: The development of a solution aimed at resolving the research problem is realised by developing an approach and subsequently deriving a computational framework implemented in a computer based system.

- ***Solution evaluation***: The evaluation of the developed solution has been performed using case studies through the computer-based system. Based on the evaluation results, the strengths and weaknesses of the system in supporting the conceptual design decision making have been identified.

- ***Thesis***: The result of the research is documented in this thesis and in some published papers.

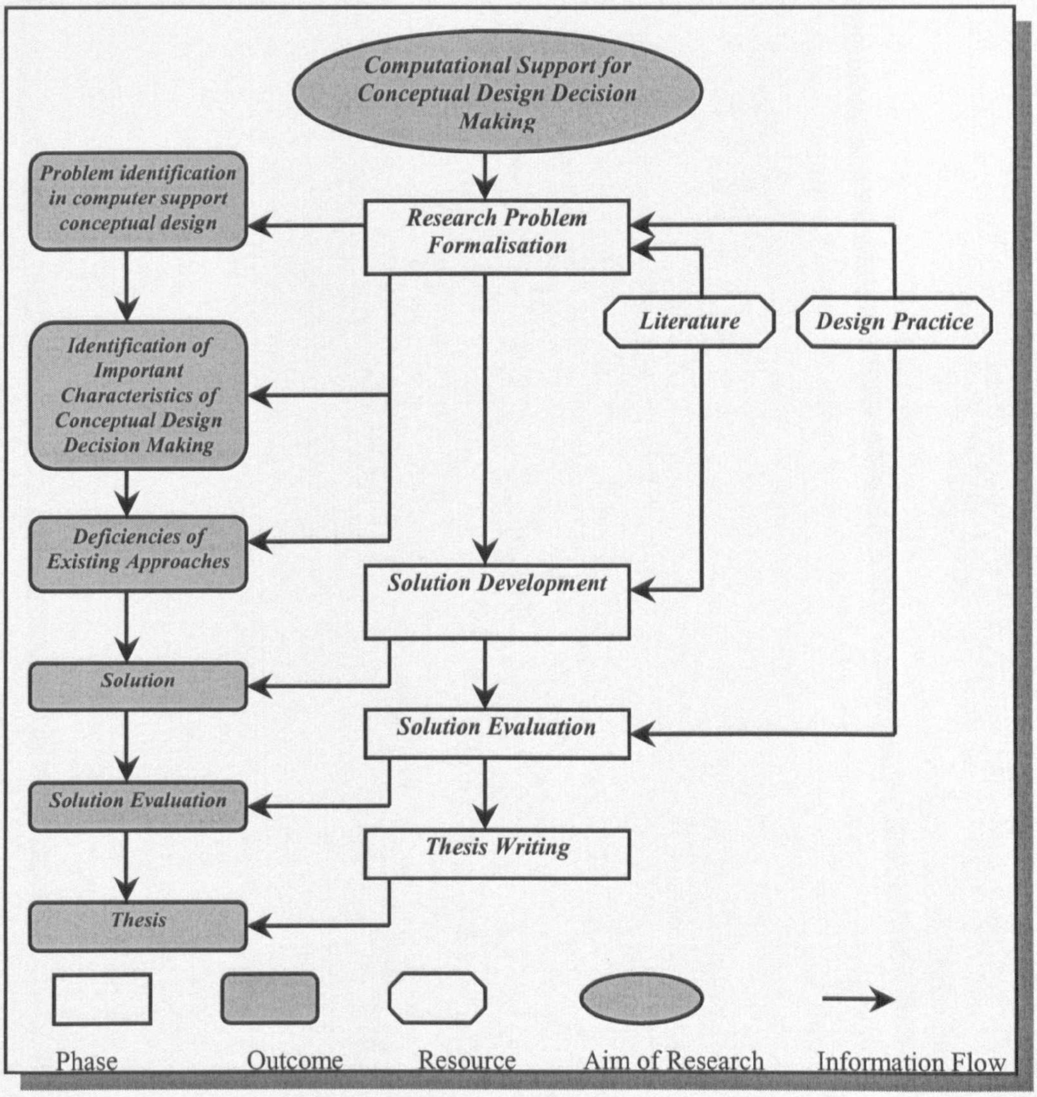


Figure 1-1: Research Methodology

The four phases in Figure 1-1, Research Problem Formalisation, Solution Development, Solution Evaluation and Thesis Writing are considered to be the main elements in conducting the research. Design Problem Identification, Identification of Important Parameters in Conceptual Design Decision Making, Deficiencies of Existing Approaches, Solution, Solution Evaluation and Thesis are the main outcomes of the research.

1.2 Structure of the Thesis

The thesis is structured as follows

- Chapter 1 presents the motivation, aim and objectives of the research. The motivation of the research is based on the current design problem expressing the role of decision making within the conceptual design process.

- Chapter 2 discusses the engineering design process in general and the conceptual design process in particular so as to provide a general background and understanding about the research problem. The role of decision making in the conceptual design process and the possible problems that are likely to be encountered in the later stages of the product development due to inefficient decision making at conceptual design stage is discussed. Different key aspects required for an effective conceptual design decision making support system are identified for further discussion.

- Chapter 3 reviews different methods developed by researchers in order to support decision making at conceptual design stage. The strengths and weaknesses of these different methods and corresponding tools/computer based systems are identified from the literature review and the current design practice.

- The findings of the review are highlighted in Chapter 4. These findings are used to formulate the research problem and outline the research questions. The research boundary is also identified to determine the scope of work.

- Chapter 5 encompasses the definition, importance and use of design context knowledge phenomenon in order to provide support during decision making at the conceptual design stage. To improve its usage in a computer system, the design context knowledge is formalized in representation and classified into categories for easy use in decision making.

- Chapter 6 presents the solution to the research problem by developing design context knowledge based function means mapping model to provide proactive and intelligent decision making support at the conceptual design stage. The working of the model as well as its successful application across different mechanical engineering design domains is described by doing five different paper based case studies carried out during the project.

- A computer prototype system PROCONDES (Pro-Active Conceptual Design) is implemented using the developed framework in Chapter 7 to demonstrate and highlight the effectiveness of the approach.

- Chapter 8 evaluates the model and the corresponding prototype system by describing a case study to show the functionality of different modules of the prototype system.

- Chapter 9 discusses the strengths and weakness of the approach as well as of the prototype system based on the results of the evaluation, and proposes areas of future work in the selected research field.

- Chapter 10 concludes the thesis by summarising the work done in the research.

2 Design Process and Decision making in Conceptual Design

The aim of this chapter is to review the design process and the role of decision making in the conceptual design process. In the first two sections, the engineering design process and the different stages involved in the design process are examined (particularly the conceptual design stage). The third section identifies and discusses important aspects, which are critical to decision making at the conceptual design stage.

2.1 Design Process

The word *Design* can be used as a noun or a verb. There have been several attempts in the past to describe and define design and the design process by different researchers [Pahl and Beitz, 1996; Suh, 1990; Pugh, 1990; Roozenburg and Eekels, 1995; French, 1985]. The Oxford Dictionary [Oxford, 1990] defines '*Design*' as:

- A preliminary plan or sketch for the making or production of a building, machine, garment, etc.
- The art of producing a building, machine, garment, etc.
- A general arrangement or layout of a product.

The aforesaid meanings of '*Design*' are interpreted differently in different backgrounds and therefore can be considered context dependent.

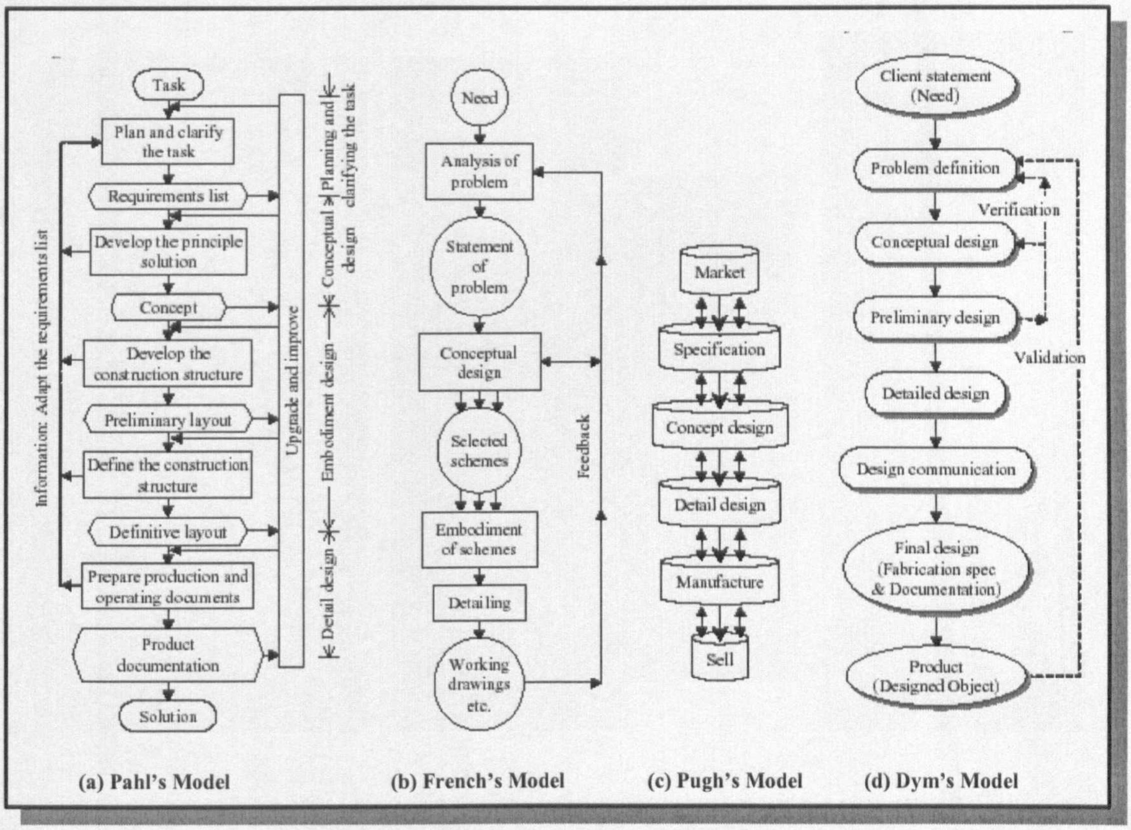
Hubka and Eder [Hubka and Eder, 1988] describe design as:

"A process performed by humans aided by technical means through which information in the form of requirements is converted into information in the form of descriptions of a technical system, such that this technical system meets the requirements of mankind".

Roozenburg and Eekels [Roozenburg and Eekels, 1995] and Hurst [Hurst, 1999] describe design as a process consisting of problem solving activities in which design solutions are generated to satisfy customer needs. The analysis of problem solving activities leads to the notion for use of computer based support systems in the design process. Suh [Suh, 1990] describe *Design* as the process of creating solutions in the form of products, processes or systems that satisfy the needs by mapping the functional requirements in the functional domain and the design parameters of the physical domain, through proper selection of design parameters. Archer [Archer, 1971] describes *design* as a process of conceiving an idea for some artefact or system and/or to express that idea in an embodiable form. All these definitions indicate that design is a process of generating some solutions and then deciding on the best possible solution(s) to satisfy the perceived requirements. *"Design"* for the purpose of this research, is a process of solution creation by mapping functional requirements and the design requirement parameters in the form of solution means [Suh, 1990]. This leads to a detailed discussion of this solution creation process, for which many so called design process models have been proposed and utilized.

2.2 Design Process Models

A number of influential engineering design process models have been proposed in an attempt to promote improvements in the understanding and practice of engineering design. Prominent contemporary contributors include Cross [Cross, 1994], French [French, 1985], Hubka [Hubka, 1982], Pahl and Beitz [Pahl and Beitz, 1996], Pugh [Pugh, 1990], Ullman [Ullman, 2002], Dym and Little [Dym and Little, 2000]. All these contributions have led to the development of a stronger theoretical background and use of a more concise and systematic approach to engineering design. However, the progressive development of these models has resulted in a consensus view as many of these models inspite of varying approaches exhibit common basic features. These include the breakdown of the design process into distinct stages or activities, leading to certain output results (specification, functional structure, layout, documentation, etc.). These design models (Figure 2-1) detail the subdivision of the overall design problem into sub- problems emphasizing the iteration and interaction within and between the stages of the design process while maintaining the progression of the design process. In spite of the differences in the underlying approaches, there are four distinctive phases i.e. *Task Clarification, Conceptual Design, Embodiment Design* and *Detail Design* in the design process. Although these phases may vary depending upon the designer and the design domain, it is possible to generalise them in a broad outline. A brief description of these design phases is discussed in the following sections.



(a) Pahl's Model **(b) French's Model** **(c) Pugh's Model** **(d) Dym's Model**

Figure 2-1: Design Process Models

2.2.1 Clarification of Tasks

The design process starts by the recognition of some needs for a new product [Pugh, 1990; French, 1985; Hurst, 1999] and with the *clarification of the tasks* phase. The outcome of this phase is a well-documented and identified understanding of the problem called a Product Design Specification (PDS).

Thorough investigation of the problem is made by the designer before a solution is sought in this phase. Large, complex and diverse problems are broken down into smaller manageable sections. The writing of a comprehensive PDS requires definition of all required *functions*, which the solution(s) must provide, and all the *constraints* within which the solution must work. The clarification phase often involves resolution of redundancy, inconsistency and ambiguity. The information required to write a PDS may be made known by customers or could be determined by calculation, testing or by information search. Although it is desirable that a fully defined PDS is written before the commencement of the design process, it is practically impossible, because the design process is iterative and the PDS is regarded as a dynamic document, which evolves alongside the design process. The PDS is questioned at all stages and references are made to the customer as and when changes are suggested by the design team. However the aim at the outset of the task clarification stage is to define the PDS as fully as possible.

2.2.2 Conceptual Design

The conceptual stage of any design is concerned with synthesis, which the new Oxford dictionary [Oxford, 1998] defines as:

> *"Combination, composition, putting together (opposite analysis), building up of separate elements, especially of conception or propositions or facts, into a connected whole, especially a theory or system".*

The conceptual design provides abstract solutions and may sometimes result in incomplete solutions that are expected to satisfy the user requirements considering all view points i.e. functional, economy, technology, servicing etc [Horvath, 2000]. The intention of conceptual design to explore the best alternatives comes from the desire to maintain high quality products, which are of good value to customers. The output of the conceptual design is the development of one or more new design concepts that would be used as the basis for embodiment and detail design [Sturges et al., 1993]. Since it more or less determines the achievable technical merit of the product and its encountered costs, this early phase of design is the most crucial part of the entire product design process.

The conceptual design phase starts with the determination of an overall function from the PDS and the important sub functions that need to be realised by the expected design solution and then establishing the relations between the overall function and the sub-functions [French, 1985]. This results in a detailed pyramid functional hierarchical structure with the overall function to be realized at the top, decomposed into more sub-functions as finer levels at the bottom level. The next step in the conceptual design process is the concept/solution generation stage. During this stage, the designer searches for working principles that can possibly be applied to achieve Functional Requirements (FR) and finding solution(s) that can realise a working principle required by FR [Pahl and Beitz, 1996]. The working principles exhibit the behaviour(s) of concept(s) to fulfil the function. The concept generation process is performed by a single method or a combination of different methods. There are several conventional, intuitive and logical methods for concept generation. These include brainstorming, literature search, analysis of existing technical systems, team discussions and design catalogues. A solution defines those physical-technical characteristics of a concept that are essential for the design to function. If there is no solution, which can realise a particular working principle then the designer has to select an alternative working principle. The process is recursively executed until all the functional requirements are fulfilled by one or more working principles, and all the working principles can be implemented by one or more solutions [Lim, 2002].

After identifying a set of feasible concept(s)/solution(s), the next stage in the conceptual design involves evaluation of the design concepts and the selection of the best possible solution(s) which satisfy the FR. The evaluation of the concepts involves identifying evaluation criteria, weighting the evaluation criteria, assigning and assessing values for each concept and determining the overall value. It is however essential that the large number of concepts have to be reduced to a single concept or just a few so as to enable the designer to pursue them further. Typically a designer has to make several thousand decisions during the conceptual design phase, which in itself poses huge responsibility on the designer. Some of the techniques used in practice for evaluation and selection of the criteria include Quality Function Deployment (QFD), Datum Method, Go/No Go Screening and Decision Matrix. The whole conceptual design phase can be summarised as a Function to Means/Solutions mapping process (Figure 2-2).

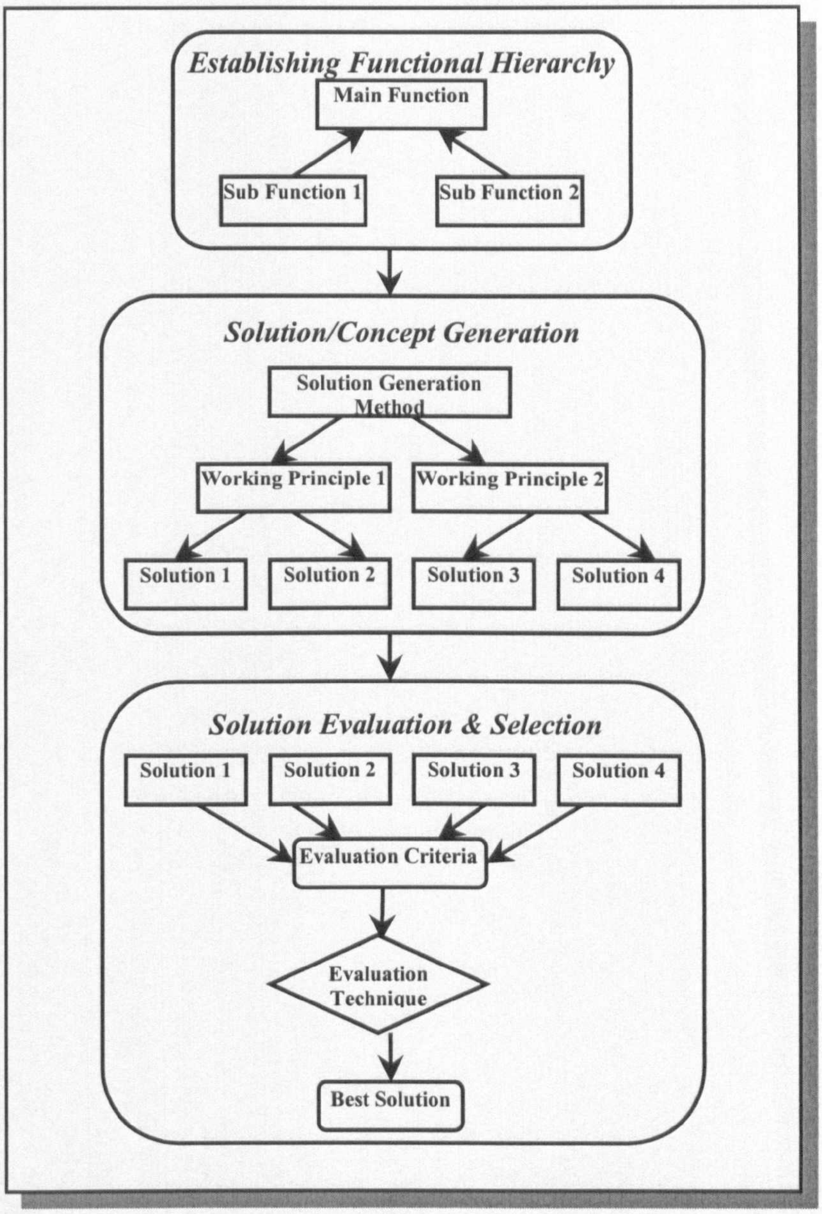


Figure 2-2: Sequence of Activities in Conceptual Design Process

Different researchers have defined conceptual design in different ways (See Appendix B). Based on the discussion in the previous graph, *function*, *behaviour* and *form* of the concept(s)/solution(s) are the major elements of information manipulated in different ways by the designer at the conceptual design phase, therefore this research adopts the definition of conceptual design as defined by Welch and Dixon [Welch and Dixon, 1992] i.e. *"Conceptual design is the transition process between* *three different information states: 1) a set of required functions; 2) a set of behaviours that fulfil the functions; 3) Final selected concept(s)/solution(s) that generate/meet those behaviours".* The conceptual design process is modelled as the function, behaviour and form of concept(s)/solution(s) framework explaining their relationships and interactions in Welch and Dixon's [Welch and Dixon, 1992] work. They argue that conceptual design starts with a set of required functions. These functions are used to search for working principles/behaviours. The behaviours are working principles that realize function(s) and are illustrated by values of different design parameters in different conditions over a period of a time. Concept(s)/solution(s) are generated in the next step to exhibit the chosen working principles/behaviours. Best solution(s) are selected based on the evaluation using different criteria as the final conceptual design solution to realize the required functions.

2.2.3 The Embodiment Design

The embodiment design phase quantifies less abstract concepts into more concrete proposals i.e. the *definitive layout* [Pahl and Beitz, 1996]. A definitive layout is worked out by incorporating preliminary *form* design, i.e. which includes shape, principal dimensions, materials and surface qualities of individual parts in the solution and the *layout* design, i.e. which includes determining the spatial relations between the parts in the solution, in accordance with technical and economic considerations.

The embodiment design can be split into two stages [Pahl and Beitz, 1996]. The first stage results in development of several alternative *preliminary layouts.* A preliminary layout consists of forms, important dimensions, materials, surface qualities of the part(s) and the spatial relationships among different parts is provisionally determined. The most promising *preliminary layout* is selected based on the degree of suitability to the functional requirements. In the second stage, the selected *preliminary layout* is further revised where all major decisions about form, important dimensions, surface qualities and spatial relationships among different parts in the solution are finalised. The outcome of the *embodiment design* stage is the development of the *definitive layout*, which has been successfully tested during this process. Pugh [Pugh, 1990] argues that due to the complex nature of the design problem it is not possible to distinguish the embodiment process from the later stages of conceptual design. However there is consensus among researchers that embodiment results in a detailed description of all aspects of the abstract concept(s)/solution(s) selected during the conceptual design stage.

2.2.4 Detail Design

The definitive layout selected during the embodiment design phase is further refined to completely specify the *structure* of the solution, the *shapes, dimensions, tolerances, surface qualities and materials* of all the individual parts used in the solution and to document them *in assembly, detail drawings and part lists.* The instructions for *production, assembling, testing, transportation, installation, use/operation, maintenance and disposal* are entirely documented as *product documents.* After producing the *product documents* the design process phase of the product life cycle finishes and the next phase i.e. production/manufacturing can be realised based on the *product documents.*

2.3 Decision making in the design process

Decision making and design are so intertwined that it has been suggested that the entire decision making can be viewed as design [Simon, 1969]. Decisions made during the conceptual design stage have significant influence on the cost, performance, reliability, safety and environmental impact of a product. Studies conducted by some researchers [Pugh, 1990; Lotter, 1986] indicate that as much as 75% of the cost of a product is being committed during the design phase. It is therefore, vital that designers have access to the right tools to support such design activities. In the early 1980s, researchers began to realize the impact of design decisions on downstream activities, as a result of which different methodologies such as design for assembly, design for manufacturing and concurrent engineering, have been proposed. While software tools that implement these methodologies have been developed, most of these are applicable only in the detailed design phase. However it is critical to understand that even the highest standard of detailed design cannot compensate for a poor design concept formulated at the conceptual design phase.

2.3.1 Importance of Conceptual Design in the Design Process

Due to the complex nature of conceptual design stage, decisions taken by designer at conceptual design stage play an important role in all subsequent phases of product life cycle [Hubka & Eder, 1988]. The importance of conceptual design to the overall success of the product is crucial as once the conceptual design process has been finished, the majority of product cost and quality has been committed as it involves selecting particular concepts/solutions that have significant impact on the subsequent product life cycle activities such as manufacturing, assembly, use, recycle/disposal etc. The impact of this commitment on the product life cycle has been demonstrated by Nicholls [Nicholls, 1990], whose studies reveal that upto 85% of the life cycle costs of a product can be committed at the end of the conceptual design phase, even though about 5% of the actual life-cycle costs have been spent. This reiterates that conceptual design is an important determinant for product quality and time to market. No matter how good the downstream processes are i.e. detail design, manufacturing, assembly, use, maintenance and disposal, they cannot compensate for poor and inadequately developed conceptual design. However, knowledge of all the design requirements, constraints during this early phase of product's life cycle is usually imprecise, approximate or unknown.

2.3.2 Decision Making in the Conceptual Design Stage

The design concept selection done while exploring solution space makes the conceptual design stage a decision intensive process [Mistree and Smith, 1993; Strarvey, 1992; Joshi, 1991]. Decisions are made on various aspects of the product being designed [Duckworth and Baines, 1998] and typical decisions involve selection of working principles and corresponding concepts and solutions. Further some decisions, which seem appropriate for one life cycle requirement, can pose problems on other life cycle phases [Hubka and Eder, 1988], which are also termed as *concept of dispositions* [Andreasen and Olesen 1993]. This concept of *disposition* implies that part of a decision taken within one functional area (e.g. product design) affects the type, content, efficiency and progress of activities within other functional areas (e.g. assembly). Therefore design decisions are associated with consequences [Andreasen and Olesen, 1993; Duffy and Andreasen, 1993] which can either be intended or unintended [Borg and Yan, 1998] and have the ability to influence the performance of other life-cycle phases in terms of measures such as cost and time. For example a small decision for use of countersink head screws instead of counter bore head screws to assemble two parts will influence a number of product life cycle phases – i.e. design, manufacture and purchase departments. Similarly a decision of recommending a long steel girder to be bolted with the steel column during installation instead of welding influence design, purchase, manufacture, transportation, installation and maintenance phases.

Design decisions not only influence different product life cycle phases but also have impact on the product's working environment in which the product is to be used or handled [Hurst, 1999]. The working environment can be influenced by various factors such as invariant noise level caused by the operation of the product and the physical/aesthetic features of the product with which a user interacts. Therefore designers must consider the influence of ergonomics as well as the environment of the product while designing a product. To elucidate, a fully functional, aesthetically appealing design of an iron handle may not be suitable for females due to its ergonomics (i.e. weight or grip). The physical, organisational and socio-economic environment in which the designer works influences the decision making at the conceptual design stage [Gero and Kannengiesser, 2003]. While some of these influences are direct, others are subtler. The direct influences are normally in the form of company policies, profit and organizational motives, international recognition and reputation of a government/company [Haik, 2003]. Designers are also influenced by the society in which they operate and their decisions are guided by political, social and economic pressures [Brimingham et al., 1997].

2.3.3 Lack of Availability of Required Knowledge

Designing has been recognised as a dynamic activity [Pugh, 1990; Gero and Kannengiesser, 2004], where decisions are taken during different phases of the design process, resulting in generation of a large amount of knowledge/information. Knowledge/information generated upto the current stage of the design process is termed as the current working knowledge [Zhang, 1998]. In order to enable effective design decisions, it is important that apart from current working knowledge, the consequences of the design decisions on different life cycle phases, external socio political and physical environment (as detailed in preceding section) and the product related domain knowledge must be made available to the designer. These varying needs have been highlighted by different researchers. For instance, the use of product related life cycle knowledge has been emphasised by Tomiyama [Tomiyama 1996], the impact of environmental considerations on designer/design process by Brimingham et al. [Brimingham et al., 1997] and the knowledge that is generated during the design process by Zhang [Zhang, 1998].

However Olesen [Olesen, 1995] argues that designers lack the required knowledge during the decision making process. MaCallum and Duffy [MacCallum and Duffy, 1987] support Olesen by attributing this problem to the traditional and formal training received by designers and their personal experience with regard to life cycle issues resulting in lack of adequate *breadth* and *depth* of knowledge required during the decision making process at the conceptual design stage. This also leads to a situation where designers lack the knowledge about the consequences of their decisions. The availability of technical information during the design stage has an important bearing on the quality of the design solution. Therefore where decision making is done with limited knowledge and insight into the problem at hand will result in low quality decision making [Duffy and Andreasen, 1995].

As discussed in section 2.3.2, there are vast amounts of knowledge/information related to a product, its life phases, the environment of the designer/product and the design process, which is not available to the designer during the decision making process due to the enormity and complexity of the information. Even when a part of this knowledge is available it is difficult to memorize it as the mental capacity of humans is limited to seven plus or minus two pieces of information, which can be handled simultaneously [Miller, 1956]. The solution therefore lies in computerization of this vast amount of information. Very few CAD tools have been developed to support conceptual design activities. This is because knowledge of the design requirements and constraints available during this early phase of a product's life cycle is usually vague, imprecise, ill structured and incomplete, making it difficult to develop computer-based systems or prototypes to support conceptual design.

2.3.4 Key Aspects of Decision Making in Conceptual Design

In order to support the conceptual design stage, designers need to know about the different interacting parameters, which are essential for effective decision making. A complete description of functional requirements [Haik, 2003] in the form of a functional hierarchy as well as decision consequences are required in order to enable effective decision making. Another aspect that requires consideration is the selection of the right criteria to evaluate different design alternatives, as focusing only on *'function'* can result in products which are not only costly to produce but take longer manufacturing lead times besides implicating on different life cycle phases [Boothroyd et al., 2002]. Therefore designers have to be fully conversant about *detailed functional requirements, decision consequences, selection of appropriate evaluation criteria and decision making theory* to evaluate different design alternatives at the conceptual design stage. These parameters are explained briefly in the following sub sections.

2.3.4.1 Detailed Functional Requirements

A Product Design Specification (PDS) document that has originated from market research and generated in consultation with the customer is normally used to describe the required functional requirements. However it is the designer's responsibility to decompose the overall high-level function into small and implementable sub-functions, because it is very difficult to find a single solution means that can achieve a specified high-level function in engineering design. This decomposition results in a functional hierarchical structure that represents a good understanding of the customers' requirements for a product. This is particularly important to functional oriented design as such a structure represents the results of the functional understanding and decomposition process. It also serves as the basis for the function mapping. During the functional decomposition, the functional requirements are often decomposed to a level where it is possible to identify potential means or mechanisms to realise these lower sub-functions, thereby aiding the designer in the decision making process.

2.3.4.2 Decisions' Consequences Awareness

As explained in section 2.3.2, every decision taken by the designer is associated with consequences [Andreasen and Olesen, 1993; Duffy and Andreasen, 1993; Swift and Raines, 1997; Ullman, 2000; Yan et al., 2002; Haik, 2003] which can either be intended or unintended and either good or problematic [Borg and Yan, 1998]. Hubka and Eder [Hubka and Eder, 1988] argue that every design decision has an influence on the product's later life cycle stages in terms of performance measures such as cost and time. Gero [Gero, 1998] argue that the conceptual design process is a sequence of situated acts. He calls this concept *situatedness* i.e. the notion that addresses the role of the context knowledge in engineering design. This implies that conceptual design is a dynamic activity, which should be undertaken in the context of external world and therefore any decisions made by the designer have implications on the external world that comprises environment of the product and users of the product. It is therefore necessary for the designers to be aware of the consequences of their decisions taken at the conceptual design stage not only on the later life phases of the product but on the whole context of the design problem under consideration i.e. the external world, life cycle phases, environment of the product in which it is used, and users of the product.

2.3.4.3 Selection of Decision Criteria & Evaluation of Alternatives

Irrespective of the selection criteria i.e. single or multi criteria, selection of decision criteria and evaluation of alternatives play an important role during decision making at the conceptual design stage [Girod et al., 2000]. It is therefore necessary to identify the meaning, nature and contents of each decision criteria before evaluation [Li and Azam, 2000]. Typical design criteria include functional requirements, cost and time considerations, quality of solution, company policies etc. It is equally important to investigate and explore the structure of criteria so that sub-criterion can be easily interpreted and applied in the evaluation process.

Decision making methods/theories relevant for supporting engineering design selection/evaluation problems have emerged from disciplines such as Operational Research (OR) and Artificial Intelligence (AI). The selection of a particular method depends upon the nature of the design problem under consideration and the judgement of the designer. An ideal concept evaluation method should be chosen based on the assessment of its relative strengths and weaknesses and should meet the following criteria [Girod et al., 2000; Ullman, 2000; Girod et al., 2003]:

(i) It should be capable for use in both qualitative as well as quantitative analysis.

(ii) It should be able to perform pair-wise comparison of design alternatives.

(iii) It should be possible to compare not only different design alternatives against design criteria but also different design criterion against designer's preferences.

(iv) It should be possible to take into account criteria with different levels of description i.e. hierarchical ranking of criteria from top to bottom level should be possible

(v) It should be possible to model clear and understandable representation on the expected performance of alternatives.

Since there exists no decision making method, which has all these qualities, it is necessary for a designer to choose a decision making method/theory, which supports a maximum level in design concept evaluation.

Apart from the three key aspects elucidated in previous sections, the context of a design problem is extremely critical for decision making at the conceptual design stage [Brimingham et al., 1997; Maffin, 1998]. Identification of the exact context of the design problem is necessary in order to select the right decision criteria and also determine the factors, which influence the designing of the product, environment of the product and the product itself [Gero, 1998]. In summary, an ideal design decision support system should enable designers by providing proactive decision support using design context knowledge.

2.4 Chapter Summary

This chapter explains the nature and characteristics of the engineering design process with specific emphasis on decision making during the design process. Section 2.2 gives an overview of different design process models, which are currently in practice as well as description about four different phases/stages of the design process, which are completed by designers while designing an artefact. The next section articulates the importance of the conceptual design stage within the design process and its role in the overall success of the product. The role of decision making in conceptual designing is highlighted by identifying three key aspects i.e. *Detailed Functional Requirements, Decisions' Consequences Awareness and Selection of Criteria and Evaluation of Alternatives*, that need to be addressed in developing an ideal decision making support methodology at the conceptual design stage. The role of context at the conceptual design stage has also been highlighted. The next chapter will review the existing methodologies and correspondingly developed computer based tools/frameworks that have been developed by different researchers to support decision making at the conceptual design stage with respect to these three key aspects as well as use of the context knowledge in engineering design.

3 Review of Work in Supporting Conceptual Design Decision Making

This chapter presents the results of a critical literature review of different methodologies, frameworks and computer based systems, which have been developed by different researchers in order to support decision making at the conceptual design stage. The strengths and weaknesses of different approaches are considered in order to present the state of the art in the field as well as to identify potential research challenges and problems arising therewith.

Since there exists a wide number of conceptual design decision support methodologies and computer based tools/frameworks, explaining them individually would make the discussion arduous. Therefore, the review is based on the three distinct viewpoints identified in Chapter 2, as the important characteristics of an ideal design decision support system i.e. *Detailed Functional Requirements, Decisions Consequences Awareness, Selection of Criteria and Evaluation of Alternatives.*

3.1 Detailed Functional Requirements

Defining detailed functional requirements is essential in order to understand the technical as well as customers requirements so as to enable effective decision making. This is done by modelling and representing detailed functional hierarchical structures using appropriate techniques. Functional requirements can be elaborated to a detailed level by decomposing them into finer resolutions, thereby creating hierarchical functional structures.

As in the conceptual design stage, function, behaviour and form of concept(s)/ solution(s) linking each other, are accorded equal importance and are modelled alongside each other. Hence, the following sub-sections present a review of function, behaviour and form modelling in conceptual design.

3.1.1 Function-Behaviour-Form Modelling

Function, behaviour and form are the major elements of information, which are manipulated in the three states of the conceptual design process as defined in Welch and Dixon [Welch and Dixon, 1992]. The first state starts with the selection of required functions and completes with the decomposition of higher level abstract functions into lower fine sub levels in a functional hierarchical structure. Working principles are selected to exhibit the behaviour of the product as well as solutions are generated to meet those behaviours in the second state of the conceptual design process. Evaluation and selection of best solution(s) is performed in the final state of the conceptual design process. Substantial work has already been done to represent the conceptual design process as a model of function, behaviour and as a structure/form/means framework [Bracewell and Sharp, 1996; Chakrabarti and Bligh, 1996; Umeda et al., 1996; Gero and Kannengiesser, 2000; Dangoumau et al, 2002; Roy et al., 2001].

While *function* reveals the intentions of the artefact, *form* specifies the composition of the artefact and as to how the components are interconnected. *Behaviour* on the other hand spells out as to how the structure of the artefact achieves its functions. The word *'function'* in design is regarded as a description of the intended action or effect produced by an object [Welch and Dixon, 1992]. Designing by functions enable one to describe the objects (which in the design context represent design problems and solutions) in terms of their known functions.

'Behaviour' of a product is defined as the set of values of different parameters, (which are related causally), which occur either at specific points in time or over a period of time. Most existing design systems explicitly represent only form, making little allusion to behaviour as a reasoning step between function and structure [Gero et al., 1992].

The characteristics of a physical solution/ means, which is used to realize a particular function is defined as *'form'* or *'structure'* of the solution. *'Form'* of a solution exhibits structure of components composed of different materials and shapes in an artefact.

3.1.2 Functional Representation in Conceptual Design

Though several methods and representations have been developed in literature, five main functional representations in mechanical artefact design are discussed in this research. The first one is a natural language-like, non-mathematical representation, where verbs and nouns are used to describe what an object does, or is supposed to do. For example, shaft is described in terms of its function as follows: i.e. *shaft* (object) *transmits torque* (function) [Chakrabarti and Bligh, 1994]. An advantage of this type of representation is that it closely resembles how designers express their ideas and therefore can be used to build a systematic library. It is not only difficult to formalise this representation in a generalised way but it also does not support any kind of manipulation of such representation. Functions represented grammatically are used in morphological analysis, whereby all sub functions at the same level of a main function are listed in the vertical column on the left hand side and the corresponding features/means of achieving a particular sub function within different conceptual alternatives/solutions on the right hand side to make up the morphological chart [Hurst, 1999].

In the second representation, function is expressed as a transformation between a system's input(s) and output(s) flow. This flow may entail movement of information, matter and energy [Pahl and Betiz, 1996]. This representation is formalisable and hence more suitable for computational development. However if a man-machine environment is to be provided, the commonly used functions expressed in the natural language type representation would have to be first mapped into this representation before any general functional reasoning support environment could be developed [Chakrabarti and Bligh, 1994]. Similarly a conversion from input/output representation to a more understandable form by human beings is required after any reasoning. Therefore this approach is costly as it involves additional overheads for interpretation of the reasoning results.

The third form of representation to model function is through Bond Graphs. Bond graphs provide a unified representation of physical systems spanning a range of applications by graphically depicting a system in terms of bonds and energy processing elements. Bond graphs describe energy conversion, flow, dissipation and causal relationships between two sets of basic energy co-variables i.e. effort and flow [Karnopp et al., 1990]. Bond Graphs are extremely useful as multi disciplinary physical systems and can be modelled using nine basic symbolic elements. However, the main disadvantages of this method are that they involve complex modelling and are restricted for use in energy systems. Therefore they are more suitable to systems, which incorporate some aspects of energy conversion and transformation.

The fourth form of representation is through qualitative physics [Forbus, 1988; Williams, 1984] where symbols are used to describe the operation of a system in terms of its processes, components or constraints. While this representation is useful to describe those systems that cannot be quantified, they prove futile in such cases where large systems need to be modelled, as they require a lot of information to model a complete system [Winsor and MacCallum, 1992].

The fifth and final representation is called the function diagram [Haik, 2003] in which the function is represented by a black box that shows the inputs and outputs to the system, including the flow of energy, material and information from and to the system. The black box is subsequently made transparent by decomposing the overall complex function into a number of functions and sub functions. While this representation is appropriate to describe abstraction and control at various levels of a complex system, it does not adequately explain the relationships present within the system i.e. between a specific function and its sub-functions as well as amongst different sub functions.

3.1.3 Form Representation in Conceptual Design

The modelling of a form of a mechanical artefact is expressed in terms of its constituent components and sub-components, and the interactions between them. The form of each artefact representation consists of the following information [Roy et al., 2001]:

1. Component/sub-component structure of the artefact.

2. Material properties of the artefact.

3. Typical shape which characterises the artefact as unique.
4. List of additional features, which are essential in order to ensure that the artefact works in a real-life environment.
5. The possible modes/situations in which the artefact might fail.

In order to support the conceptual design process, various researchers have represented the aforesaid information using different methods. These methods include natural language syntax based representations, graph based approaches and graphical modelling of components. Depending on the nature and complexity of the information about the form of mechanical artefacts, any one of these methods can be used individually or through a combination approach to model the form of component concepts generated during the conceptual design stage.

3.1.4 Behavioural Representation in Conceptual Design

Though functional and form models explain the intentions, composition and relationships present within the components in an artefact, they are however insufficient to synthesize the entire artefact behaviour. This is due to the fact that functional models in general do not adequately capture all the properties related to a function and therefore do not completely define the design problem. For instance, the functional requirement of a mating shaft and bore cannot be expressed completely by the diameters of the shaft/bore or by spatial relationships indicating the fit condition between them. This is because they do not provide other functional design details such as contact pressure, contact force, rotational torque, rotational speed etc. at the shaft-bore interface, which in turn varies under different working environments over a period of time.

Behaviour can be represented through different representation schemes like bond graphs, behaviour graphs and natural language type representations. Behaviour of a function is context sensitive and as such, behaviour comes into play only in the context of the design environment. The context of the design solution can include non-exhaustive list of parameters and their corresponding attributes. For instance variables such as *temperature, humidity, vibration, water proof* etc can be included as part of environment attributes; *conductivity, strength, durability* etc as part of material attributes; age profile, demographic, lifestyles etc as user attributes and so on.

3.1.5 Typical Systems Using Representations of Function, Behaviour and Form

Some of the work reported by researchers in representing function, behaviour and form of means during conceptual design stage are illustrated here. A detailed review of the different methodologies/frameworks using the representations is given in table A-1 in Appendix-C.

FBS Modeller

FBS Modeller consists of a knowledge base of functions, a component database and a mapping mechanism between them [Umeda et al., 1996]. Function decomposition is done using the function decomposition knowledge stored in the knowledge base. Then each basic function is mapped to a component in the component database. The behaviour of each function as well as the functional structure is qualitatively analysed according to the Qualitative Process Theory [Forbus, 1984].

Since FBS Modeller does not have a generic method of decomposing function, it is not possible to decompose a function not present within the functional knowledge base. Since there are predefined sets of components, which can be mapped onto functions, it restricts the designer from exploring more design alternatives. Further, the major drawback of the FBS Modeller is that it is incapable of performing life cycle based analysis of the selected components, thereby restricting its usage.

Schemebuilder

Schemebuilder employs bond graphs as its design language and supports conceptual and embodiment stages of design for interdisciplinary systems such as mechatronics [Bracewell and Sharpe, 1996; Yan and Sharpe, 1996]. Since it uses bond graphs it allows representation of functional and behavioural aspects of energetic systems in interdisciplinary fields.

Based on functional requirements specified by the designer, Schemebuilder searches within its knowledge base for components satisfying the required input or output properties and then decomposes the required function into sub-functions by applying the selected components. Based on the above, it then automatically generates product models represented as tree structures termed as "FEST-ER" (Functional Embodiment Structure – Extended Recursively), which is an extension of the Function/Means tree. Since Schemebuilder integrates SIMULINK [Cavallo et al., 1996] and AutoCAD [Yarwood, 2004], it enables designers to conduct dynamic simulation based on bond graphs and also enables them to work on the spatial layout of components.

While it facilitates product modelling and design exploration in multi disciplinary design problems, its usage is restricted to handling energetic relationships by virtue of using the bond graph method. Further, it also presents difficulties while representing kinematic or spatial relationships such as behaviour of link mechanisms or collision of objects.

FDS- A Functional Design Software System

The Functional Design Software (FDS) [Kirschman, 1996] proposes a taxonomy based on the four primary mechanical engineering concepts of Power/Matter, Motion, Control and Enclosure. These four areas have been broken down into a group of phrases, which describe individual functions. Specific forms that fulfil the required function are chosen based on set of metrics, which in turn is based on the voice of the customer. These metrics are Pleasure, Protection, and Inverse Cost (Icost). These metrics allow the designer to compare generic forms based on constraints, criteria, and behaviours developed as part of the product specification.

These metrics are used through the multi attribute utility theory, a general decision making method that has its origin in the field of operational research. Once the multi attribute scaling factors are determined by making trade-offs between the three metrics, the Pleasure, Protection and Icost values are combined to provide a single metric value (called the PPI value), which describes the form. The PPI value enables the designer to choose between forms to fulfil a specific function.

While FDS covers most of the functions used in mechanical engineering, it does not generate kinematic or spatial behaviours of the forms mapped onto functions. Hence it is impossible to explore different design solutions, as only predefined static forms from the database of the system are mapped onto the required functions and no new forms are considered to completely analyse the behaviour of the product from different perspectives. As evaluation is based on the predefined set of metrics, life cycle analysis of the forms cannot be carried out.

A further review has been undertaken and the detailed results can be seen in Appendix C. The key findings of this review are summarised in section 3.5.1.

3.2 Decisions' Consequences Awareness

There are number of approaches and methods which enable designers to be aware of the consequences of their decisions taken during the conceptual design stage on the later life cycle stages of the product. A review of these methods is detailed in the following sections.

3.2.1 Quality Function Deployment (QFD)

Quality Function Deployment (QFD) is a structured approach to defining customer needs or requirements and translating them into specific plans to produce products to meet those needs [Roozenburg and Eekels, 1995]. The "voice of the customer" is the term used to describe these stated and unstated customer needs or requirements. The voice of the customer is captured in a variety of ways i.e. through direct discussion or interviews, surveys, focus groups, customer specifications, observation, warranty data, field reports, etc. This understanding of the customer needs is then summarized in a product planning matrix or "house of quality". These matrices are used to translate higher level "what's" or needs into lower level "how's" i.e. product requirements or technical characteristics to satisfy these needs as shown in Figure 3-1. The next step is to identify relationships between the "what's" and the "how's". There could be one to many relationships between these two elements. Through QFD, users are encouraged systematically to reveal such what-how relationships.

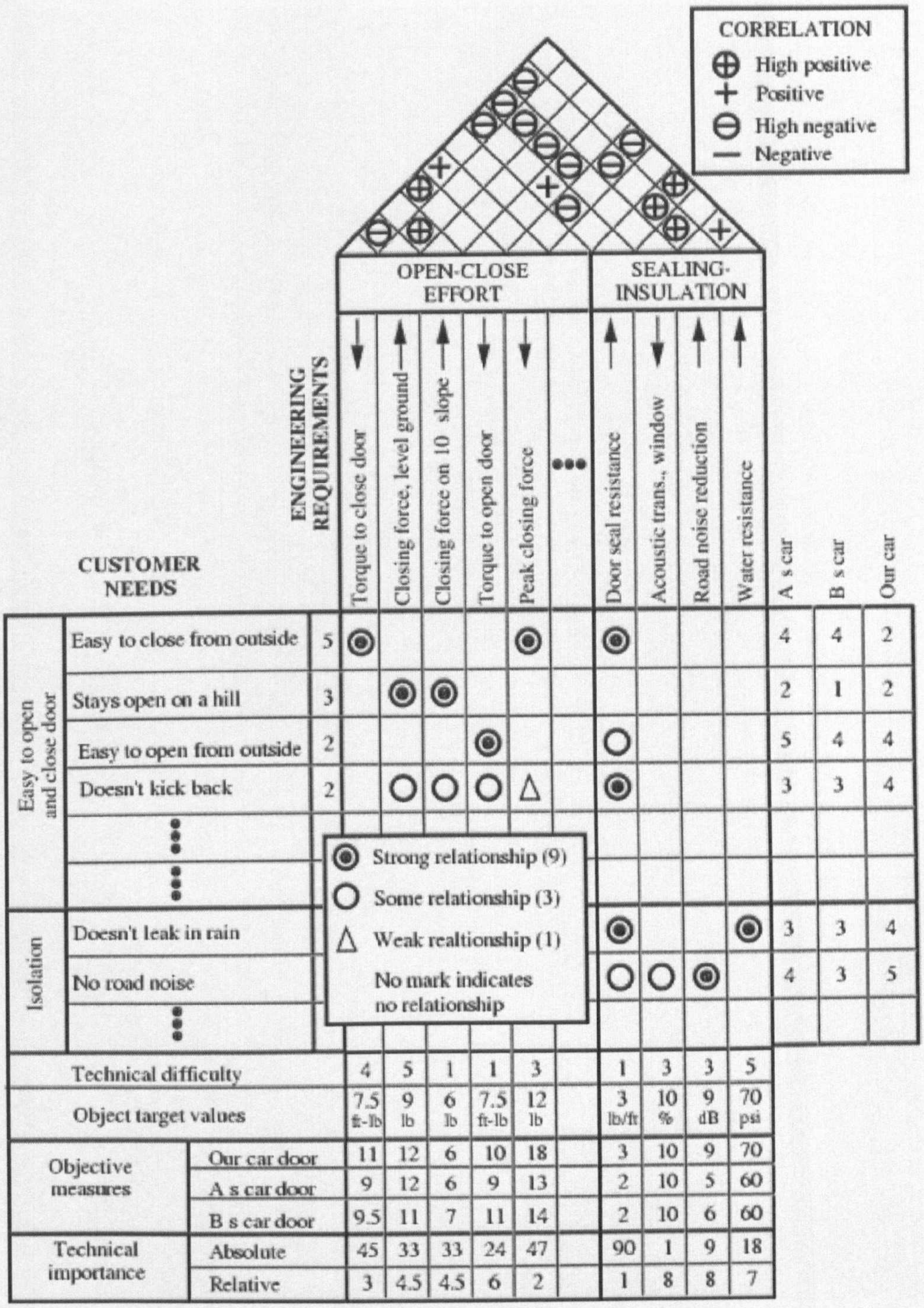


Figure 3-1: A typical QFD matrix [Crawford, 2005]

QFD enables assimilation of a great deal of information about a particular solution through a chart, which in turn enable users to make important comparisons and decisions [Crow, 2002]. The basic Quality Function Deployment methodology involves four basic phases that occur over the course of the product development process. During each phase one or more matrices are prepared to help plan and communicate critical product and process planning as well as design information. This QFD methodology flow is represented in Figure 3-2.

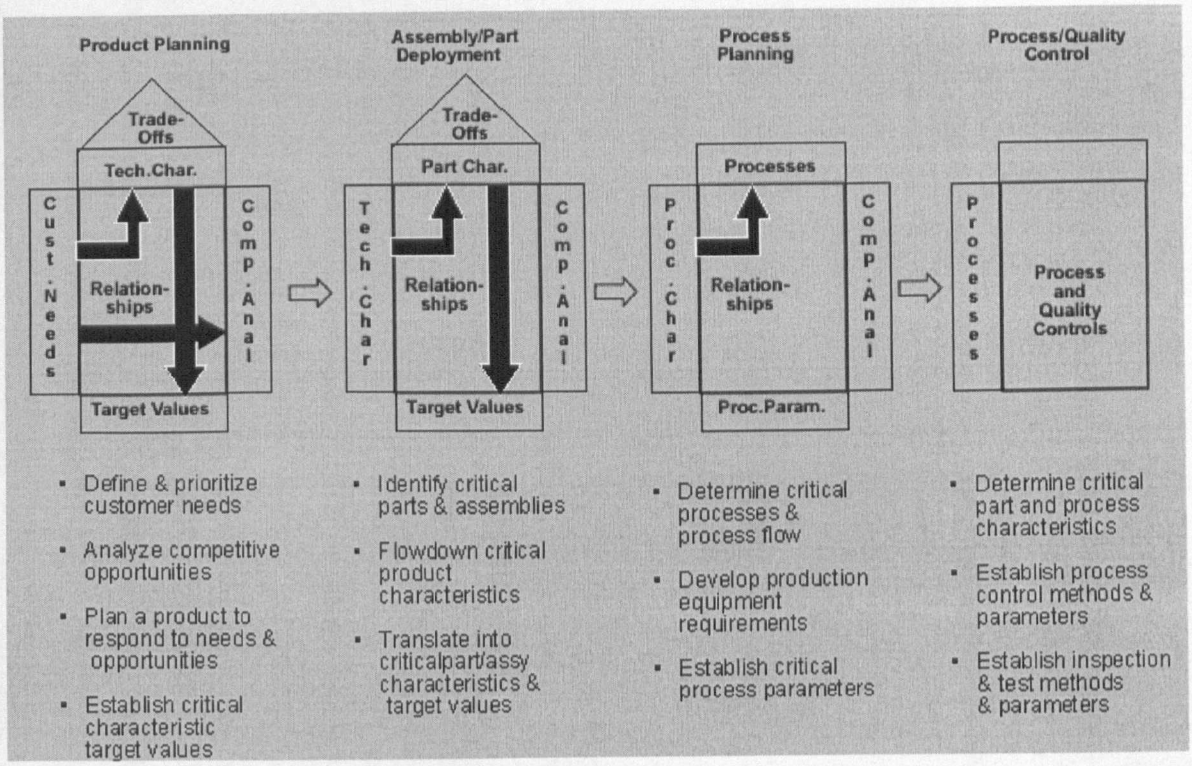
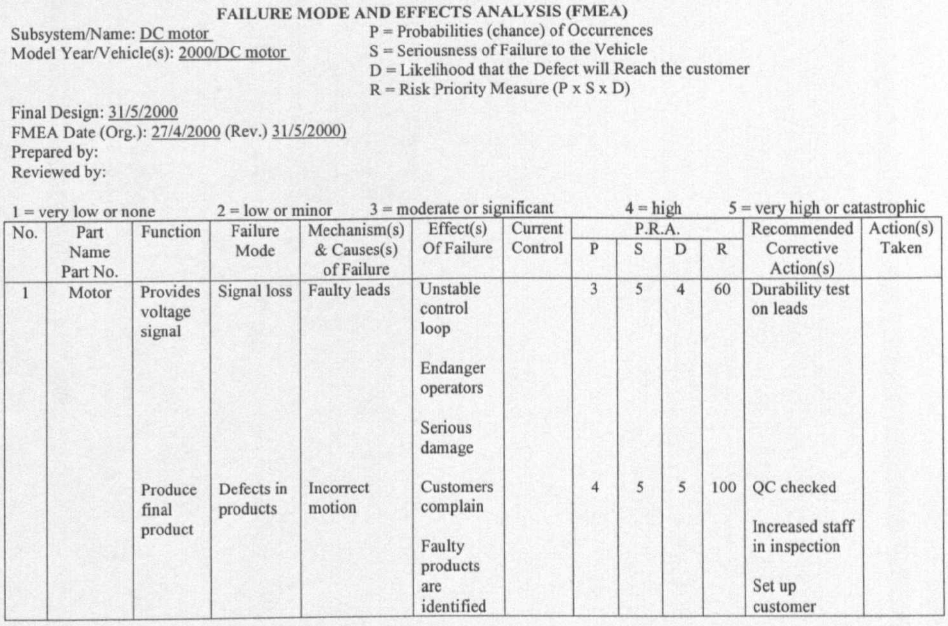


Figure 3-2: Implementation of Four-Phase QFD Approach [Crow, 2002]

The QFD matrix provides a method of representing known interactions between the various requirements. Documenting interactions among the evolving specifications enable users to explicitly focus and overcome inherent conflicts, which is superior as compared to rework [Clausing, 1993]. However, QFD does not proactively support designers in revealing 'what' these interactions are, it only assists in documenting those that are revealed [Borg, 1999]. Further, the strength of QFD is limited to the user's knowledge of the problem domain in identifying, which design requirements interact with which product life cycle related issues.

3.2.2 Failure Modes & Effect Analysis

Failure Modes and Effects Analysis (FMEA) is a methodology used for analysing potential reliability problems early in the development cycle where it is easier to take actions to overcome these issues, thereby enhancing reliability through design [Pahl and Beitz, 1996]. FMEA is used to identify potential failure modes, determine their effect on the operation of the product, and identify actions to mitigate the failures. FMEA consists of these successive stages i.e. *Describe product or process*, *Define functions, Identify potential failure modes*, *Determine causes*, *Detect methods/current controls*, *Calculate risk*, *Take action and Assess results* [Stamatis, 1995].



FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

Subsystem/Name: DC motor
Model Year/Vehicle(s): 2000/DC motor

P = Probabilities (chance) of Occurrences
S = Seriousness of Failure to the Vehicle
D = Likelihood that the Defect will Reach the customer
R = Risk Priority Measure (P x S x D)

Final Design: 31/5/2000
FMEA Date (Org.): 27/4/2000 (Rev.) 31/5/2000)
Prepared by:
Reviewed by:

1 = very low or none 2 = low or minor 3 = moderate or significant 4 = high 5 = very high or catastrophic

No.	Part Name Part No.	Function	Failure Mode	Mechanism(s) & Causes(s) of Failure	Effect(s) Of Failure	Current Control	P.R.A.				Recommended Corrective Action(s)	Action(s) Taken
							P	S	D	R		
1	Motor	Provides voltage signal	Signal loss	Faulty leads	Unstable control loop Endanger operators Serious damage		3	5	4	60	Durability test on leads	
		Produce final product	Defects in products	Incorrect motion	Customers complain Faulty products are identified		4	5	5	100	QC checked Increased staff in inspection Set up customer	

Figure 3-3: An analysis of "DC-Motor" using FMEA technique [Adapted from FMEA, 2004]

A crucial step in FMEA is anticipating what might go wrong with a product and ensuring that it is adequately addressed. The early and consistent use of FMEA in the design process allows the engineer to address design problems thereby producing reliable and safe products that appeal to customers [Ranky, 1994]. An effective use of FMEA provides the following benefits:

- Improve product/process reliability and quality.

- Increase customer satisfaction.
- Early identification and elimination of potential product/process failure modes.
- Prioritise product/process deficiencies.
- Capture engineering/organization knowledge.
- Emphasize problem prevention.

FMEA requires designers to list down the components making up the sub-assembly being assessed [Stamatis, 1995; Ranky, 1994; Pahl and Beitz, 1996], thereby providing a means of taking into consideration potential problems *late* in the design process when the design is to be signed off. The potential disadvantage of the process is therefore a late realisation about the consequences of decisions taken. Further, since the FMEA technique requires team effort, it is subject to the limitations associated with team design approach, i.e. subjectiveness and bureaucracy [Norell, 1993].

3.2.3 DFX Guidelines

"Design for X" guidelines method is essentially a tool in the form of a check list [Huang, 1996] of *do and don't rules* to ensure that a design solution satisfies a 'X' area. Design for X (DFX) methodologies are the most effective approaches of implementing concurrent engineering concept in product development. These guidelines allow designers to converge on a solution satisfying X-ability [Boothroyd et al., 2002]. For example, a design for assembly (DFA) guideline is to 'minimize' the number of parts in an artefact to reduce assembly operations. 'X' has two meanings [Andreasen and Olesen, 1993], *a life-phase aspect* e.g. assembly (DFA) or manufacturing (DFM) or a *performance measure* e.g. cost (DFC). However, some researchers have extended this definition to include certain aspects not directly related to product, but which either has an impact on the product or in the way it is designed, like design for environment (DFE) [Graedel and Allenby, 1996] or design for distribution (DFD) [Macgregor, 2002].

DFX guidelines explicitly provide designers with codified knowledge of areas, which they are not usually familiar [Andreasen and Olesen, 1993]. It also provides a means of formally capturing knowledge concerning relationships between artefact solution parameters and life-phase system behaviour, thereby enabling such knowledge to be shared, distributed and reused during subsequent design sessions [Borg, 1999].

DFX guidelines normally enable designers in generating solutions that satisfy a single life phase aspect. Although the use of multiple design guidelines popularly called as DFX Meta methodology [Huang, 1996] is possible, it usually results in conflicting recommendations. This implies that users have to identify the interacting relationships between different X abilities and make comparisons before choosing a particular alternative, which in itself could be very complex and tedious. In fact, it has been found in practice that it is very difficult to compare more than three different X guidelines simultaneously. Further, these guidelines enable the generation of solutions for a particular selected domain thereby limiting their use for other domains. For example, design for manufacturing guidelines for sheet metal components is completely different from that of thermoplastic components. This domain specific segmentation not only prevents designers from rapidly exploring alternative domains, but also does not enable designers to foresee associated total life opportunities and problems [Borg, 1999]. Since these guidelines tend to be generic they do not take into account the artefact's life specific scenario like actual manufacturing concerns of the user etc [Parsaei and Sullivan, 1993].

3.2.4 Feature Based Designing

According to FEMEX (Feature Modelling Experts) working group [Weber, 1996] a feature is defined as follows: *"A feature is an information unit (element) representing a region of interest with a product"*. It has a semantic meaning in design, process planning, manufacture, cost estimation and other engineering disciplines. However, manufacturing feature, which is the most well known type of feature, is used to indicate form elements that are described on a higher level than the points, lines and surfaces that are found in the traditional geometric models. Examples of such form features are bend, holes, slots, notches etc. However, form elements such as blocks, plates, cylinder and cones can also be considered as form features but only if they have any semantic meaning. For example a fine finished rectangular wooden *block* implies a block featuring a rectangular *shape*, made up of *wood* and has *fine* surface finish. All these attributes of the *block* feature exhibit a semantic meaning.

These features capture knowledge from an artefact's particular region to the artefact's specific life issues such as *process planning* [Gao et al., 1992; Wierda, 1991; Liu 2000], *manufacturability* [Molloy and Browne, 1993], *assembly* [Jared and Limage, 1994], *production cost* [Feng and Kusiak, 1996] and product realization systems such as tools and machines specifications [Lee and Kim, 1998; Case, 1992].

A feature-based computer modelling of a product is performed by two different approaches [Martino et al., 1994] i.e. *design by features* and *feature recognition*. In the first approach the candidate solution is created by combining different features [Case, 1994] and the solution is subjected to analysis to reveal specific life cycle issues of the product. In the second approach, features are extracted from the geometric model of the part using some recognition tools [Pham and Dimov, 1999], which are then further analysed in order to reveal the specific artefact's life cycle requirements.

The limitation of the feature-based design tools is that they focus more on one aspect, i.e. on individual features rather than on life cycle issues. Further, they provide late awareness to the designers regarding their design decisions i.e. they provide awareness at the analysis stage rather than at the synthesis stage, after the candidate solution has already been generated [Borg, 1999]. Another limitation of this approach is that designers can model artefact solutions and foresee consequences of their solutions only with a predefined life phase model and not a specific life phase model. For example, some form features can reveal the problems that can occur during the manufacturing phase of that particular form feature but not during the use phase. Further, features are suitable only for component-based design and not for assembly level design to reveal life cycle constraints.

3.2.5 Artificial Intelligence Based Methods

Artificial Intelligence (AI) is the capability of a device/software to perform functions that are normally associated with human intelligence, such as reasoning and optimisation through experience. AI is the branch of computer science that attempts to approximate the results of human reasoning by organizing and manipulating factual and heuristic knowledge. AI based methods which make the designers aware of their decisions in the later life cycle phases of the product are normally in the form of constraint based networks, knowledge based systems and case based reasoning tools [Borg, 1999].

3.2.5.1 Constraint Based Networks

Constraint satisfaction problem (CSPs) are often formulated in AI tasks where CSPs, values are assigned to variables subject to a set of constraints. Constraint specification represents the relationships among the variables. A constraint network (CN) is a declarative structure that consists of nodes and arcs. While nodes represent the variables or the constraints [Yang and Yang, 1997], arcs represent the relationships among the variables and the constraints. The variables are labelled by an interval, a set of possible values or constant values. The constraints are in the form of any type of mathematical operations or binary relations and must be satisfied by some subset of parameter values within the network. The mathematical operations can be multiple inputs single output (MISO) or single input single output (SISO). Constraint propagation is utilized to perform inference about the quantities. Different propagation techniques are formulated based on the type of variables and the definition of satisfaction in the constraint satisfaction problem.

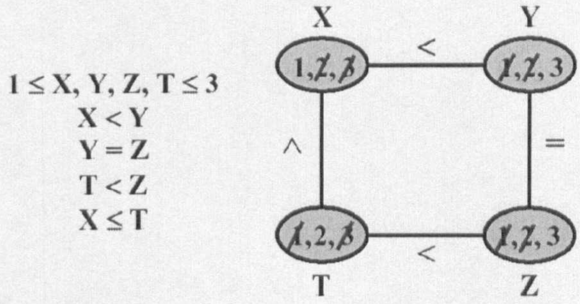


Figure 3-4: An example of a constraint network [Bartak, 1998]

Constraint satisfaction can be defined as a general problem in which the goal is to find values for a set of variables that will satisfy a given set of constraints [Wen, 1996]. These problems are solved either by human beings or by computers depending on the complexity of the problem. While the designer assigns some initial values to the variables in the network, the constraint satisfier infers values for other variables attached to that particular variable, analyses new state of variables in the network and highlights any constraint violations caused by the designer's decisions. Whilst the constraint-modelling environment does not provide for the recording of every decision and alternative, the results and implications of these decisions are embodied in the various sets of constraint rules [Medland et al., 2003].

Constraint solving methods help designers to gain insights into incomplete design solutions and to explore and optimise design solutions [Swada, 2001]. Constraints can express the restrictions exerted on objects in a design problem by defining the functionality, material properties and other life cycle issues in the form of some guidelines for instance DFX guidelines [O'Sullivan, 1997]. However Constraint Networks (CN) do not readily support providence during solution synthesis, when new parameters are added. It rather supports artefact life cycle issues' awareness after solution synthesis and during solution analysis [Borg, 1999]. This awareness is late as conceptual design solutions are already synthesised. Therefore the designer cannot be made aware of any life cycle consequence of selecting a particular solution using the CN technique. Also the current CN techniques can only support one life cycle aspect. Therefore it is difficult to model multi DFX approach using the CN technique.

3.2.5.2 Expert Systems

An expert system is an artificial intelligence application that uses a knowledge base of human expertise to solve problems. The degree of problem solving is based on the quality of the data and rules obtained from the human expert [Miles and Moore, 1994]. Expert systems are designed to perform at a human expert level. The utility of expert systems in supporting life-oriented product design from the perspective of decisions' consequences awareness is shown by developing various applications such as reported by [Swift, 1987; Dym and Levitt, 1991; Borg et al., 2000; Xue, 1999; Mills and Gomaa, 2002].

Every expert system consists of two principal parts: the knowledge base and the inference engine. *Knowledge base* contains both factual and heuristic knowledge. While *factual knowledge* relates to knowledge that is widely shared, typically found in textbooks or journals, *heuristic knowledge* relates to the less rigorous, more experiential, judgmental knowledge of performance. There are several knowledge representation methods used to represent both types of knowledge in expert systems such as production rules, predicate logic, semantic networks and frames. The second part of expert systems is *Inference engine,* which is a reasoning mechanism and performs reasoning using inference rules to draw conclusions. There are two main methods of reasoning involving chaining of IF-THEN inference rules. If the chaining starts from a set of conditions and moves toward some conclusion, the method is called *forward chaining.* If the conclusion is assumed to be true (for example, a goal to be achieved) but the required conditions to derive the conclusion are not known, then reasoning backwards is called for, and the method is called *backward chaining* [Addis, 1987].

Knowledge based systems are helpful in predicting consequences about a candidate solution that would occur in later life cycle stages of the product using reasoning process [Zha, 2002]. However most of the knowledge-based systems provide multiple but segmented views related to different life cycle concerns about a particular candidate design solution [Borg, 1999]. Knowledge maintenance is another major issue that needs to be addressed in knowledge-based systems as life cycle oriented design involves constant inputs of dynamic knowledge into the knowledge base. The maintenance of knowledge base is difficult in those circumstances where knowledge is not properly structured [Brewster, 2003].

3.2.5.3 Case Based Reasoning Tools

Reasoning is often modeled as a process that draws conclusions by chaining together inference rules. Case based reasoning (CBR) presents a different view as the primary knowledge source is not in the form of generalized rules but is in the form of memory of stored cases containing specific and previous work. In CBR, new solutions are generated by retrieving the most relevant cases from memory and then adapting them to the new situations rather than by chaining. Thus in CBR, reasoning is based on remembering [Leake, 1996].

There are two types of case-based reasoning tasks, interpretive CBR and problem solving CBR. Interpretive CBR uses prior cases as reference points for classifying or characterizing new situations whereas problem-solving CBR uses prior cases to suggest solutions that might apply to new circumstances. Interpretive CBR involves four steps. In the first step the reasoner performs situation assessment to determine which features of the current situation are really relevant. Based on the results of the situation assessment, the reasoner retrieves relevant prior cases in the second step. In the third step, the reasoner then compares those cases to the new situation to determine which interpretation(s) apply. Finally in the fourth step the current situation and the interpretation are then saved as a new case on which future reasoning is based. The goal of problem-solving CBR is to apply a previous solution to generate a solution to a new problem. For example, case-based design, planning, and explanation systems all retrieve and adapt solutions of similar previous problems. Like interpretive CBR, problem-solving CBR involves situation assessment, case retrieval, and similarity assessment/evaluation. In addition, the similarities and differences between new and previous cases are used to determine how the solution of the previous case can be adapted to the new situation. For example, a case-based planning system generates a new plan by retrieving a previous plan for a similar goal, determining the differences between the old and new goals, and adapting the plan to take account of the new goals. It is clear from this review that the reasoning and mapping techniques of CBR method are of direct relevance to knowledge representation in this research.

Specifically, a CBR based tool can represent artefact and related life phase knowledge for a particular life cycle phase such as assembly issues as shown in [Kim, 1997; Belecheanu et al., 2003]. While a single retrieved case can provide designers with the knowledge of relationships between an artefact and the related life phase issues [Wood and Agogino, 1996], it is however left to the user in a CBR approach to form an assessment about the interactions between different life cycle issues stored in different cases. Further, retrieved cases are rarely a perfect fit to the current situation, meaning that case adaptation is required to foresee artefact life issues specific to the current situation [Haque et al., 2000], thereby acting as a deterrent for proactive case adaptation. This research review therefore concludes that CBR is not suitable for knowledge representation in this research.

3.2.6 Design of Experiments/Taguchi's Method

The operation of the product or achievement of a performance characteristic of a product can be mathematically related to a product or process design parameters. These relationships can be used to calculate optimum product and process design parameters. However, when these relationships are unknown, Design Of Experiments (DOE) method can be used to determine optimum parameter values, thereby developing a robust design [Hicks and Turner, 1999]. A robust product works according to its intended function, no matter how much variation occurs in the product's manufacturing process, variation resulting from deterioration during use [Crow, 2002a]. Genichi Taguchi's [Taguchi, 1993] introduced this robust design method by presenting a concept of "loss to society" represented by a quadratic relationship between increasing costs (loss to society) to critical design parameters whose values vary from the desired mean values. DOE method desensitise a product's performance characteristic(s) to the variation in the critical product and process design parameters [Crow, 2002a].

DOE approach is based on a fractional experiment, during which an experiment is performed with only a fraction of possible experimental combinations of design parameter values. Orthogonal arrays are used in the design of an experiment by describing the test cases to conduct the experiment. Normally, two orthogonal arrays are used; a design factor matrix and a noise factor matrix. The noise factor matrix indicates the variation in critical design parameters, which are difficult to control due to their variation during manufacturing or use life phase. The experimental results are summarized into a metric called the signal to noise ratio (Figure 3-5), which determines the effectiveness of the achieved mean value of the parameter and the amount of variability that has been experienced through the DOE technique. This helps designer to identify the parameters that will have the greatest effect on the achievement of a product's performance characteristics. This approach of designing and conducting an experiment to determine the effect of design parameters and noise factors on the product performance characteristics is called as Design of Experiments (DOE) method [Crow, 2002a].

Though DOE is a good technique for developing a robust product solution capable of working in different working environments with the similar levels of efficiency, it allows designers to foresee problems and control only those parameters relevant to a particular life phase that is currently in use, thereby not catering for other life phase scenarios. Further, DOE is more of an analysis type approach, which is applied after the solution has been synthesized completely. Therefore it can be effectively applied only at embodiment and detailed design stage and this makes it not suitable for this research.

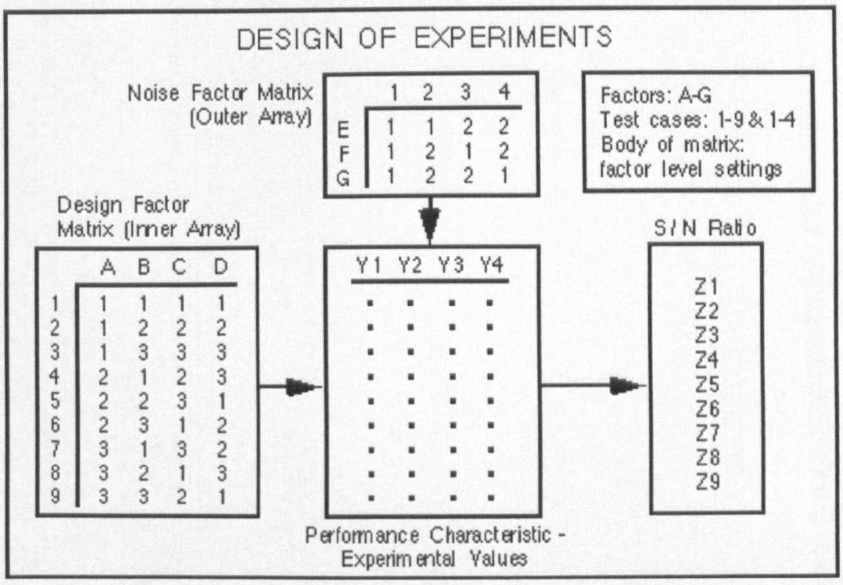


Figure 3-5: An example of Design of Experiments [Crow 2002a]

3.3 Selection of Criteria and Evaluation of Alternatives

Engineering design, a decision problem with multiple criteria can be defined as follows [Scott and Antonsson, 1999]:

> *"Given several performance criteria, which are to be simultaneously optimised, determine a method for comparing any two or more design alternatives that depend only on the values of the individual criteria for each alternative".*

The selection of a right decision criteria and an appropriate evaluation method to evaluate difference design alternatives is also important to perform an effective decision making at the conceptual design stage. The following subsections further highlight the importance of decision criteria and description of different evaluation methods used at present during conceptual design decision making.

3.3.1 Selection of Design Decision Criteria

The critical aspect of decision making is to ensure that one has the right information. Though complete and reliable (perfect) information may result in good decisions, it is never possible to obtain perfect information in real life, as it is only theoretically possible. Therefore most decisions in real life are made on the information with a degree of uncertainty [Zha, 2003]. Due to this factor, decisions are normally made on experience and statistics, which are rooted on sound scientific principles in order to enable effective decision making. It is therefore crucial to have the right information when a specific criterion is to be used [Cardinal and Mekhlilef, 2004].

Design criteria are the explicit goals that a product must achieve in order to be successful. Designers use these criteria as their basic tool in evaluating a design solution's potential for success and how well it fits into the functional requirements of the product. Designers need explicit design decision criteria in order to evaluate recommended design solutions of products [Scaravetti et al., 2004].

Design criteria can be divided into primary and secondary criteria. Primary criteria are those that constitute a successful product; the product will be unsuccessful if it does not meet these goals. Secondary criteria are those features that are highly desirable but not absolutely essential. Separating primary and secondary criteria establishes a clear hierarchy in design choices. Often, implementing one criterion makes the implementation of other infeasible or costly, or a secondary criterion may be sacrificed in favour of a primary criterion.

Since each decision criterion is defined differently in different design problems [Dejeu et al., 2004], it is necessary to identify the meaning, nature and contents of each decision criterion before applying it for evaluation [Li and Azam, 2000]. Examples on criteria for decision making include decision axioms, guidelines, rules of thumb, maximizing rules, and minimizing rules. The use of a criterion is dependent on the context of design problem under consideration and also on the type of decisions being made. In the context of mechanical artefact design problems, the selection of criteria depends upon the functional requirements, designer's preference/experience and company policy/guidelines [Ullman, 2000]. Reduced product cost, lead time and improved product quality being regarded as the ultimate goals/effects of using such criteria for decision making [Borg et al., 1999a].

3.3.2 Evaluation of Design Alternatives

Important tasks in mechanical artefact engineering design involve the generation, evaluation and selection of design alternatives to fulfil a particular need/function. [Scott and Antonsson, 1999] stated the latter problem as *"Find the best alternative(s)"*. Determination of the *"best"* can be redefined as *"Find the lightest alternative"*, or, *"Find the stiffest alternative"*. It becomes easier and understandable in phrase *"Find the lightest and stiffest alternative"* [Scott & Antonsson, 1999]. This directive is not sufficient to choose between one alternative that is stiff and heavy and another alternative that is light but works ok [Scott & Antonsson, 1999]. Most methods supporting the evaluation of different design alternatives have originated from Multi-Criteria Decision Making (MCDM) (An area of Operational Research field) [Girod et al., 2000]. Research in Artificial Intelligence (AI) and knowledge engineering forms the basis to develop a number of methods for the representation of uncertainty in design decision making information [Yang and Sen, 1997]. Evaluation methods (Multi-Attribute Utility Theory, Issues Based Information System Model, Pugh's Method, Quality Function Deployment and Analytic Hierarchy Process) have been developed specifically for design evaluation and selection situations, where some of these theories reuse principles from OR and AI [Girod et al., 2000]. A brief overview of these methods is illustrated in the following subsections.

3.3.2.1 Multi-Attribute Utility Theory (MAUT)

A method with the strong axiomatic basis is Multi-Attribute Theory (MAUT) [Keeney and Raiffa, 1976; Schafer, 2001]. This method uses utility functions to translate each alternative's expected performance, restricted to each criterion, i.e. the alternative's attributes, in numeric utility scores. It is assumed that all performance assessments as well as factors describing the decision criteria's importance can be quantified. These factors are used for aggregating the numeric utility scores into an overall utility for each alternative. The aggregative model of MAUT offers clear decision making process and a reflection of the decision maker's beliefs and preferences in ranking the available alternatives. The MAUT method involves:

1. Defining decision alternatives and evaluating them against relevant attributes.
2. Relative weights are then assigned to show preferences of the attributes.
3. An overall evaluation of each alternative is then derived from the combination of evaluation results taking consideration of attribute weights.
4. Finally decision sensitivity is analysed.

Specific merits of this method are: (i) use of independent performance rating scales leading to the establishment of not only a relation between different alternatives, but also between the alternatives and the ideal goal; (ii) it supports an open alternative space by allowing for the easy addition of new alternatives; and (iii) it supports an open criteria space through simple, independent, and direct weight assignments. The main drawback of this method is that all inputs must be quantitative, which implies that quantification of qualitative subjective information may imply a level of precision that was not actually available.

3.3.2.2 IBIS Model

Issue Based Information System (IBIS) is a model for organizing the deliberation process that occurs during complex decision making [Ullman and D'Ambrosio, 1995]. The IBIS model organizes the deliberation process into a network of three data elements i.e. *Issues, Positions,* and *Arguments.* An *issue* is an identified problem to be resolved by deliberation. Each issue can have many *Positions* that are the proposed solutions developed to resolve the issue. Each position can have any number of *Arguments* that support or oppose that *Position.*

In IBIS model information is expressed informally, so that the design space can include quantitative or qualitative data and deterministic or distributed data in support of the product or process. IBIS model also supports the process of deliberation by capturing the design rationale [Blessing, 1993]. Blessing [Blessing, 1993] proposes a *decision matrix* based on IBIS where design tasks such as problem definition, conceptual design and detail design are represented as *issues.* The issues are solved in three steps i.e. *Generate, Evaluate* and *Select* corresponding to the *Positions* and *Arguments* of IBIS model. Both *Evaluate* and *Select* steps are equivalent to *Arguments* in IBIS model as the participants involved in the deliberation process give arguments in favor of and against the generated solutions while evaluating and selecting them for further work. Although IBIS can model complex decision making information, it offers no automated life cycle support beyond the representation of issues, proposals and argument decisions. It is the responsibility of participants involved in the deliberation process to provide support to decision making using these representations, which is limited due to problems involved in team based approaches.

3.3.2.3 Pugh's Method

Pugh's [Pugh, 1990] method is the popular name for the decision matrix method, which is a minimized on-paper form of MAUT. Selection among itemized alternatives is accomplished by a relative comparison to a set of criteria defined by the issue. Each alternative is weighed by its ability to meet each criterion. This method is used to support judgments about qualitative information. It also results in an abstract satisfaction calculation for each alternative. Pugh's method supports an individual decision maker by using consistent information. The merits are: (i) the method is simple and easy to use; and (ii) it is not necessary to quantify qualitative information. The drawbacks are: (i) all quantitative information has to be transformed into qualitative statements; (ii) all criteria are assumed equally important; and (iii) since the method is based on relative comparisons, no ratings can be generated and it is difficult to include new alternatives and criteria.

3.3.2.4 Quality Function Deployment (QFD) Method

Decision making with Quality Function Deployment QFD, as described by Hales [Hales, 1995], involves qualitatively comparison of all alternatives to a datum. The advantages of this method are that it not only introduces weights for each of the criteria, but there is a mechanism to ensure a strong relation between the decision criteria and the customer requirements. However the method only compares all solutions with respect to decision criteria leaving the task of selecting the best solution to the designer.

3.3.2.5 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) [Saaty, 1990] is a method that arranges all decisions factors in a hierarchical structure, which descends from an overall goal to criteria, sub-criteria and finally to the alternatives, in successive levels. The decision maker is required to create matrices for pair-wise comparisons of the decision criteria's importance as well as for the alternatives performances. A ranking of the alternatives, at the bottom of the hierarchy, is achieved by a procedure that vertically calculates the horizontal comparison ratios. The merits of this method are: (i) it is capable to provide an overview of the complex relationships between decision elements, i.e. criteria and alternatives, by structuring them in hierarchies; and (ii) the resulting rankings are always transitive as well as complete. Drawbacks are: (i) because of the pair-wise comparisons no independent ratings are produced; (ii) the inclusion of new alternatives and criteria requires the repetition of pair-wise comparisons for re-establishing a ranking order.

None of the above mentioned decision making methods/theories model uncertainty in information.

3.3.2.6 Uncertainty Representation Methods

The methods described above assume that the available information is known with certainty. However, this assumption is not always valid. There are some very sophisticated methods for the support of design decision making problems, which can model different forms of uncertainty in information [Girod et al., 2003]. The advantage of most of the developed methods is their capability of modeling subjective belief regarding the expected performance of alternatives. However, they are not able to model possible uncertainty produced by `vagueness', e.g. linguistic imprecision.

For the engineering decision support system, Yang and Sen [Yang and Sen, 1997] developed a method based on "evidential reasoning in design" using the Dempster Shafer theory of evidence [Shafer, 2005]. A method that applies fuzzy weightings for decision criteria and fuzzy scores for the alternatives' performances is discussed by Thurston and Carnaha [Thurston and Carnaha, 1992; Wang, 2002]. Their method applies a linguistic universe of discourse, which offers the decision-maker some predefined linguistic terms, such as 'low' or 'very low', to express vaguely known performances of alternatives and weightings for the decision criteria's importance. The merit of this method is that linguistic uncertainty, i.e. vagueness, is recognized as element of the decision model. This means that human decision makers can express themselves in a very natural way without being required to force these natural expressions into other types of information formats. The drawback is the high computational effort needed for processing the fuzzy sets.

3.4 Context in Design

Designers need to be aware of the consequences of their decisions on different aspects as described in section 2.3.4.2 and in the last paragraph of section 2.3.4.3. These aspects consist of the life cycle phases of the product, the user of the product and the environment of the product in which the product is used and disposed of. Moreover socio-economic factors and other pressures exerted by the external environment on the designer need to be considered while making a design decision [Maffin, 1998]. All these aspects can be considered fully and simultaneously during decision making only by completely identifying the whole context of the design problem under consideration. The following sub-sections illustrate the meaning of context and its use in different disciplines including engineering design.

3.4.1 Context Definition

The study of context spans varied disciplines [Penco, 1999], which include Philosophy, Communication, System Science, Linguistic, Industrial Engineering and Artificial Intelligence. Oxford [Oxford, 1998] defines the word *'Context'* as *"the circumstances that form the setting for an event, statement, or idea, and in terms of which it can be fully understood and assessed".* The above definition is widely used in natural language, where people associate it to the notion of social context, economical context etc [Longueville and Gardoni, 2003]. Consequently, in order to understand related information, context factors must be explicitly accessed. The main contributions in context definition are proposed by the CONTEXT series conferences [Brezillon and Cavalcanti, 1997]. This is an interdisciplinary community with contributions from artificial intelligence, linguistic, natural language processing, knowledge engineering, philosophy and system modelling.

3.4.2 Context in Engineering Design

There are many uses for the word 'Context' in design, and information/knowledge described as 'Context' is also used in several ways. One dictionary definition of context is *the set of facts or circumstances that surround a situation or event.* Since these circumstances *surround* the event, they are not part of the event itself, giving a useful initial description of context in design as *information not necessary for the representation of the product itself, yet which has an impact on the process of designing and therefore on the artefact i.e. its end product* [Brezillon and Cavalcanti, 1997].

Charlton and Wallace [Charlton and Wallace, 2000] summarised design context interpreted by different researchers as follows:

- *"The life cycle issue(s), goal(s) or requirement (s) being addressed by the current part of the product development process: e.g. safety; usability; assembly.*

- *The function(s) currently being considered as an aspect of the product: e.g. transmitting a torque; acting as a pressure vessel.*

- *The current phase of the product life cycle phase: e.g. design, manufacturing, marketing and disposal.*

- *The activity within the current life cycle phase: e.g., concept generation during design, operating an emergency stop during use.*

- *The physical surroundings with which a part of the product can interact, including either internal or external aspects of the product's environment; e.g. the components in a hydraulic system; the temperature of the operating environment; the manufacturing environment; aspect of the surrounding landscape reflected in an architectural design".*

Of relevance to engineering design, a brief review of the work related to 'Context' in the fields of Artificial intelligence (AI), Engineering Design and Knowledge Engineering is discussed in the following section.

3.4.3 Review of Context in AI, Engineering Design and Knowledge Engineering Domains

Pereira and Pollack [Pereira and Pollack, 1991] present a system, called CANDIDE, to incrementally interpret natural language utterances in context, where context independent and context dependent aspects of an interpretation are separated. Bigolin and Brezillon [Bigolin and Brezillon, 1997] used context to simplify the translation from system's requirements expressed in natural language to an entity-relationship model. This example shows the feasibility of use of natural language to model *'Context'* or contextualised information to support decision making at the conceptual design stage.

Funk and Miller [Funk and Miller, 1997] discussed the aspects of context, which are necessary to perform human factors interface adaptation for cockpit information management system, and contrast these aspects with context subsets, which have traditionally been used for this purpose. A framework and supporting rationale for representation of context characteristics have been developed using a vocabulary based on tasks and goals as the foundation of context representation and tracking. This work shows that context information can be represented using a combination of verbs and nouns as has been the case of function representation method (verb-noun pair) adopted in this research.

Bouzy and Cazenave [Bouzy and Cazenave, 1997] investigated the use of contextual knowledge in order to simplify knowledge representation in very complex domains and systems. In the case of a complex domain like the game of Go [McAdams, 2005], they have demonstrated various types of context citing examples of temporal, goal, spatial and global contexts used in the Object Oriented Paradigm (OOP) to represent different types of knowledge. This shows that different types of context knowledge related to different phases of life cycle, user of the product and other aspects could be structured in object oriented hierarchical structure for representation and reasoning to generate design decision consequences.

Brezillon and Pomerol [Brezillon and Pomerol, 1996] have pointed out that lack of explicit representation of context in knowledge based systems result in failures such as exclusion of user involvement, incorrect use of knowledge, inadequate knowledge and inability to generate relevant explanations for users. This example highlights the importance of proper representation and structuring of context knowledge before its use to support decision making at the conceptual design stage.

Very few researchers have provided a contextual framework to explore relationships between the design context, practice and external environment. Maffin [Maffin, 1998] has presented a contextual framework to explore the relationships between the design context and design practice. The engineering design context is represented in terms of 'hard' factors i.e. internal and external to a company, which influence both the requirements and characteristics of design projects. Design context is captured in terms of a company's unique internal and external attributes (i.e. its organization, markets, products, production process, suppliers, local and global environment), its strategic policies and the key features of the specific projects. Hales [Hales, 1993] has presented a contextual model, which incorporates environmental influences at the macroeconomic, microeconomic, and corporate and project levels by using pre-developed checklists to allow the designer to assess the impact of these influences on the project design. Gero and Kannengiesser [Gero and Kannengiesser, 2000] use the term *Situatedness* to refer to the notion that addresses the role of the context knowledge in engineering design. They argue that designing is an activity, during which the designer performs actions in order to change the external representation of the design.

This review clearly indicates that the use of *'Context'* in engineering design is limited to the consideration of only some aspects like dynamic nature of design process, socio economic pressures on designer, environmental influences and company's policies. There is not a single work representing the holistic view of *'Context'* in design i.e. from other perspectives apart from these aspects, which is necessary to perform an effective decision making.

3.5 Review of the Frameworks and the Tools

The results of the review of existing methods in three different areas *detailed functional requirements, decisions' consequences awareness, selection of decision criteria and evaluation of alternatives* are discussed in sections 3.1, 3.2 and 3.3 in terms of their strengths and weaknesses. In order to identify to what extent that these methods have been applied and implemented in engineering design, a thorough review of corresponding frameworks and tools developed by different researchers using these methods has been undertaken. The results of this review will provide supporting evidence of the review in previous sections and lead to the identification of weakness of the methods discussed in the previous section. The details are presented in Appendix-C in the form of three Tables A-1, A-2 and A-3.

In keeping with the same criteria used to review conceptual design decision support methodologies described in Chapter 2, this review uses the same important key aspects/characteristics of ideal decision support systems. These characteristics are: *Detailed Functional Requirements, Decisions' Consequences Awareness* and

Evaluation of Alternatives. The following sub sections present a summary of each table.

3.5.1 Review of the Tools and the Frameworks in Detailed Functional Requirements

A review of tools in terms of detailed functional requirement is carried out from four different perspectives i.e. functional *representation/decomposition, behavioural representation, form/structure modelling* and *support for decision making*. The use of the aforesaid perspectives is due to the fact that behaviour and form of solution are also modelled alongside function in the conceptual design stage so as to illustrate their relationships. Therefore, this review illustrates the use of different techniques to represent detailed functional requirements, behaviour of solution and any support to decision making provided by these developed frameworks and tools. The review of tools in Table A-1 illustrates strengths and weaknesses as described in the following two sub sections.

3.5.1.1 Strengths of the Tools and the Frameworks Reviewed in Table A-1

The tools and frameworks in Table A-1 show the following strengths:

- Good support for detailed description of functional requirements to establish a functional structure. This has been shown in Schemebuilder using bond graphs and natural language based representation in Function to Form Mapping Model, Function Design Model, FBS and FDS.

- Systematic design by decomposing higher level abstract functions into lower fine sub levels creating a functional hierarchical structure. This has been accomplished in Schemebuilder, FuncSION and Welch and Dixon [Welch and Dixon, 1992].

- Effective use of available fundamental technologies like Matlab in Schemebuilder and knowledge based systems in FuncSION to exhibit the behaviour of the artefact.

- Thorough and detailed representation of the form/structure of the generated solutions using natural language in Function to Form Mapping Model and Welch and Dixon [Welch and Dixon, 1992].

3.5.1.2 Weaknesses of the Tools and the Frameworks Reviewed in Table A-1

The weaknesses can be summarised into the following points:

- Limited scope in representing the functionality of systems due to the fact that limited application domains have been identified and corresponding functions developed. Hence it is impossible to apply these systems to broader engineering design. This has been experienced in Schemebuilder as it has been based on bond graphs, therefore it can represent only energetic type functions. Similarly FuncSION and Function to Form Mapping Model can represent only transformation of motion and conversion of energy type functions, giving no explanation to represent other type of functions such as assembly/conveyance functions.

- Difficulty in establishing a new generic function representation for a new design problem because systems use only pre-defined functions stored either in a library or from knowledgebase/database. This has been shown in models and systems such as Function to Form Mapping Model, FBS and FDS.

- Limited behaviour of the artefact in exhibiting kinematic and spatial relationships in some of the systems. For example Schemebuilder and FuncSION do not represent behaviour of the product in different life cycle phases.

- Poor visualization of spatial arrangements between different components and structure of artefact using text based representation of the form of artefact, as has been the case for most of the systems.

- Weak or no support for decision making in generating different alternatives using expert systems and evaluating different alternatives using matrices based on the voice of customer. There is no consideration of life cycle knowledge and interactions between functional requirements and life phase requirements while evaluating different design alternatives, thus the generated alternatives are not fully explored.

3.5.2 Review of the Tools and the Frameworks in Decisions' Consequences Awareness

The review of tools in this category is undertaken from two perspectives i.e. awareness about *single life cycle phase (single X) or multiple life cycle phases (multi X)* and awareness provided at the *synthesis stage* or the *analysis stage.* The choice for use of these two perspectives is due to the fact that it helps in identifying the strengths of the frameworks and the tools in providing consequences awareness about multiple life cycles. It also helps in identifying the timing of this awareness i.e. whether awareness occurs during or after the conceptual design stage. The review of the tools in Table A-2 illustrates strengths and weaknesses as described in the following two sub sections.

3.5.2.1 Strengths of the Tools and the Frameworks Reviewed in Table A-2

The tools and frameworks in Table A-2 show the following strengths:

- Good detailed consequence awareness about one particular life cycle phase in most systems. This is the case for *assembly* in Fuzzy DFA, Pham and Dimov [Pham and Dimov, 1999], Swift et al. [Swift et al., 2004]; *manufacturability* in Baragetti and Rovida [Baragetti and Rovida, 2001] and Xu et al. [Xu et al., 2002]; *use* in Decision Capturer, RelFMECA and DECMAT; *recycling* in Ferrao et al. [Ferrao et al., 2003] and *environment* in RAEGIE.

- Effective reuse of past similar design cases in a new design problem as shown in CCSS [Xu et al., 1999] and seamless integration with modern CAD design tools in Jerzy et al. [Jerzy et al., 2002].

- A structured approach to consequences awareness for one particular life cycle phase in order to support the decision making process. The approach is generic and can be used for any mechanical design domain as has been strongly demonstrated in systems such as Decision Capturer and RelFMECA.

3.5.2.2 Weaknesses of the Tools and the Frameworks Reviewed in Table A-2

The tools and frameworks in Table A-2 show the following weaknesses:

- Generated awareness is limited to only one particular life cycle phase describing no implications of design decisions on other life cycle phases as shown in Decision Capturer, Pham and Dimov [Pham and Dimov, 1999], Ferrao et al. [Ferrao et al., 2003] and RAEGIE.

- Limited number of life cycle phases considered exhibiting awareness, with three phases as maximum. This has been found in IKA, which provides awareness for *use* and *assembly* phases. Similarly awareness related to *manufacturing* and *assembly* phases is provided in Changchien and Lin [Changchien Lin, 1996] and Xue et al. [Xue et al., 2002], neglecting the consequences related to all other life cycle phases.

- The presented awareness is often segmented into separate life phases and has no causal interaction with each other.

- Late presentation of decisions' consequence awareness in the design stage as has been the case in most of the systems such as Fuzzy DFA, Changchien and Lin [Changchien and Lin, 1996], Ferrao et al. [Ferrao et al., 2003], RAEGIE, DECMAT, Design-Expert and Jerzy et al. [Jerzy et al., 2002]. This occurs during the embodiment and the detailed design stage when conceptual design is finished and the conceptual solutions are already generated.

- Not suitable for multiple domain component design. This can be seen in Pham and Dimov [Pham and Dimov, 1999] and Baragetti and Rovida [Baragetti and Rovida, 2001] for machined components, Changchien and Lin [Changchien Lin, 1996] for rotational parts, Ferrao et al. [Ferrao et al., 2003] and RAEGIE for automobile components, Medland et al. [Medland et al., 2003] for conveyors, Ip and Kwong [Ip and Kwong, 2002] for injection moulding domain giving no description on how the developed tools can be scaled up for use in the other domains/type of components.

3.5.3 Review of the Tools and the Frameworks in the Evaluation of the Alternatives

To review the tools with respect to the evaluation of alternatives, the review in this category is carried out from two perspectives, i.e. *number of criteria (single or multiple)* considered and *type of analysis (qualitative & quantitative)* performed by the different tools and the frameworks while evaluating the different design alternatives. These two perspectives have been chosen because it is important to determine how many levels of criteria are supported by the selected alternative evaluation method. It also enables understanding if there are any restrictions imposed in performing the type of analysis due to the use of the selected alternative evaluation method. The review of tools in Table A-3 illustrates strengths and weaknesses as described in the following two sub sections.

3.5.3.1 Strengths of the Tools and the Frameworks Reviewed in Table A-3

The tools and frameworks in Table A-3 show the following strengths:

- ❑ Conflicts are identified and resolved in relation to multiple criteria requirement among different alternatives to support the designer in decision making as shown in DEACE.

- ❑ Good reuse of interactions of multiple criteria through the use of relationships between them stored in database or knowledge base during the decision making process as shown in Dejeu et al. [Dejeu et al., 2004] and CDFMC.

- ❑ Good support to model uncertain information and vagueness in decision making using fuzzy qualitative ratings in CDFMC.

3.5.3.2 Weaknesses of Tools/Frameworks Reviewed in Table A-3

The tools and frameworks in Table A-3 show the following weaknesses:

- ❑ Most of the systems use only a single predefined criterion like DEACE and CDFMC, making them impossible to cope with the new design problems if a new criterion or more criteria are added.

- No method is provided to incorporate designer's preference of criteria in Ariel and Reich [Ariel and Reich, 2003].
- Some systems use heuristics knowledge/rules such as CDFMC, neglecting life cycle considerations and other implications due to a lack of consideration of design decisions on the environment that the product and the user will interact.

3.6 Chapter Summary

This chapter presents a review of existing methods/techniques in the field of the design decision making from three perspectives i.e. *Functional Structure Modelling, Decisions' Consequences Awareness and Selection of Criteria and Evaluation of Alternatives,* which have been identified as three distinctive characteristics of importance in decision making at function based conceptual design stage. Each of these three characteristics is represented by different methodologies/frameworks developed by different researchers. Taking this review further, a review of the different frameworks and the tools, which implemented these, methodologies have also been undertaken. A brief summary of the review in terms of their strengths and weaknesses is presented in the chapter whereas the detailed review is presented in Tables A-1, A-2 and A-3 in Appendix C. The chapter also presents the description of '*Context*' in general and elaborates the use of '*Context*' in engineering design by providing an overview of the work done by different researchers. The review results presented in this chapter are also a part of the contribution that this PhD project makes. Although the reviewed methods and corresponding tools and frameworks described in Appendix C have been critically analysed before, they were not reviewed from the perspective of decision making across three different areas of conceptual design. This review highlights a number of deficiencies and shortcomings exist in different methods and associated tools and frameworks with respect to support for decision making at the conceptual design stage. These weaknesses are summarised as follows:

- Awareness provided to the designer regarding design decisions is often late i.e. as this is only available at the analysis stage when a conceptual solution is already generated.

- In addition to late awareness, the awareness is segmented also i.e. it is only related to a specific life cycle aspect without any interaction/relationship with other life cycle phases.

- There is a lack of understanding about the artefact's behaviour i.e. behaviour is represented from a narrow perspective such as functional, kinematic and spatial behaviour ignoring the whole context of the design problem. Further, there exists no methodology/framework, which illustrates context sensitivity of the behaviour of a design solution.

- There is not a single methodology, which provides knowledge/information support during the decision making from a holistic perspective of the design problem i.e. from the life cycle view, designer's geo-socio-political environment view and from the product's use/working environment view.

- Tools and frameworks developed so far do not support design context knowledge based designing approach. Therefore there is a need not only to identify the whole *context* or *contextualised information/knowledge* of design but also to formalise it in some structured form and present it for designer's consideration early during the synthesis stage of the design, i.e. when the decision making takes place at the conceptual design stage.

- Most of the developed tools/frameworks are suitable only for a particular type of engineering design domain/components. This domain specific type framework development poses problems in scaling up the developed tool to be used for other domains/type of components beyond the intended domain.

This summary indicates that there is no existing method/technique, which provides a holistic support for the conceptual design decision making by enabling consequences awareness from a range of different perspectives early at the synthesis stage of the design process. This review also provides a good understanding of the state of the art in the conceptual design and engineering decision making within product life cycle phases. In particular it also shows that there are possible techniques, which could be used in this research to solve a part of the research problem. For example clear and understandable natural language based textual representation of functions in verb-noun form can be used in this research as it has been successfully used by different researchers to represent functions in different systems. Also as decision making at the conceptual design stage involves both quantitative and qualitative analysis of information, one or more evaluation of alternative methods like Analytic Hierarchy Process (AHP), Multi Attribute Utility Theory (MAUT) and other methods can be successfully used to evaluate different design alternatives against the selected criteria. Overall the review of existing work in this chapter highlights the need of the development of a new approach to support conceptual design making in order to overcome different deficiencies and weaknesses identified in the current methods and suggesting possible techniques/methods that can be used to solve a part of the research problem. Based on the reviews, the next chapter formulates the research problem by highlighting the deficiencies of the existing support identified in this chapter and the focus of the research work of this PhD by identifying research questions and setting the research boundary.

4 Established Research Problem

This chapter discusses the research problem formulated on the basis of discussion and outcomes of the preceding chapters. The main findings of the review of the related methodologies/frameworks are highlighted in section 4.1. Based on these findings, the research problem is established in section 4.2 detailing the research questions, which arise from this discussion. Finally the research boundary of the research work is defined, so that the focus and areas of research work are clearly identified.

4.1 Findings of Review of Methods and Tools Done in Chapter 3

Chapter 3 discussed in detail about different methods/techniques, which are currently in practice from the perspective of three key characteristics i.e. *Detailed functional Requirements*, *Decisions' Consequences Awareness* and *Selection of Criteria and Evaluation of Alternatives* as well as *Context Knowledge* in function based conceptual design decision making. Although a summary of deficiencies and shortcomings found in the reviewed methods/frameworks/tools is presented in the section 3.6, it is important to elaborate these deficiencies in detail in order to find out their impact on support to decision making provided at the conceptual design stage. The key findings in terms of deficiencies and shortcomings identified in this research review are explained in the following sections.

4.1.1 Lack of Understanding about Artefact's Behaviour and Artefact Modelling

Section 3.1.4 describes behaviour as an important link between function and form of selected means/solution and its importance in actual working environment. Table A-1 in Appendix-C presents an overview of different prototype systems/methodologies developed by different researchers in modelling function, behaviour and form of means/solution. While most of the systems presented in the review represent *function* and *form* in detail, they only provide a brief understanding and representation of the behaviour of the product being designed. Behaviour provides a platform for reasoning between function (i.e. design purposes) and structure (i.e. components of the design) [Gero et al., 1992]. There is therefore a need to explicitly define and represent behaviour as a reasoning step during function to form mapping. Since behaviour of a solution is context sensitive, there is a need to first define the context of a design problem and the solution and then address the issue of understanding and representing behaviour within this context.

4.1.2 Segmented and Late Design Consequences Awareness

As explained in section 2.3.2 each design decision cause consequences [Swift and Raines, 1997], which could influence the later life cycle stages [Hubka and Eder, 1988] of the product in terms of cost, time, quality etc. It is therefore necessary that designers are aware of these consequences. Further as detailed in subsections under section 3.2 different techniques/methods are currently used to enable designers to be aware of the consequences of their decisions at the conceptual design stage. The corresponding prototype systems, which have been developed implementing these techniques/methods along with their strengths and weaknesses, are elicited in Table A-2 in Appendix-C. Most of the systems developed do not provide for designers to be aware of their decision consequences during early stages of the design process i.e. they are made aware only during the analysis stage when the solutions in the conceptual design process have already been synthesized and selected for further work/analysis during embodiment design phase. Further, since the awareness related to different life phases is segmented, i.e. if one design decision influences a life phase, then this awareness is enacted by the single consultation is separated and has no causal interaction with another awareness which might be caused due to this decision's influence on another life phase. However, it is important for the designer to be aware of these interactions simultaneously, to find the impact of selecting a particular solution on different life phases of product at a single point in time. This will enable the designer to make an informed decision either by relaxing some functional requirements through a trade-off in the currently selected solution or by exploring more solutions, which have less negative impact on different life phases of the product. At present, however, designers are unable to foresee the consequences and the interactions of their decisions on different life phases simultaneously.

4.1.3 Improper Selection of Decision Criteria

Table A-2 and Table A-3 in Appendix-C indicate that most of the systems/frameworks developed take into account only functional requirements as well as cost, quality, time and in some cases company policies as decision criteria. They however neglect the consequences of selecting a particular design solution on all later life cycle stages of the product simultaneously. As argued by different researchers [Duffy and Andreasen, 1993; Andreasen and Olesen, 1993] and international regulatory bodies like European Commission [IPP, 2003], consideration of life cycle requirements are necessary to improve the quality of decision making, implying that life cycle requirements must be included in the defined criteria apart from function, cost, quality, time in order to make an informed decision. Thus improper selection of decision criteria results in a design solution, which does not adequately addresses life cycle concerns of the product.

4.1.4 Lack of Consideration of Design Context Information

As argued by Gero [Gero, 1998] conceptual design is a dynamic activity, which interacts with the current situation of the external world and any decisions made by the designer have implications on the external world (like environment of the product and users of the product). As discussed in the reviews done in sections 3.2, 3.4.3 and 3.5.2, there is no single method/system, which addresses the dynamic nature of the conceptual design process. It is necessary for the designers to be aware of the consequences of their decisions taken at conceptual design stage not only on later life phases of product but also on the whole context of design problem under consideration i.e. external world, life cycle phases, users of product, environment with which the product interacts. To elucidate, when there is a lack of consideration of the whole design context requirements, it will result in products that might be performing the required functions but not successfully adopted by the users of the product or the environment in which they work or may encounter problems during their different life cycle phases.

4.2 Research Problem

Based on the shortcomings identified in the previous section and review presented in Chapter 3, this PhD research argues that there is a need for a new framework which provides proactive decision making at the conceptual design stage for mechanical artefact design, which allows the designer to model the behaviour of the selected design solution by identifying the context of the design problem, bringing different downstream product life cycle consequences simultaneously for the designer's consideration. Based on the above and due to limitation of human mental capacity of memorising and processing knowledge, the research problem is formulated and presented here as:

> *"Investigate a computational framework to support proactive decision making for mechanical artefact design at the conceptual design stage by explicitly highlighting design decision consequences to designers, caused by considering what is termed as design context, which takes into account the life cycle, product and its user environment".*

4.2.1 Research Questions

The research problem presented above raises a number of research questions, which are addressed in this research:

- What is design context knowledge?
- How to formalize design context knowledge and its consequences?
- How to utilize design context knowledge in decision making at the conceptual design stage?
- How to use downstream design solution consequences that occur at later life cycle stages simultaneously to aid the designer in decision making?
- How to organize and use the huge chunk of design context knowledge and related consequences in a computational form?

- How to maintain design context knowledge?

4.3 Research Boundary

In order to focus on the research work, this thesis bounds the established research problem in the following way:

- Only function based conceptual design problem is considered i.e. component based conceptual design problem in which different standard components are assembled so as to realise a particular function is outside the scope of this research work.

- Only mechanical design domain is selected, with a particular focus on sheet metal stamped parts.

- Conceptual design problem is considered only from a c*onstructional* [Andreasen and Hansen, 1996] point of view.

- It is assumed that decision making process is undertaken by a single designer only i.e. not a team-based approach.

- Complete and precise design information is considered while decision making under *uncertainty* and *vagueness* is not considered.

4.4 Chapter Summary

This chapter establishes the research problem by explaining the shortcomings of the current methodologies identified from the review of literature in the previous chapter and explains the need to provide proactive support to the designer during decision making at the conceptual design stage. Based on the above, research questions are raised which will be addressed during this research and the research boundary is set in order to focus the work on the identified research problem. The next chapter formalises *design context* knowledge as a key element in supporting the conceptual design decision making.

5 Characterizing Design Context Knowledge

The summary of literature review presented in section 3.6 has clearly identified that there is no single methodology/tool, which considers the impact of the whole design context on the decision making at the conceptual design stage. As discussed in section 4.1.4, there is a lack of consideration of design context knowledge and its implications during the decision making due to lack of understanding and non-availability of a proper formalism of the design context knowledge. This chapter therefore presents a detailed study on design context knowledge and characterises and argues this knowledge as an important element in conceptual design decision making. Building on the review done in section 3.4, the first section formalises *Design Context Knowledge* into different groups. The second section illustrates the use of *Design Context Knowledge* in supporting decision making in conceptual design and the final section classifies the context knowledge groups into different categories so that it can be used in decision making.

5.1 Formalisation of Design Context Knowledge

While there exists several definitions of design context knowledge as mentioned in section 3.4.2, the interpretation of *'Context'* in design varies among different researchers due to its broad nature. This PhD thesis refers *'Context'* as a knowledge having information about surrounding factors and interactions which have an impact on the design and the behavior of the product and therefore the design decision making process which result in design solutions at a particular moment of time in consideration. Therefore it can be defined as ***the related surrounding knowledge of a design problem at a given moment in time for consideration***. This thesis argues that a good understanding of design context is essential for successful design and any design support system should investigate how the design context information can be used to provide effective support.

Based on the discussion in sections 4.1.4, 3.4.2 as well as the definition of design context knowledge in the previous paragraph, this PhD thesis formalizes design context knowledge in six different groups.

5.1.1 Life Cycle Group

This group of context knowledge comprises knowledge related to different life cycle phases of a product, which governs the transformation of a product from its conception to disposal/recycle phase. Life phase system knowledge includes all relevant information, which has an impact on the product being currently designed when the product undergoes that particular life phase. This also includes knowledge about machines and processes that interact with the product when it passes through different life phases.

5.1.2 User Group

Contextual knowledge related to the user group comprises knowledge about the intended user and the interaction of the user with the solution product. This may include age group information, gender related knowledge, product preferences in terms of weight, size, colour, texture, appearance and other aesthetics values. Cultural and geographical requirements/considerations like use of product in a modern western society or a less developed society as well as acceptability of a product in a particular cultural environment influenced by a particular factor like religion etc.

5.1.3 Product Related Group

Product related group includes knowledge about the product itself i.e. a particular domain knowledge involving material requirements of the product, type of material, quantity of product, production rate, interaction between the product and the environment, including either internal or external aspects of the product's environment. This group also includes knowledge related to reusable product design information based on past design cases of early version of the design patent.

5.1.4 Legislation & Standards Group

Legislation by different national and international bodies governing the design of a specific feature of a product and its interaction during different life phases is an important source of context knowledge. The legislations result in formulating standards, rules and codes of practice pertaining to different aspects of the product like manufacturing/assembly, maintenance, use, disposal and safety.

5.1.5 Company Policies

Company policies and standards play an important role in designing a product as well as its interaction with its different life phases. Therefore the knowledge related to specific company policies for designing a product or a specific feature of the product is an important part of context knowledge.

5.1.6 Current Working Knowledge

Design context knowledge can be dynamic in nature because as the design process evolves, the associated design solution information becomes richer and more concrete. This is normally termed by designers as current working knowledge [Zhang, 1998], which includes partial solution information, generated upto the current stage of the design process for a given problem.

5.2 Supporting Decision Making Using Design Context Knowledge

Decisions taken during conceptual design affect all the downstream phases of the product life cycle and each design decision has downstream consequences [Borg et al., 2000]. As there can be more than one solution to a problem; this implies that the design solution space should be explored in detail to generate a best solution at the conceptual design stage, taking consideration of design decision consequences imposed not only on later product life cycle stages but also on users of product and environment with which the product would interact during its use, manufacture and other life cycle phases.

Design context knowledge is an important source of product background knowledge as it can enable design consequences to occur. By exploring design context knowledge, designers can gain insights and understanding of the design problem and solutions generated with an increasing emphasis on identifying optimal product life cycle performance based solutions. Although Product Design Specifications (PDS) document [French, 1985] prepared prior to the start of design process must have all the knowledge/information which is related to the *functions* that are to be realized as well as the *constraints* related to different views of the product within which the product solution must work, it has been found that PDS is often ignored during the design process, forcing researchers to develop methodologies pertaining to different life phases like Design for Manufacturing [Boothroyd et al., 2002], Design for Multi-X [Borg, 1999]. The next section therefore explains the link between PDS and the Design Context Knowledge.

5.2.1 Link between PDS and Design Context Knowledge

The purpose of writing a Product Design Specification (PDS) document is to enable the exact formulation of the design problem. It involves writing all functional requirements as well as constraints to which the desired design solution must satisfy. Ideally a PDS should contain all relevant context knowledge and information, which is mentioned in different formalised groups of context knowledge as mentioned in sub sections of section 5.1. However due to the complexity and non-availability of the desired knowledge and information as discussed in section 2.3.3, it is not possible to write a comprehensive PDS which incorporates all knowledge/information necessary to support decision making at the conceptual design stage.

Very often the PDS document consists of the desired functional requirements, customer requirements as well as some manufacturing constraints but does not account for the dynamic nature of the product design process [Gero and Kannengiesser, 2000]. They argue that PDS must be a fluid document [Pugh, 1990] and it must be updated and revised throughout the design process whenever it is needed, though this seldom happens in practice. The PDS needs to be updated regularly so as to incorporate the constraints resulting from the evolution of the current working knowledge [Zhang, 1998]. Therefore, this PhD thesis argues that the design context knowledge is an extension of PDS due to its dynamic nature i.e. the inclusion of current working knowledge besides incorporating knowledge from a range of different perspectives like product related, life cycle related, user of product and designer/product environment related knowledge.

This thesis further argues that reasoning using context knowledge results in design context knowledge consequences [Yan et al., 2002]. These consequences are important and provide relevant pieces of information needed for proactive and intelligent conceptual design decision support to designers in their attempt to make informed decisions. For this purpose, there is a need to identify and classify design context knowledge so that it can be formally used for assisting decision making at the conceptual design stage.

5.3 Classification of Design Context Knowledge

Design context knowledge formalised in the first five groups, is of a static nature and can be further classified into different categories of knowledge depending upon the nature of a design problem and the application domain under consideration. This new classification can make it easy to use this knowledge in decision making. First three groups of knowledge are generic in their application, they capture broad knowledge related to the mechanical design domain and can be used in any design organisation. Therefore this PhD thesis has classified these three groups into ten more refined categories of context knowledge [Rehman et al., 2004]. This classification stems from the work undertaken by other researchers in the field of product life cycle modelling [Hubka and Eder, 1988], context modelling [Pomerol and Brezillon, 2001; Gero and Kannengiesser, 2000; Brezillon and Cavalcanti, 1997] and design synthesis for multi-x [Yan et al., 2002; Borg et al., 1999b] in the mechanical engineering design domain. It is important to emphasize here that these categories of context knowledge are by no means exhaustive or fixed. The number of categories can be more or less depending on the application domain and the nature of the design problem under consideration. However in the context of mechanical artefact design, particularly in sheet metal component design, these ten categories can be used to fully explore the context knowledge, which is important for consideration at the conceptual design stage. It is argued that the approach taken in this research is generic in nature and the same approach can be applied to other applications with more categories of design context knowledge. These categories are explained in following sub sections.

5.3.1 User Requirements/Preferences Context Knowledge

This category of context knowledge deals with the users of the product and is defined as *the knowledge about the requirements/preferences of the user of the product.* This type of knowledge is important to understand the intended users of the product and their preferences about the product. It deals with the following questions like; Who will be the user of product? What will be their age group? What is the gender of the user? Are there any specific requirements of the user e.g. colour preference, time impression of a product, less sharp edges, easy to handle, modular etc? Reasoning using product user requirements can help the designer by gaining an insight about the user preferences in the selection of a particular solution, which would be considered as more suitable by the user. In industrial product design, weight of material used in the product is important from the perspective of the user. For example a product being made of aluminium material is lighter compared with that made of mild steel or other forms of alloy steel. Therefore this product would be easier to handle for females and children. Similarly another example of this type of knowledge could be a requirement of a different size and shape of handle bar for an iron or a kettle for children as compared to one for the adult group. Using this type of knowledge, it is clear that ergonomic data/information can also be a part of user related design context knowledge.

5.3.2 Product/Components' Material Properties Context Knowledge

This category of context knowledge is defined as *information related to product's material properties* and includes general material specifications of the components like type of material, specification, strength, durability, allowable stress, hardness etc. Knowledge related to product material properties is essential for selecting a particular solution means to an identified functional requirement. Providing timely information to the designer using background reasoning about material properties would help the designer in selecting those solutions, which are feasible. For example *Soldering* could be a means of fulfilling '*Provide Assembly*' function. However if one of the mating part's materials is plastic, *Soldering* cannot be used as a means of realizing *Provide Assembly* function.

5.3.3 Quality of Means/Solution During Use Context Knowledge

This category of context knowledge deals with the behaviour of solution/PDE under consideration in actual working environment. This also implies how much a selected solution/PDE deviates from the desired behaviour due to the quality of the solution and the influence of the working environment. It is defined *as the measure/degree of fulfilling the intended function by a solution in different working environment/conditions*. This knowledge is about the adaptability of the selected solution to different working conditions like, high temperature environment, increased vibration, shock/impact load application etc. This type of information helps the designer in selecting those solutions, which give the desired functional performance consistently under different working conditions. In the case of sheet metal components, an example is the improper use of a sheet metal leaf spring in a high temperature environment where its load bearing capacity is significantly reduced. Another example of this type of knowledge is when a friction belt is used in a high temperature environment, the belt slack will be significantly bigger and this has a big performance consequence if it is decided to use the belt in such an environment.

5.3.4 Pre Production Requirements Context Knowledge

This category of context knowledge is defined as *the information required to prepare the material (i.e. cut material to the correct size, straightening the stock, cut edges and so forth) before a component is manufactured and information about any additional items required in realizing a solution*. Context knowledge related to pre production requirement can be used for the analysis and the evaluation of a component against the pre production requirements before it can be manufactured. An example of pre production requirement is the use of shielding flux as well as the preparation of edges before welding two sheet metal plates. This type of context knowledge is normally referred as life cycle specific context knowledge. Reasoning using pre production requirements involves evaluating and comparing the time required and the cost incurred on the pre production processes and bought in components for the different solutions. This is an important source of knowledge about the constraints that preliminary manufacture/assembly systems impose on design decisions of a product. Designers are often unaware of these limitations and as design decisions become more relevant to function related factors, it is very difficult, if not impossible, for designers to foresee these potential decision consequences. Similar to reasoning mechanism related to other categories of knowledge, Life Cycle Consequences (LCCs) can be used in function reasoning. Designers can be proactively supported with timely prompts about the potential downstream implications of a design decision at an early stage [Borg and Yan, 1998]. For example, committing *Hole-Fastener* as the selected solution to realise the function **Provide Assembly,** triggers a piece of LCC that the designer violates the design for assembly principle as this decision results in more parts for the design compared with a snap-fit solution. This implies additional tooling will be required, assembly time will be increased and consequently cost will also be increased during the pre manufacturing stage. Through LCCs based reasoning, suitable PDEs for a functional requirement can be evaluated against some criteria (time, cost, etc.) to select a solution means with least negative consequences.

5.3.5 Production Requirements Context Knowledge

Production requirement knowledge is defined as *the knowledge about actual manufacturing/production requirements for a solution/PDE*. This category of context knowledge also comes under the group of Life Cycle Context Knowledge. For example in case of *Provide Assembly* function the potential solution means could be *Slot-fit, Hole-fastener, Lancing* and Soldering. Now each of these solutions can only be realized by manufacturing/stamping some manufacturing features on mating components. For example a sheet metal based slot-fit solution requires a rectangular slot on a female part and a double 90^0 bend on a male part. Having so many features for an assembly indicates a complex assembly process and as a consequence a higher manufacturing cost. This information is important for the designer not only to analyse the ease of manufacturing of a specific solution/feature on the component but also to compare the cost incurred in manufacturing each of these solutions. This, therefore, provides support to the designer in selecting manufacturable solutions that involve less manufacturing time and consequently a lower manufacturing cost.

5.3.6 Post Production Requirements Context Knowledge

Postproduction requirement knowledge defines *a special process that is needed after manufacturing/inscribing a solution on the component.* An example of such a requirement can be the retightening of a specifically designed nut in a hole-fastener solution during service/use. Another example is the removal of shielding flux from a welded component after the welding process finishes. Reasoning using this type of context knowledge generates consequences about life phase systems (Maintenance/Service) and helps the designer in avoiding unintended and problematic/costly consequences. The consequence in the first example is the time required and cost of equipment incurred in retightening the special nut. Therefore it is necessary to compare the time required and the cost of equipment that would be incurred during the use/maintenance/service phase of a product among all the potential solutions in order to select the low cost solution.

5.3.7 Production Equipment Requirements Context Knowledge

The knowledge related to Production Equipment Requirement comes under the category of life cycle context knowledge and deals with *knowledge of Tooling/Machines required to manufacture a particular solution on a component.* Providing timely information to the designer about the type and cost of machine/tooling that would be required to manufacture/realize a selected solution will help in making a cost effective decision. An example could be the use of fine blanking dies for high surface finish in punching/blanking operation of sheet metal components instead of ordinary dies which are less costly, but requires a secondary trimming operation to get high surface finish of the product.

5.3.8 Quantity of Product Required Context Knowledge

The quantity of a product or a component required is an important factor in selecting a particular manufacturing solution to realize a certain function. The quantity of a product directly affects the selection of a production method and the associated equipment. Higher equipment cost can only be justified if the return (on mass produced components) is sufficiently high. Therefore the information about quantity of product is necessary at the conceptual design stage to select a suitable manufacturing solution, which can be cost effective.

5.3.9 Achievable Production Rate Context Knowledge

Some solutions or features on a component are time consuming and difficult to manufacture. Selecting these design solutions can decrease the desirable production rate of the component. Therefore it is necessary to consider the achievable production rate of each solution using the selected production equipment before making the decision in selecting the final design solution. The higher achievable production rate will not only reduce the lead-time of the product, but also reduce the production overhead costs thus reducing the overall product cost. It is clear that the achievable production rate should be used to help evaluate design solutions, which affect the lead-time and production cost.

5.3.10 Degree of Available Quality Assurance Techniques Context Knowledge

This category deals with the available quality assurance techniques, which confirms that the manufactured solution conforms to functional requirements and there are certain quality assurance methods/techniques, which can concur this conformity during the use of the product. An example of this type of information is the availability of non-destructive testing methods like X-Ray and ultrasound to determine the strength of a metal joint during its operation/use phase. Selection of a solution with a high degree of available quality assurance techniques helps in avoiding accidents or breakdowns due to regular checking of performance of solution during use, resulting in lower maintenance cost as well as reduced time in maintenance/repair work.

The context knowledge classified in the above mentioned categories are the ones, which have been considered to be generic in the sheet metal domain. However in a typical company scenario as well as while designing a particular sheet metal product, there will be more context knowledge categories based on company policies and international standards/rules/legislations etc. These categories need to be considered so as to provide effective proactive decision making support at the conceptual design stage.

It is argued in this research that if the above categories of context knowledge can be used and represented in this research, new and additional categories of context knowledge could also be incorporated in a similar fashion.

5.4 Chapter Summary

This chapter discusses the formalisation of *Design Context Knowledge* into six different groups. Use of Design Context Knowledge in assisting decision making at the conceptual design stage is presented by classifying groups of context knowledge into different categories and proposing reasoning of these categories in order to generate design context knowledge consequences which can be used to assist the designer in making an informed decision about selecting a particular solution at the conceptual design stage. It is argued that the amount of knowledge/information presented in each context knowledge category varies between different design problems and the application domain under selection. However, this chapter presents a generic methodology/approach to make use of the design context knowledge and its subsequent classification into different context knowledge categories. The next chapter proposes a generic framework explaining the use of these context knowledge categories alongside current working knowledge by developing a Function to Means mapping model to support decision making at the conceptual design stage.

6 Function to Means Mapping Model Development

This chapter discusses the development of a new Function-Means mapping model based on Design Context Knowledge. The first section explains the function mapping mechanism and reveals a new concept termed as *Product Design Elements* as an alternative to *Solutions/Means* to realize the required functional requirements. This first section also describes the Product Design Elements based functional design approach. The second section highlights the development of the Design Context Knowledge based Function and the PDEs mapping model as a proposed method to support decision making during conceptual design. The third section uses a case study to explain the working of the model. The final section gives a summary of other paper-based case studies, which are detailed in Appendix-E to illustrate the application of the model in different domains.

6.1 Function Mapping

Function mapping in conceptual design is to derive and generate conceptual solutions to specified design problems from the functional viewpoint, evaluate their suitability and map them to the design problems. This process involves deriving implementable functions by decomposing them into finer resolutions, identifying means to realise them and evaluating those means by reasoning using existing and new knowledge/information against evaluation criteria. The first step is representing those functions using some appropriate method during the function mapping process.

6.1.1 Function Representation

The most effective and understandable function representation method is to decompose higher level functions into lower sub level functions and to use them for reasoning in a manual or a computational environment [Winsor and MacCallum, 1992]. There are five existing methods to represent functions as discussed in section 3.1.2. This research uses natural language based non-mathematical representation, where verbs and nouns are used to describe what a product does or is supposed to do. Functions are represented using a combination of *operators* and *operand.* Operators are *verbs* whereas operands are *nouns*. For example *Provide* (Verb-Operator) *Support* (Noun-Operand) function is read as *Provide Support* function. After selecting an appropriate method to represent functions, the next step is to decompose the higher-level functions into smaller functions.

6.1.2 Function Decomposition

This research adopts the design method proposed by Pugh [Pugh, 1990] and assumes that a design process starts with the market research to formalise a product design specification (PDS) document. Using the PDS, it is possible and even desirable to describe and concentrate on the functional requirements, which constitute the key aspect of product engineering design, so as to decompose the overall high-level function into small and implementable sub-functions. This is due to the fact that rarely it is possible to find a single solution, which can achieve a specified high-level function in engineering design. This decomposition often results in a function hierarchy. A well-decomposed function hierarchical structure represents a good understanding of the customers' requirements for a product. This is particularly important to function oriented design as such a structure represents the results of the functional understanding and the decomposition process which also forms the basis for the function mapping. During the functional decomposition, the functional requirements are often decomposed to a level where it is possible to identify potential means or mechanisms to realise these small sub-functions. For example, in machine component design, one of the desired function requirements could be *Convert Motion,* which can be further decomposed into *Convert Rotary Motion into Translatory motion* and *Convert Rotary Motion into Rotary motion* (Figure 6-1).

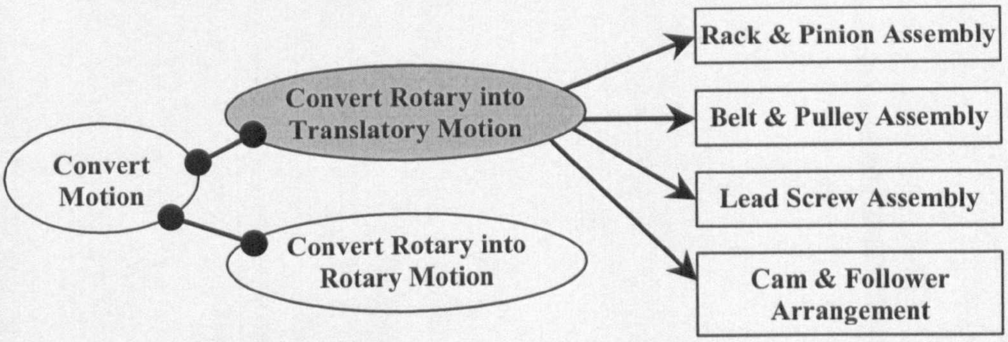


Figure 6-1: An example of function decomposition

6.1.3 Identification of Solution Means

A potential solution for *Convert Rotary Motion into Translatory motion* from the function means mapping library could be a *Rack & Pinion Assembly.* Observing the product from the constructional point of view [Andreasen and Hansen, 1996] results *in product breakdown structure (PBS).* Borg et al. [Borg et al., 1999a] presented this structure as a number of elements called *product design elements (PDE).* The term PDE could be used to refer the following:

- *a product:* the artefact purposely designed for the user such as a telephone.
- *a subassembly:* an element consisting of a set of components, such as telephone enclosure, which consists of other elements like numeric buttons, plastic cover etc.
- *a component*: a single material product produced without any assembly operation; for example plastic cover.
- *a component building element:* an element or a feature that constitute the component, for example the plastic material , or punch holes in the cover of the telephone etc.

Using the above PDEs structure and focusing on the metal component design, consider a sheet metal product as shown in Figure 6.2. This product can be broken down to different hierarchical level of PDEs such as:

- *Sub-assembly PDEs*: i.e. elements consisting of more than one product components. An example is base and support strip assembly of power unit. This sub-assembly is regarded as PDE at sub-assembly level.
- *Component PDEs*: a single material product component produced without any assembly operations; e.g. the base and strip of the power unit which are considered as two separate PDEs;
- *Component building PDEs:* component design elements that constitute a component e.g. for a computer power unit's casing, component elements

include the blank, slot, hole, material, snap-fits and rib features.

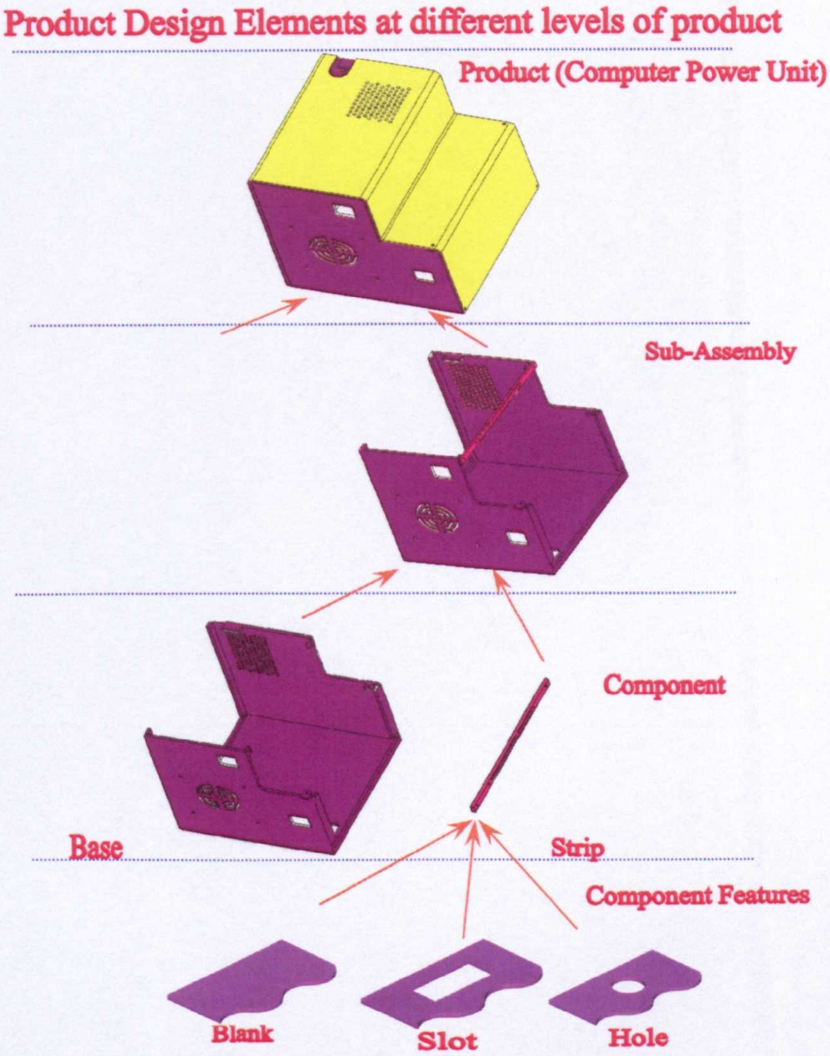


Figure 6-2: Product Design Elements (PDE) at different levels of a sheet metal product

From the viewpoint of component building PDEs, the term "feature" is considered relevant within the above mentioned hierarchical structure. *Feature* is considered to be an information element defining a region of interest within a product and the feature description contains the relevant properties including the values and the relations of properties of a product [Brunetti and Golob, 2000]. The means of achieving a function could be manufacturing features as shown in Figure 6-3; i.e. four possible manufacturing features presented as a means to realize a *Provide Semi-Permanent Assembly* function.

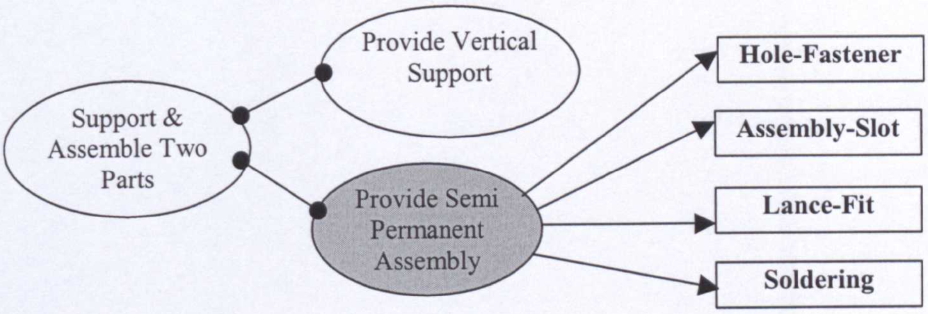


Figure 6-3: Function-PDEs Association

6.1.4 PDE Based Design

Figure 6.3 shows different PDEs at component building level as manufacturing features. A PDE at component building level is used as a reusable design information unit (element) representing a potential solution means for a function requirement. Designing by functions or "functional design" refers to the process of generating a design solution from the product function point of view, using available well-understood function-PDEs relationships to identify suitable means in the form of PDEs. For a given functional requirement, PDEs are the information carriers that allow the mapping between function requirements and physical solutions of a product. They are the vehicles, which bring basic design information to the downstream product realisation phases for embodiment, detailed part design and also to the later life cycle processes. Through this association, the function-means mapping algorithm can be used to identify suitable PDEs for a chosen implementable function. Therefore PDEs can be used as the key to function-oriented design in mapping PDEs to function requirements [Rehman and Yan, 2003]. For a decomposed function structure, this research proposes and implements the following design context knowledge based Function to PDE mapping model to identify the suitable means to realise a chosen function.

6.2 Design Context Knowledge based Function to PDE mapping Model

Conceptual design as discussed in section 2.2.2 is a function to means mapping process, during which decision making takes place regarding the selection and evaluation of design alternatives. In order to support decision making at the conceptual design stage, a new function to means mapping model is proposed here in this research, which uses design context knowledge to support decision making. During the Function to PDE mapping process, explorations of many available alternatives can certainly inspire designers to think of an alternative function structure to generate optimal and innovative design solutions. Figure 6-4 shows a generic process model of Function to PDE mapping developed in this research [Rehman and Yan, 2003].

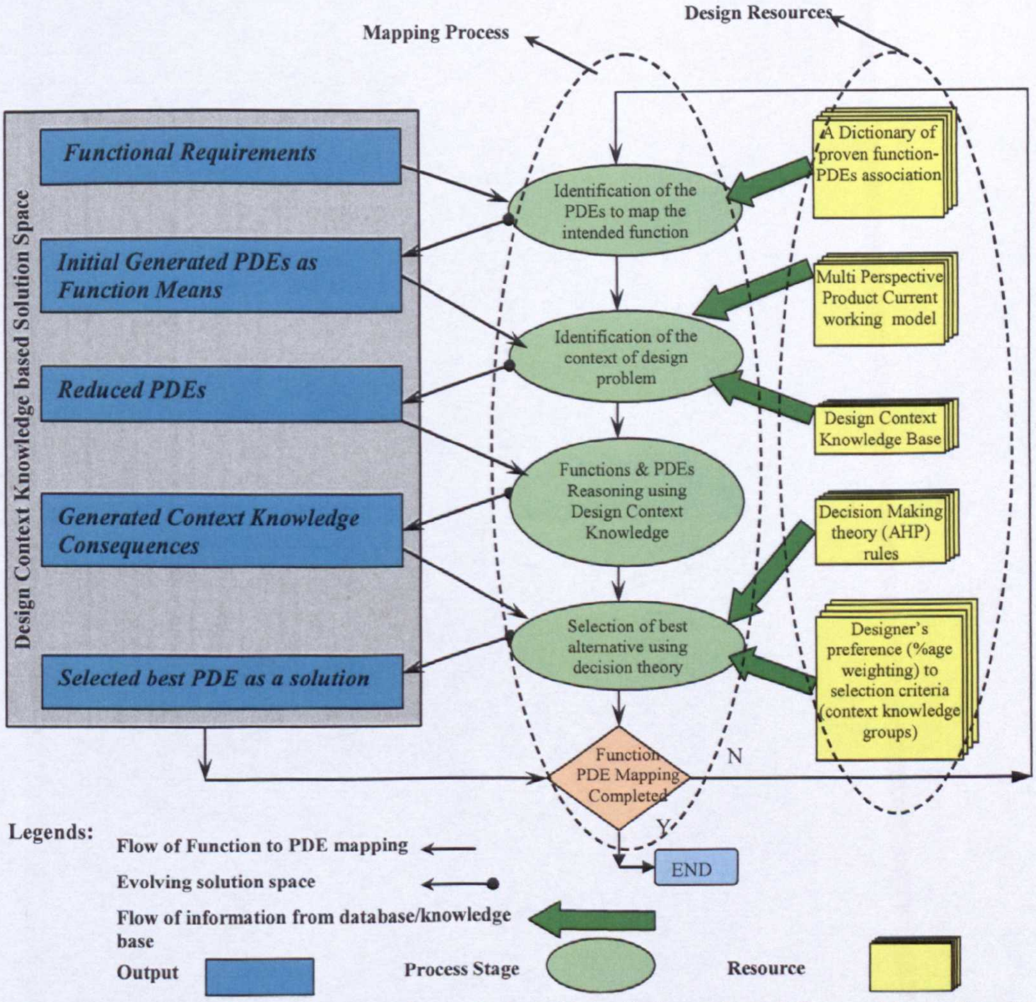


Figure 6-4: Design Context Knowledge Based Function-Means Mapping Model

6.2.1 Overview of the Model

The model consists of three groups of information or activities. The first group (i.e. the left hand column of the shaded rectangular box) is called the *Design Context Knowledge Based Solution Storage* and models a solution space in which the new decision made from an earlier design stage becomes the output to support the subsequent stage of the function to PDE mapping process. The second group (i.e. the right hand column of multiple square blocks) is called *Design Resources* and consists of resources to support the decision making. These include database, library of functions, function means association dictionary, design context knowledge base, Analytic Hierarchy Process (AHP) rules and designer preferences through which knowledge/information is input to different stages of function to PDE mapping process. The third group (i.e. the central column of the oval shaped blocks) is called the *Design Context Knowledge Based Mapping Process* and describes the four stages of function to PDE mapping process, which is detailed below.

At every stage during the mapping process, the designer uses the inputs from the solution space and the design resources and generates new potential solution(s) thereby evolving the design solution. During the first stage, the designer takes the *Functional Requirements* and a *Dictionary of Proven Function-PDEs association* as inputs which result in *Initial Generated PDEs as output.* At the second stage, the designer takes these *Initial Generated PDEs* and searches for suitable models from the *Multi Perspective Product Current Working Model* library. This *Current Working Model* and the *Design Context Knowledge Base* are used to identify the exact context of the design problem i.e. functional requirements and solution information in different contexts. The design context knowledge base also facilitates the designer to reduce the initial set of PDEs into a reduced sub-set of PDEs, which don't comply with the desired physical properties as defined in the functional requirements.

During the third stage, the designer takes this reduced set of PDEs as inputs and performs function and PDEs reasoning simultaneously using the design context knowledge to generate *Context Knowledge Consequences* as the output of this stage. At the final stage of the model, the designer uses the *Generated Context Knowledge*

Consequences, AHP rules and the *Designer's Preference* as inputs and performs *decision making* by selecting the *best solution,* which not only fulfils the functional requirements, but also accounts for the whole context of the design problem under consideration. This life cycle awareness is performed, by timely prompting the designer about these consequences, thereby providing proactive decision making support to the designer.

This whole process of function to PDE mapping spanning these four stages, is iterated for all functions in a given design problem, until all functions are realized by selecting the best solutions as described above. At this stage, function to PDE mapping is completed for a design problem.

The detailed description of different stages of the model is shown in the following sections.

6.2.2 First Stage

The first stage of the model as shown in Figure 6-5 identifies suitable PDEs on the basis of desired decomposed functional requirements using a dictionary of proven function-PDEs association. Functions are represented in the natural language based *verb-noun* pair form. Functional structure is derived into a hierarchical form where the most abstract function is placed at the top of the hierarchy as the base class function. This function is further decomposed into sub class functions with finer resolutions. This decomposition process continues until all implementable sub functions are derived.

The dictionary of function-PDEs association can be developed by writing function-PDE mapping algorithm on the basis of knowledge available about different functions, PDEs and their relationships in literature, through experience and past case studies. This research derived a dictionary of well-proven PDEs associated with its able function(s) for mechanical artefact design domain as shown in Figure 6-6. The figure describes different classes of functions used in mechanical artefact design focusing only on assembly/conveyance type functions to evaluate the Function to PDE mapping model.

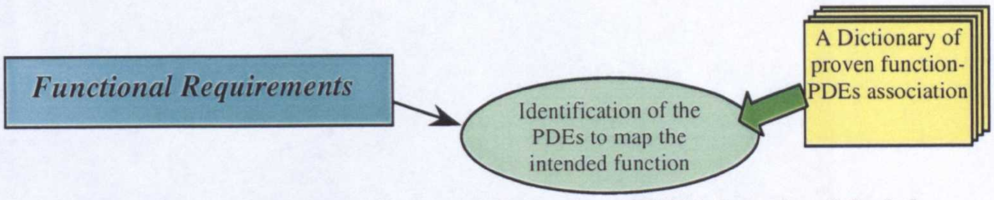


Figure 6-5: First Stage of Function-PDE Mapping Model

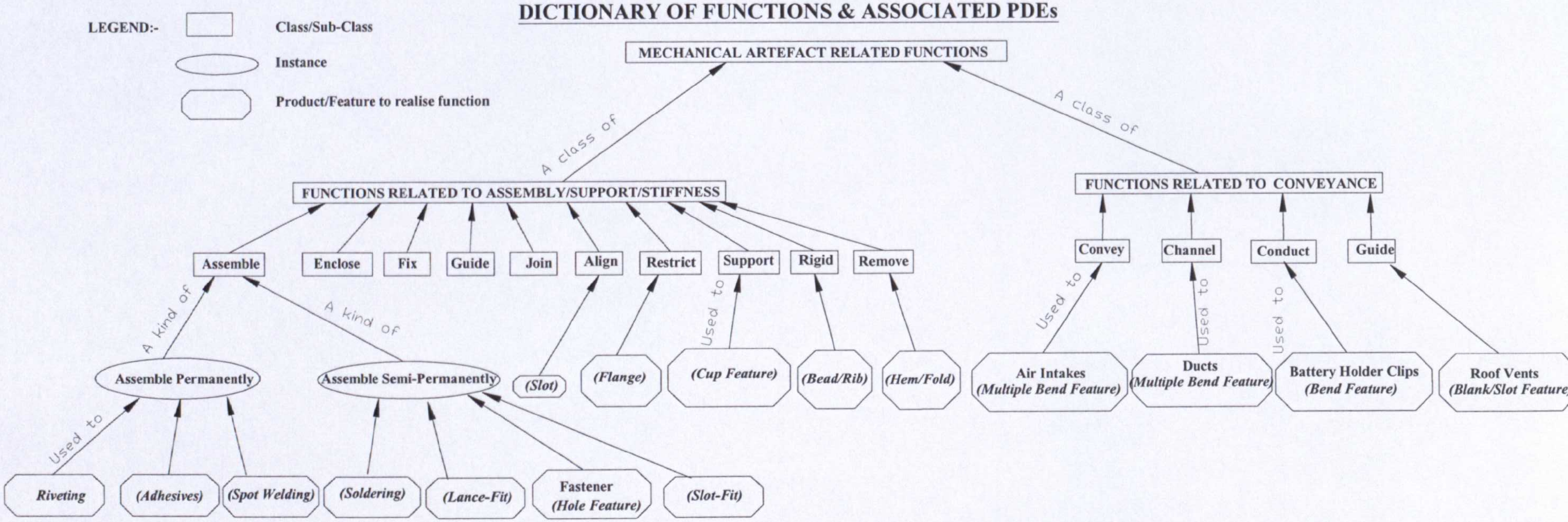


Figure 6-6: Functions and associated PDEs from dictionary

6.2.3 Second Stage

During the second stage, once a list of suitable PDEs is generated, then the context of design problem is identified, using design context knowledge base and multi perspective current working models of the product, as depicted in Figure 6.7.

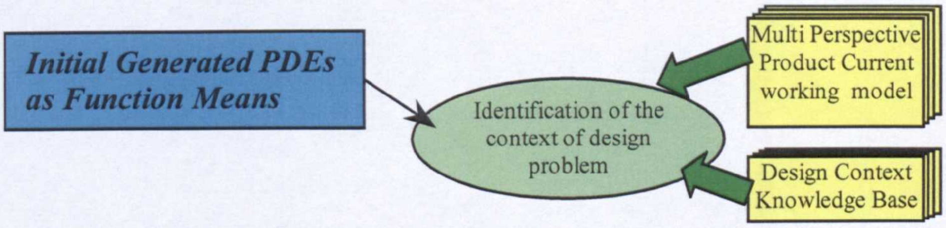


Figure 6-7: Second Stage of Function-PDEs Mapping Model

The context knowledge is formalised into six groups as presented in section 5.1. This research has taken three groups for further exploration as mentioned in section 5.3. These three groups are *General Product related Context Knowledge Requirements, Life Cycle Context Knowledge Requirements and User Context Knowledge Requirements* as shown in Figure 6-8.

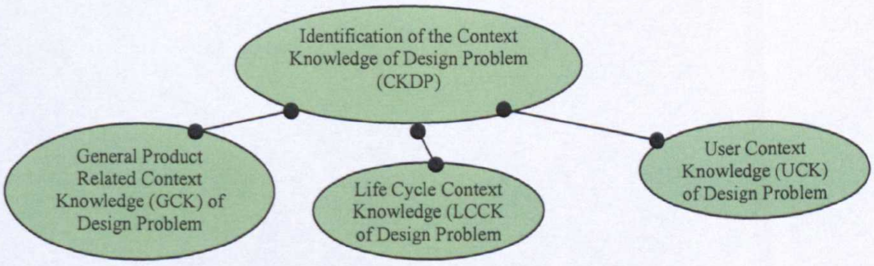


Figure 6-8: Formalism of Design Context Knowledge

These three groups are further decomposed and classified into different knowledge categories as presented in section 5.3 to fully represent the functional requirements from different perspectives as shown in Figure 6-9. The number of categories in each of the three groups depends upon the nature of the design problem under consideration starting from one to nth. Thus context knowledge is used in order to classify functional requirements into different knowledge requirement categories.

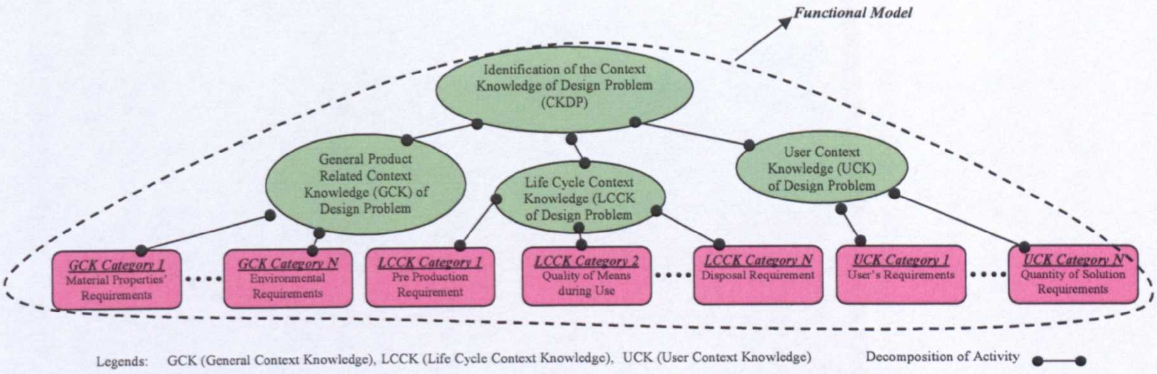


Figure 6-9: Classification of Design Context Knowledge

As shown in the above figure, this whole process of converting functional requirements into different categories of knowledge requirements is defined as the *functional model,* which captures design requirements from ten identified categories in this research.

The generated PDEs can be further decomposed into different attributes like *Material attributes* (Name, Physical properties), *Form attributes* (Shape, Structure) and *Surface Finish* attributes (Type of Finish, Degree of Finish). This decomposition process results in Form/Structural model of PDEs/Solutions as shown in Figure 6-10. This helps to reduce the initial set of PDEs, by discarding those PDEs/solutions whose material, form and surface finish attributes do not comply with those required in the function are discarded for functional evaluation, thereby retaining a reduced set of PDEs for further exploration. It is not however necessary that a reduced set of PDEs/solutions is always obtained as it depends upon the nature of functional requirements.

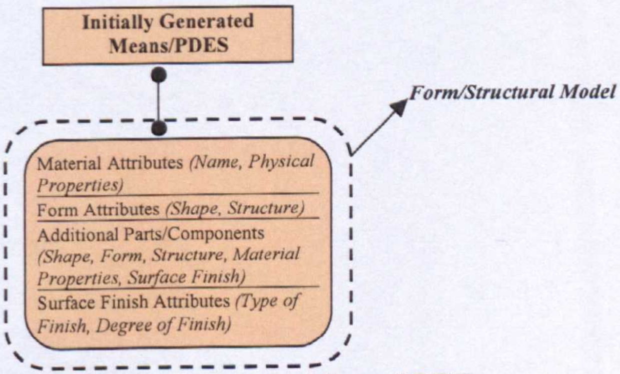


Figure 6-10: Decomposition of PDEs

Multi perspective current working model is the partial information generated regarding the proposed solutions/PDEs until the current stage of the design process. This has been termed by Zhang [Zhang, 1998] as current working knowledge. Current working knowledge is therefore elicited from these decomposed PDEs using the design context knowledge base. This current working knowledge is further decomposed into the same number of knowledge categories (i.e. starting from one to nth) as that of the functional requirements under the three different groups as shown in Figure 6-11. But these pieces of knowledge are in the form of available/generated properties for each of the design solutions/PDE under consideration. These categories of generated context knowledge form the *behavioural model*, as behaviour of a product is context sensitive and as such, behaviour comes into play only in the context of the design environment.

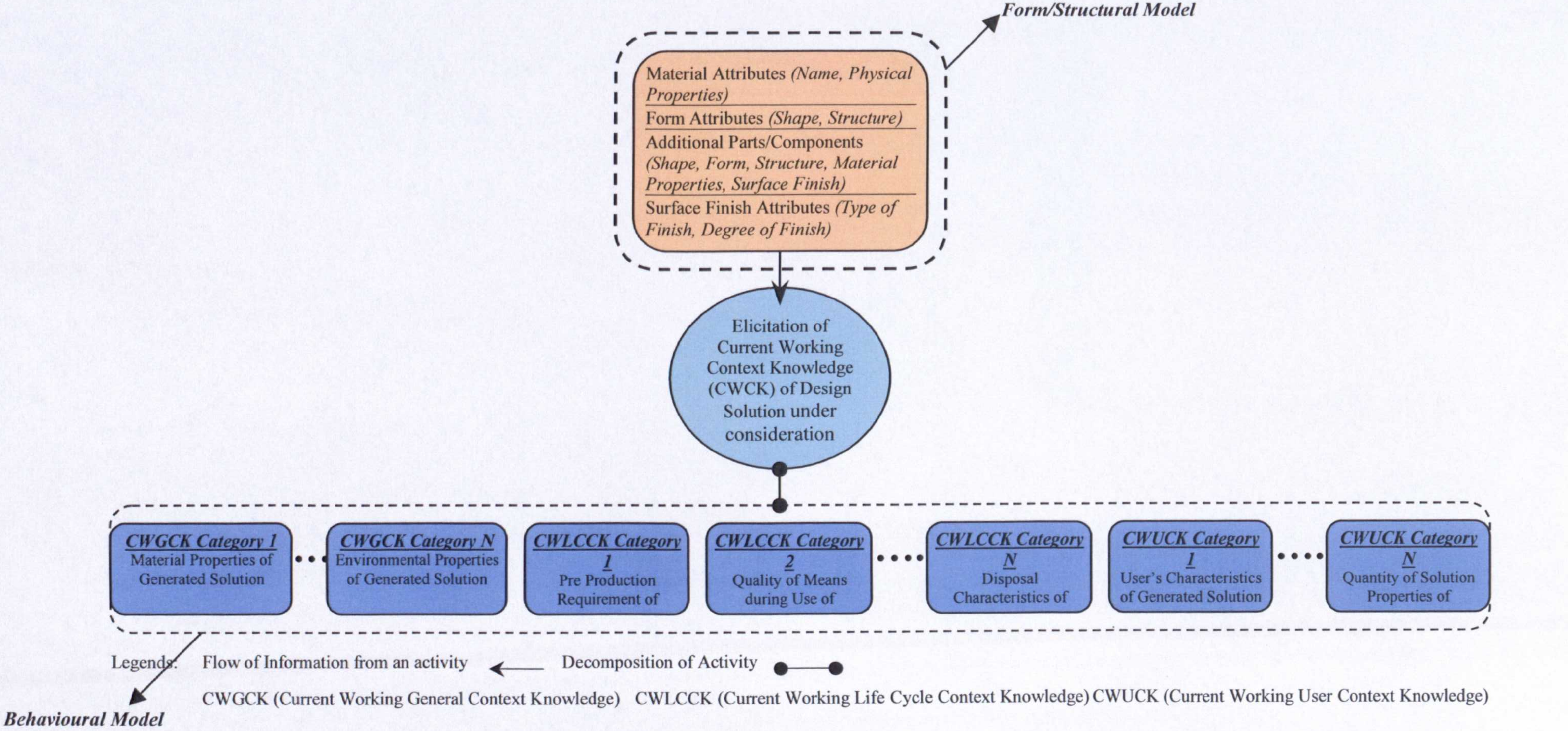


Figure 6-11: Elicitation of current working knowledge

6.2.4 Third Stage

With the use of an extensive function–PDEs association dictionary support, many PDEs can be mapped onto a function, which can be provided to a designer for his consideration. This can be a demanding task if each of these PDEs is to be evaluated manually. Given that the final selection of design solutions follow strict deadlines, computer based reasoning can be used to resolve the problem. The third stage of Function to PDE mapping model involves reasoning as shown in Figure 6-12. To effectively support designers in these circumstances, this research has developed a reasoning mechanism using design context knowledge [Rehman and Yan, 2004b].

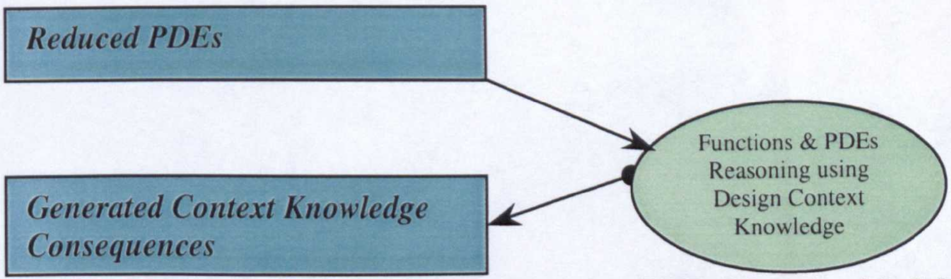


Figure 6-12: Third Stage of Function-PDEs Mapping Model

6.2.4.1 Reasoning Mechanism

Having functional requirements as context knowledge requirements in different categories and generating information about each solution/PDE in terms of the same categories enable the use of simultaneous rule based reasoning to elicit context consequences for each category. Further, use of reasoning based on design context information spells out the life cycle behaviour of a product. Due to an extensive formalised representation of a function using their associated attributes developed in this research, it is possible to use design context information in function and solution/PDE reasoning. Simultaneous rule based reasoning of functional requirements and solution properties elicits consequences for each context knowledge category as shown in Figure 6-13.

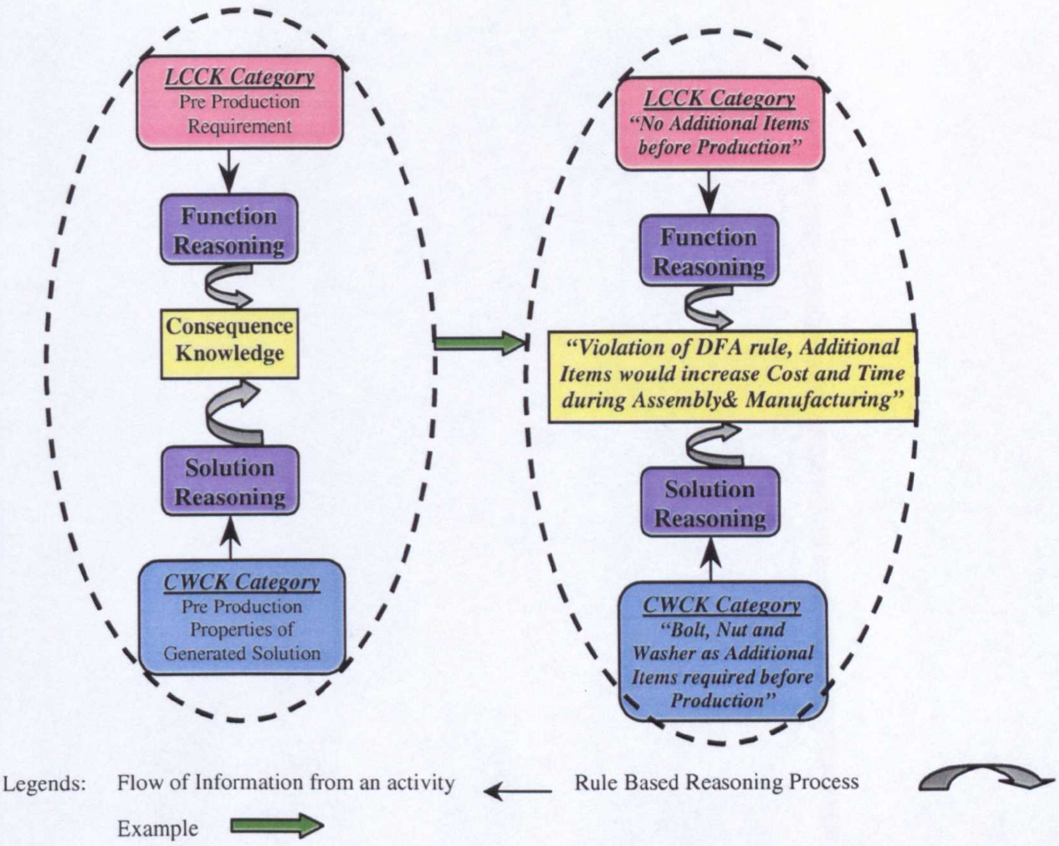


Figure 6-13: An Example of Reasoning Process

This process of reasoning applies to all context knowledge categories i.e. in three groups simultaneously. The reasoning mechanism (shown in Figure 6-14) is used to help the designer explore different life cycle related, product and user related design solution consequences that would occur at later life cycle stages due to decision commitment of a PDE as a design solution at the conceptual design stage. Thus potential good or bad consequences are generated by simultaneously reasoning the required context knowledge in each category and the generated context knowledge of the PDEs/solution within the same category.

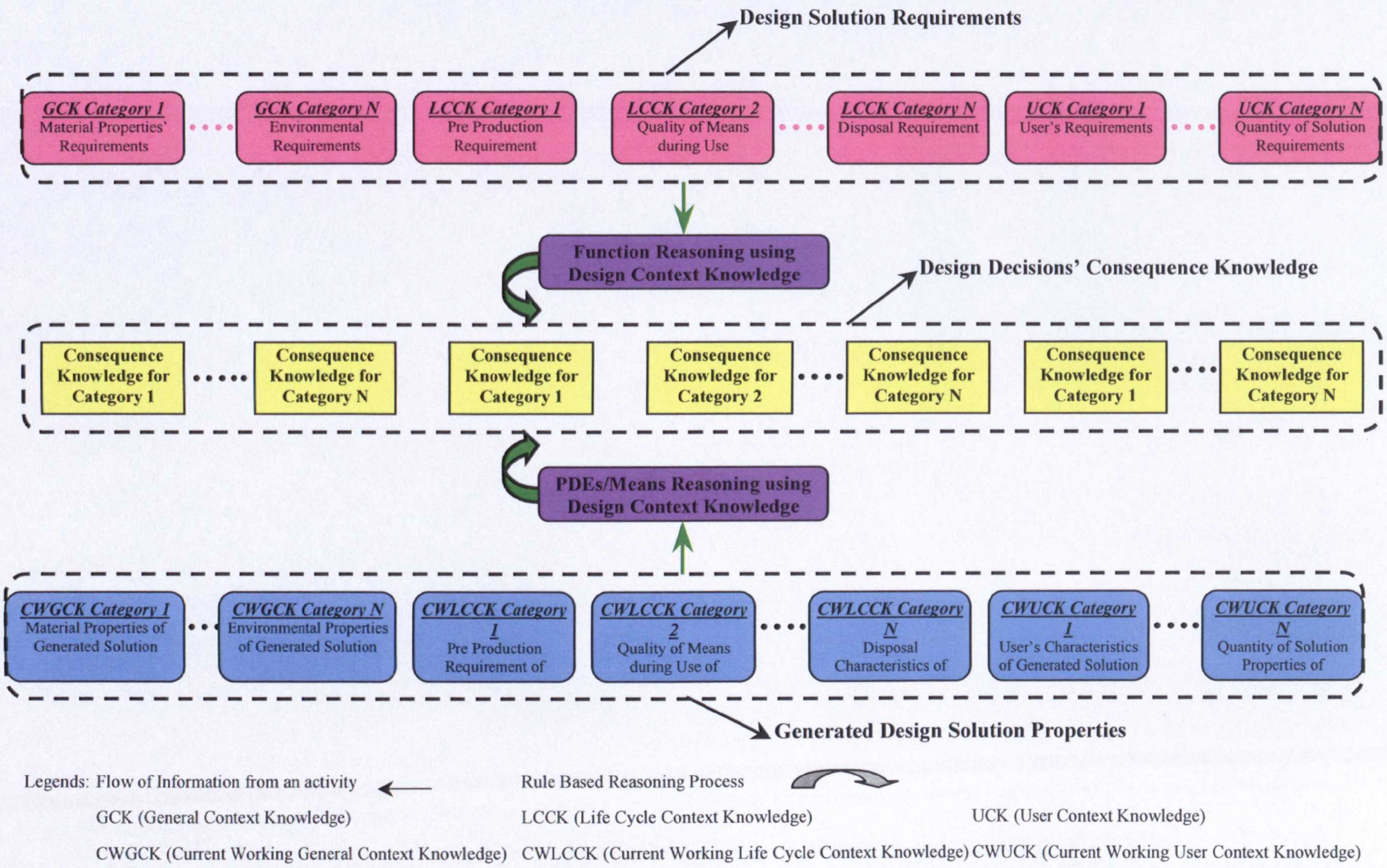


Figure 6-14: Reasoning mechanism of Function to PDEs Mapping Model

6.2.5 Fourth Stage

Once the design solution/life cycle consequences are illustrated for different scenarios for each of the PDEs, it is possible to select a PDE with least negative consequences as the best solution to a conceptual design problem by using designer's preference in terms of weighting and decision making theory rules during the fourth stage of the model as shown in Figure 6-15.

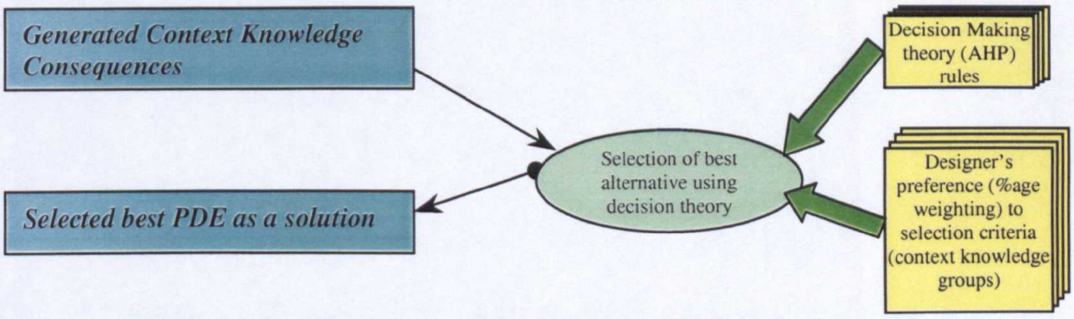


Figure 6-15: Fourth Stage of Function-PDEs Mapping Model

6.2.5.1 Decision Making Using Analytic Hierarchy Process

Having reviewed the different decision making methods available at present (i.e. elucidated in section 3.3.2), this research uses Analytical Hierarchy Process (AHP) [Saaty, 1990] for decision making and selection of an optimal PDE alternative at the conceptual design stage for mechanical artefact design. The choice of this method was made due to the following merits offered by the AHP method:

1. AHP can be used for both quantitative and qualitative subjective information analysis.

2. Since the chosen research problem requires pair-wise comparison, (i.e. the chosen PDE selection problem, requires pair-wise comparison of each PDE alternative against other PDEs), the use of AHP method seems appropriate.

3. This method provides comparison of different design alternatives against design criteria but also provides for comparison of different design criteria against designer's preferences.

4. By virtue of adopting the model, it is possible to take into account criteria with different levels of description i.e. hierarchical ranking of a criterion from the top to the bottom level is possible.

A detailed explanation of Analytic Hierarchy Process with its working is explained in Appendix-D. The context consequence information generated due to reasoning in each context knowledge category is analysed and assigned degrees of suitability on a scale of 0 to 5. The fewer the problematic consequences, the higher the degree of suitability. The relative weighting among ten design context knowledge criteria (i.e. preference of one criterion over other) is done by assigning percentage weighting (out of 100) for each context knowledge category based on the designer's preference. The assignment of numerical rating to each of the design alternatives under each context knowledge criterion category is done by converting the degree of suitability of each alternative into a weighting factor. The weighting factor is based on the comparison scales defined in decision making theory - Analytic Hierarchy Process as shown in Figure 6-16.

1 Objectives i and j are of equal importance.
3 Objective i is weakly more important than j.
5 Objective i is strongly more important than j.
7 Objective i is very strongly more important than j.
9 Objective i is absolutely more important than j.
2,4,6,8 Intermediate values

Figure 6-16: Original AHP Rating Scales

This research has modified the original rating scales of Analytic Hierarchy Process by changing the strength attribution of the scales to clearly reflect more variation in pair wise relationships among different alternatives. Currently the third, fourth and fifth levels are as follows: -

Level 3: ***5 Objective i is strongly more important than j***
Level 4: ***7 Objective i is very strongly more important than j.***
Level 5: ***9 Objective i is absolutely more important than j***

The words "strongly" and "very strongly" do not adequately reflect the variation about the strength of the relationships. In fact, the moderate strength in the relationship of the variables is not represented through the current scaling system. Therefore in order to make a clear distinction between third, fourth and fifth levels of the present scaling system, the author has proposed to use the terms "moderately", "strongly" and "absolutely" instead of "strongly", "very strongly" and "absolutely". This proposed change is essential even from a linguistic perspective so as to accord appropriate ratings when responses are elicited from designers to indicate their levels of preference. Therefore the revised scales for third, fourth and fifth levels appear as follows:

Level 3: ***5 Objective i is "moderately" more important than j***
Level 4: ***7 Objective i is " strongly" more important than j***
Level 5: ***9 Objective i is "absolutely" more important than j***

The modified scales of AHP are explained below and shown in Figure 6-17.

CRITERIA	TOP 1	TOP 2	TOP 3	TOP 4	TOP 5
LEFT 1	1	1/3	1/5	1/7	1/9
LEFT 2	3	1	1/3	1/5	1/7
LEFT 3	5	3	1	1/3	1/5
LEFT 4	7	5	3	1	1/3
LEFT 5	9	7	5	3	1

1: Both criteria of equal importance
3: Left weakly more important than top
5: Left moderately more important than top
7: Left strongly more important than top
9: Left absolutely more important than top

1/3: Top weakly more important than left
1/5: Top moderately more important than left
1/7: Top strongly more important than left
1/9: Top absolutely more important than left

1 Objectives i and j are of equal importance.
3 Objective i is weakly more important than j.
5 Objective i is moderately more important than j.
7 Objective i is strongly more important than j.
10 Objective i is absolutely more important than j.
2,4,6,8 Intermediate values

Figure 6-17: Modified AHP Rating Scales

On the basis of these new scales and the method of normalization of AHP, the degree of suitability is converted into a weighting factor and the matrices are generated for all the ten categories of context knowledge. After determining the relative weighting factors of each criterion and the numerical rating of different alternatives, the final task of selecting the best design alternative is performed by calculating the highest added normalized value for each design alternative. This is done by multiplying the designer's preference (percentage weighting) of one criterion over the others by the numerical rating of different alternatives. The AHP process provides total control to the designers to decide their preferences of one criterion over the others in terms of percentage weighting based on their experience, company policies and other factors, thereby making the task of decision making more flexible and designer centred and controlled. The alternative with the highest added normalized value is considered to be the best amongst all the alternatives.

6.3 Working of the Model

As an example to show how this Function to PDE mapping model works, a case study of sheet metal component assembly design problem has been selected. This case study involves the design of fixing of a LED/ switch PCB panel on to the front sheet metal casing of a computer workstation as shown in Figure 6-18. The power switch for turning the computer off and on, reset switch and hard disk indicator are mounted on LED/switch PCB panel as shown in Figure 6-18. The PCB panel has to provide access to the plastic cover so that when the plastic cover is assembled on the casing, the switches on the panel have direct contact with the buttons on plastic cover. Due to a *Design for Aesthetics* requirement to have a curved front cover, the PCB panel needs to be raised close enough to facilitate the design of interface plastic cover buttons and visualization of the LED. Four possible means/solutions have been identified in order to realize *"Provide Curved Access"* function as shown in Figure 6-19. This is derived from the mapping search algorithm, which performs key word search in order to map possible means to a required function from the library of functions and their associated means. Once the keyword is mapped onto a PDE, it will be identified as a suitable candidate and the search continues until all PDEs in the library are evaluated based on the search criteria.

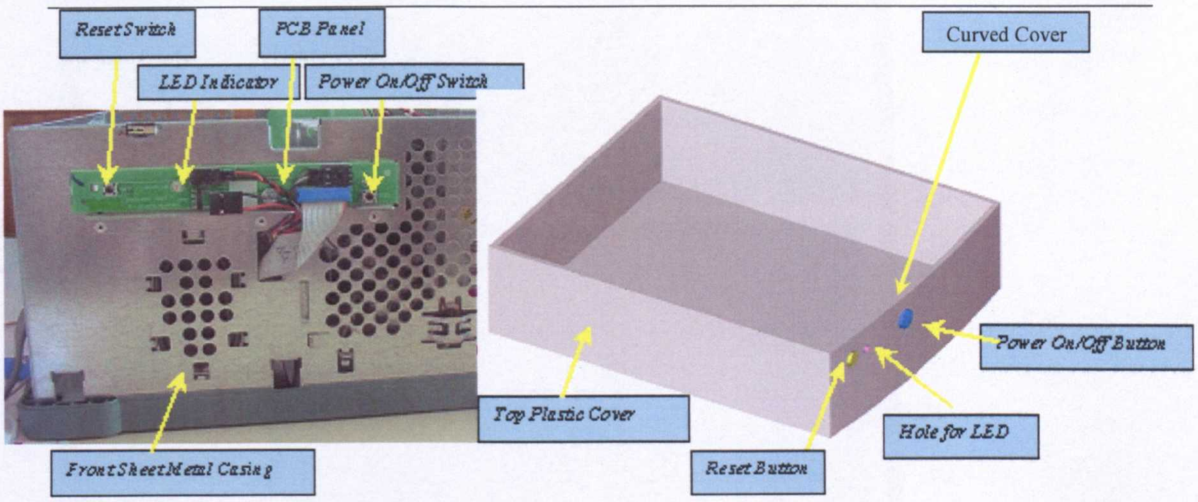


Figure 6-18: Picture of front of an open computer workstation showing sheet metal casing and plastic cover

Therefore the functional requirement can be defined here as *"Provide Curved Access"*.

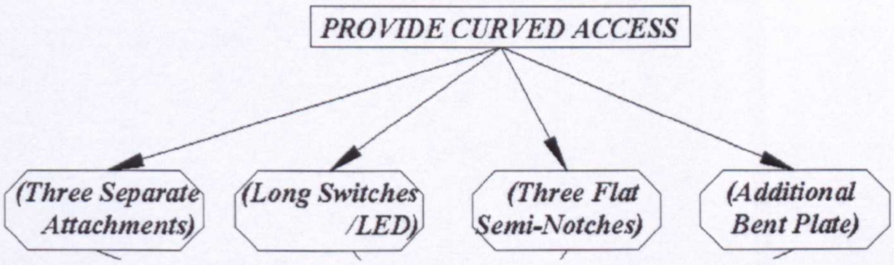


Figure 6-19: Possible Means/Solutions to realize the function

A brief description of these solutions shown in Figure 6-19 is given here:

- *Three Separate Attachments* in Figure 6-19 means that there should be three different rectangular box type attachments of different heights to be fixed on the front sheet metal casing. This is due to different sizes of buttons on plastic casing as well as to provide the curved access for LED. Two attachments contain switches for turning the computer on/off and resetting the computer, whereas the third attachment is used for a LED to indicate the working status of the hard disk. Thus one panel is to be replaced by three separate attachments.

- *Long Switches/LED* means that instead of providing a mechanism of tapered attachment of panel to base plate, the access can also be provided by increasing the length of the buttons on the base plate or the switches on the panel.

- *Three Flat Semi-Notches* means that three small Semi-Notches with different heights are stamped on the base plate. The surfaces of these three notches make a plane, which is tapered to the plane of the base plate, so that the panel can be attached through some glue/soldering on these notches at a required angle.

- *Additional Bent Plate* indicates that a new bent plate is attached to the front sheet of the metal casing at the required tapered angle, so that the LED/switch panel can be mounted/attached to give a curved access to plastic cover.

The potential solutions generated through PDEs based function-reasoning need to be evaluated using design context (background) information based reasoning mechanism in order to support the designer to select a suitable means. With the context information available under *Life Cycle Related, Product Related, User Related* Groups and under *Current Working Knowledge*, the context information reasoning mechanism aims to detect any 'unfit'/unfeasible PDE from the initial mapped PDEs in order to reduce the initial set of PDEs to a reduced subset of PDEs. In this example the initial function requirement ***"Provide Curved Access"*** has been matched with four possible PDE/means to implement this requirement.

6.3.1 Context Knowledge Reasoning

Context knowledge for the design problem under consideration is generated for each of the ten categories of context knowledge. As soon as one of these four means/solutions is selected, context consequence knowledge is generated in each one of the ten categories of context knowledge. The design context knowledge presented in this case study has been collected from different books and literature review [Carlson, 1961; PMA, 1995; Pearce, 1991; Langton, 1963; Breitling and Altan, 1997; Duggirala and Shivpuri, 1999; Eary 1974] specific to sheet metal forming design, sheet metal working machinery and sheet metal research. This information is analysed by manually reasoning the context knowledge requirement for each category and subsequently rating each design solution/means in terms of the degree of suitability for that particular context knowledge category as shown in Table 6-1.

The scale and range of degrees of suitability are arbitrarily set as shown below:

Strength of Suitability	***Degree***
Absolutely High	5
Very High	4
High	3
Low	2
Very Low	1
Not suitable	0

The number of problematic consequences generated in each category simultaneously depends upon the candidate design solution and the category of context knowledge under consideration. For example in *User Requirements* category *Additional Bent Plate* solution illustrates a good consequence (*No Sharp Edges*) therefore it is assigned a degree of suitability of 4, whereas *Three Separate Attachments* solution gives a slightly problematic consequence (*Few Edges*) and hence has been assigned a score of 2.

Similarly in *Pre-Production Requirement* category selecting *Additional Bent Plate,* as the candidate solution would violate the design for assembly rule/guideline i.e. the number of parts required in realization (manufacturing/production) should be kept to a minimum, because it would increase the cost of the solution and therefore is a problematic consequence. Table 6-1 highlights different good and problematic consequences of selecting a particular solution on different product life cycle phases, user and on the product itself.

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Three Separate Attachments	*Few edges*	2
Long Switches/ LED	*No sharp edges*	4
Three Flat Semi-Notches	*Very few sharp edges*	3
Additional Bent Plate	*No sharp edges*	4

1) User Requirements

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Three Separate Attachments	*Can be used*	4
Long Switches/ LED	*Can be used*	4
Three Flat Semi-Notches	*Can be used*	4
Additional Bent Plate	*Can be used*	4

2) Component Material Properties

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Three Separate Attachments	*High Impulsive load resistant*	4
Long Switches/ LED	*Very Low Impulsive load resistant*	2
Three Flat Semi-Notches	*High Impulsive load resistant*	4
Additional Bent Plate	*High Impulsive load resistant*	4

3) Quality of Means during Use

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Three Separate Attachments	*Three small size plates required*	2
Long Switches/ LED	*No additional item required*	4
Three Flat Semi-Notches	*No additional item required*	4
Additional Bent Plate	*One big size bent plate required*	1

4) Pre-Production Requirement

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Three Separate Attachments	*Double 90° bending as well as assembly of three plates with base plate*	1
Long Switches/ LED	*Long Switches and Long LED required*	3
Three Flat Semi-Notches	*Three flat semi notiches of different heights required*	3
Additional Bent Plate	*Bending of plate required*	4

5) Production Requirements

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Three Separate Attachments	*Deburring is required*	3
Long Switches/ LED	*No post processing requirement*	4
Three Flat Semi-Notches	*Deburring is required*	3
Additional Bent Plate	*No post processing requirement*	4

6) Post-Production Requirements

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Three Separate Attachments	*Low costly simple mechanical/hydraulic presses can be used to create bends bolting or soldering can be used to attach bends with base plate*	1
Long Switches/ LED	*No equipment required*	4
Three Flat Semi-Notches	*Low costly simple mechanical/hydraulic presses can be used to create notches*	2
Additional Bent Plate	*Low costly simple mechanical/hydraulic presses can be used to bend the plate*	3

7) Production Equipment Requirements

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Three Separate Attachments	*Can be used for any number of units*	4
Long Switches/ LED	*Can be used for any number of units*	4
Three Flat Semi-Notches	*Can be used for any number of units*	4
Additional Bent Plate	*Can be used for any number of units*	4

8) Quantity of Product Required

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Three Separate Attachments	*Can be used for very low production rate*	1
Long Switches/ LED	*Can be used for high production rate*	4
Three Flat Semi-Notches	*Can be used for medium production rate*	3
Additional Bent Plate	*Can be used for low production rate*	2

9) Achievable Production Rate of Means

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Three Separate Attachments	*No inspection techniques are available*	4
Long Switches/ LED	*No inspection techniques are available*	4
Three Flat Semi-Notches	*No inspection techniques are available*	4
Additional Bent Plate	*No inspection techniques are available*	4

10) Degreee of Available Quality Assurance Techniques

Table 6-1: Context information generated under different categories of context knowledge for mounting of LED/PCB switch panel on sheet metal casing

6.3.2 Relative Weighting and Numerical Rating

The relative weighting among ten-design knowledge criteria (preference of one criterion over other) can be done by giving percentage weighting out of 100 for each of the categories. Assignment of relative weighting depends upon different factors like cost consideration, designer's preference, and company policy. For example some companies prefer a low cost product thus compromising the quality of the product. In this case study the relative preferred weightings by the designer are shown in Table 6-2. The highest weighting factor (35%) is given to *Quality of Means During Use* category because it is important that the selected solution continuously gives good performance during the repeated use of the power on/off and reset buttons. The second (20%) and third (15%) higher weightings are given to *Pre-Production Requirement and Production Requirement* categories. This decision is taken to reduce the number of components and the complexity of component features, thereby reducing the overall cost and lead time.

No.	***Criterion***	***Weighting factor %***
1	User Requirement	**2.5**
2	Component Material Properties	**2.5**
3	Quality of Means During Use	**35**
4	Pre-Production Requirement	**20**
5	Production Requirement	**15**
6	Post Production Requirement	**5**
7	Production Equipment Requirement/Cost	**10**
8	Quantity of Product Required	**2.5**
9	Achievable Production Rate of Selected Means	**5**
10	Degree of Available Quality Assurance Techniques	**2.5**
	Total	**100**

Table 6-2: Relative weighting of criterion categories

The assignment of the numerical rating to each of the design alternatives under each context knowledge criterion category is done by the converting degree of suitability of each alternative described in the previous section into a weighting factor. This is done by using the comparison scales defined in a decision making theory named Analytic Hierarchy Process (AHP). AHP is a method that arranges all decisions factors in a hierarchical structure, which descends from an overall goal to criteria, sub-criteria and finally to the alternatives, in successive levels. The decision maker is required to create matrices for the pair-wise comparisons for the different alternatives' performances using conversion scales against each criterion. These scales as previously shown in Figure 6-17 are shown in Figure 6-20.

1: Both criteria of equal importance	
3: Left weakly more important than top	***1/3: Top weakly more important than left***
5: Left moderately more important than top	***1/5: Top moderately more important than left***
7: Left strongly more important than top	***1/7: Top strongly more important than left***
9: Left absolutely more important than top	***1/9: Top absolutely more important than left***

Figure 6-20: Comparison scales to convert degree of suitability

On the basis of these scales and degree of suitability, matrices are generated for all the ten categories of context knowledge and these matrices are shown in Table 6-3 and Table 6-4.

Rating of Alternatives on User Requirement (Specific Age Group/Gender)

ALTERNATIVES	Three Separate Attachments	Long Switches/LED	Three Flat Semi Notches	Additional Bent Plate
Three Separate Attachments	1	1/5	1/3	1/5
Long Switches/LED	5	1	3	1
Three Flat Semi Notches	3	1/3	1	1/3
Additional Bent Plate	5	1	3	1

ALTERNATIVES	Three Separate Attachments	Long Switches/LED	Three Flat Semi Notches	Additional Bent Plate	Average %
Three Separate Attachments	0.071	0.079	0.045	0.079	6.9
Long Switches/LED	0.357	0.395	0.409	0.395	38.9
Three Flat Semi Notches	0.214	0.132	0.136	0.132	15.3
Additional Bent Plate	0.357	0.395	0.409	0.395	38.9

{0.357=5/(1+5+3+5)}

Rating of Alternatives on Component Material Properties

ALTERNATIVES	Three Separate Attachments	Long Switches/LED	Three Flat Semi Notches	Additional Bent Plate
Three Separate Attachments	1	1	1	1
Long Switches/LED	1	1	1	1
Three Flat Semi Notches	1	1	1	1
Additional Bent Plate	1	1	1	1

ALTERNATIVES	Three Separate Attachments	Long Switches/LED	Three Flat Semi Notches	Additional Bent Plate	Average %
Three Separate Attachments	0.250	0.250	0.250	0.250	25.0
Long Switches/LED	0.250	0.250	0.250	0.250	25.0
Three Flat Semi Notches	0.250	0.250	0.250	0.250	25.0
Additional Bent Plate	0.250	0.250	0.250	0.250	25.0

Rating of Alternatives on Quality of Means During Use (Degree of Fulfilling Intended Function in Different Conditions)

ALTERNATIVES	Three Separate Attachments	Long Switches/LED	Three Flat Semi Notches	Additional Bent Plate
Three Separate Attachments	1	5	1	1
Long Switches/LED	1/5	1	1/5	1/5
Three Flat Semi Notches	1	5	1	1
Additional Bent Plate	1	5	1	1

ALTERNATIVES	Three Separate Attachments	Long Switches/LED	Three Flat Semi Notches	Additional Bent Plate	Average %
Three Separate Attachments	0.313	0.313	0.313	0.313	31.3
Long Switches/LED	0.063	0.063	0.063	0.063	6.3
Three Flat Semi Notches	0.313	0.313	0.313	0.313	31.3
Additional Bent Plate	0.313	0.313	0.313	0.313	31.3

Rating of Alternatives on Pre-Production Requirement {Preparation of Component(s)}

ALTERNATIVES	Three Separate Attachments	Long Switches/LED	Three Flat Semi Notches	Additional Bent Plate
Three Separate Attachments	1	1/5	1/5	3
Long Switches/LED	5	1	1	7
Three Flat Semi Notches	5	1	1	7
Additional Bent Plate	1/3	1/7	1/7	1

ALTERNATIVES	Three Separate Attachments	Long Switches/LED	Three Flat Semi Notches	Additional Bent Plate	Average %
Three Separate Attachments	0.088	0.085	0.085	0.167	10.6
Long Switches/LED	0.441	0.427	0.427	0.389	42.1
Three Flat Semi Notches	0.441	0.427	0.427	0.389	42.1
Additional Bent Plate	0.029	0.061	0.061	0.056	5.2

Table 6-3: Relative rating of four design alternatives against different context knowledge categories

Rating of Alternatives on Production Requirement

ALTERNATIVES	Three Separate Attachments	Switches/LED	Semi Notches	Additional Bent Plate
Three Separate Attachments	1	1/5	1/5	1/7
Long Switches/LED	5	1	1	1/3
Three Flat Semi Notches	5	1	1	1/3
Additional Bent Plate	7	3	3	1

ALTERNATIVES	Three Separate Attachments	Switches/ LED	Semi Notches	Additional Bent Plate	Average %
Three Separate Attachments	0.056	0.038	0.038	0.079	5.3
Long Switches/LED	0.278	0.192	0.192	0.184	21.2
Three Flat Semi Notches	0.278	0.192	0.192	0.184	21.2
Additional Bent Plate	0.389	0.577	0.577	0.553	52.4

Rating of Alternatives on Post Production Requirement {Special Process(s) Required}

ALTERNATIVES	Three Separate Attachments	Long Switches/LED	Three Flat Semi Notches	Additional Bent Plate
Three Separate Attachments	1	1/3	1	1/3
Long Switches/LED	3	1	3	1
Three Flat Semi Notches	1	1/3	1	1/3
Additional Bent Plate	3	1	3	1

ALTERNATIVES	Three Separate Attachments	Long Switches/ LED	Three Flat Semi Notches	Additional Bent Plate	Average %
Three Separate Attachments	0.125	0.125	0.125	0.125	12.5
Long Switches/LED	0.375	0.375	0.375	0.375	37.5
Three Flat Semi Notches	0.125	0.125	0.125	0.125	12.5
Additional Bent Plate	0.375	0.375	0.375	0.375	37.5

Rating of Alternatives on Production Equipment Requirement/Cost (Tooling/Machine Cost Required)

ALTERNATIVES	Three Separate Attachments	Long Switches/LED	Three Flat Semi Notches	Additional Bent Plate
Three Separate Attachments	1	1/7	1/3	1/5
Long Switches/LED	7	1	5	3
Three Flat Semi Notches	3	1/5	1	1/3
Additional Bent Plate	5	1/3	3	1

ALTERNATIVES	Three Separate Attachments	Long Switches/ LED	Three Flat Semi Notches	Additional Bent Plate	Average %
Three Separate Attachments	0.063	0.085	0.036	0.044	5.7
Long Switches/LED	0.438	0.597	0.536	0.662	55.8
Three Flat Semi Notches	0.188	0.119	0.107	0.074	12.2
Additional Bent Plate	0.313	0.199	0.321	0.221	26.3

Rating of Alternatives on Quantity of Product Required

ALTERNATIVES	Three Separate Attachments	Long Switches/LED	Three Flat Semi Notches	Additional Bent Plate
Three Separate Attachments	1	1	1	1
Long Switches/LED	1	1	1	1
Three Flat Semi Notches	1	1	1	1
Additional Bent Plate	1	1	1	1

ALTERNATIVES	Three Separate Attachments	Long Switches/ LED	Three Flat Semi Notches	Additional Bent Plate	Average %
Three Separate Attachments	0.250	0.250	0.250	0.250	25.0
Long Switches/LED	0.250	0.250	0.250	0.250	25.0
Three Flat Semi Notches	0.250	0.250	0.250	0.250	25.0
Additional Bent Plate	0.250	0.250	0.250	0.250	25.0

Rating of Alternatives on Achievable Production Rate of Selected Means

ALTERNATIVES	Three Separate Attachments	Long Switches/LED	Three Flat Semi Notches	Additional Bent Plate
Three Separate Attachments	1	1/7	1/5	1/3
Long Switches/LED	7	1	3	5
Three Flat Semi Notches	5	1/3	1	3
Additional Bent Plate	3	1/5	1/3	1

ALTERNATIVES	Three Separate Attachments	Long Switches/ LED	Three Flat Semi Notches	Additional Bent Plate	Average %
Three Separate Attachments	0.063	0.085	0.044	0.036	5.7
Long Switches/LED	0.438	0.597	0.662	0.536	55.8
Three Flat Semi Notches	0.313	0.199	0.221	0.321	26.3
Additional Bent Plate	0.188	0.119	0.074	0.107	12.2

Rating of Alternatives on Degree of Available Quality Assurance Techniques

ALTERNATIVES	Three Separate Attachments	Long Switches/LED	Three Flat Semi Notches	Additional Bent Plate
Three Separate Attachments	1	1	1	1
Long Switches/LED	1	1	1	1
Three Flat Semi Notches	1	1	1	1
Additional Bent Plate	1	1	1	1

ALTERNATIVES	Three Separate Attachments	Long Switches/ LED	Three Flat Semi Notches	Additional Bent Plate	Average %
Three Separate Attachments	0.250	0.250	0.250	0.250	25.0
Long Switches/LED	0.250	0.250	0.250	0.250	25.0
Three Flat Semi Notches	0.250	0.250	0.250	0.250	25.0
Additional Bent Plate	0.250	0.250	0.250	0.250	25.0

Table 6-4: Relative rating of four design alternatives against different context knowledge categories

6.3.3 Selection of the Best PDE/Design Solution

After determining relative weighting of each criteria and the numerical rating of the different alternatives, the final task in this case study is to find the best design solution/alternative out of these four alternatives *(Three Separate Attachments, Long Switches/LED, Three Flat Semi-Notches, Additional Bent Plate,).* The calculation of best alternative is shown below in Table 6-5. The table shows that the highest added normalized value of 2797.3 for *Three Flat Semi-Notches* and hence ***Three Flat Semi-Notches*** is considered the best alternative out of four alternatives proposed in order to provide *Curved Access* of LED/switch PCB panel to the cover of workstations.

{17.3=2.5x6.9}

No.	CRITERIA	WEIGHTING (%)	RATING OF SUITABILITIY OF ALTERNATIVES (%)							
			THREE SEPARATE ATTACHMENTS		LONG SWITCHES/ LED		THREE FLAT SEMI NOTCHES		ADDITIONAL BENT PLATE	
1	User Requirement	2.5	6.9	17.3	38.9	97.3	15.3	38.3	38.9	97.3
2	Component Material Properties	2.5	25.0	62.5	25.0	62.5	25.0	62.5	25.0	62.5
3	Quality of Means During Use	35	31.3	1095.5	6.3	220.5	31.3	1095.5	31.3	1095.5
4	Pre-Production Requirement	20	10.6	212.0	42.1	842.0	42.1	842.0	5.2	104.0
5	Production Requirement	15	5.3	79.5	21.2	318.0	21.2	318.0	52.4	786.0
6	Post Production Requirement	5	12.5	62.5	37.5	187.5	12.5	62.5	37.5	187.5
7	Production Equipment Requirement	10	5.7	57.0	55.8	558.0	12.2	122.0	26.3	263.0
8	Quantity of Product Required	2.5	25.0	62.5	25.0	62.5	25.0	62.5	25.0	62.5
9	Achievable Production Rate of Selected Means	5	5.7	28.5	55.8	279.0	26.3	131.5	12.2	61.0
10	Degree of Available Quality Assurance Techniques	2.5	25.0	62.5	25.0	62.5	25.0	62.5	25.0	62.5
	Added Normalizd Values for Each Alternative	***100.0***		***1739.8***		***2689.8***		***2797.3***		***2781.8***

{1739.8=Column Sum}

Table 6-5: Evaluation of alternatives according to AHP method

It has been observed that the current design used by the manufacturer of the desktop computer station considered in this case study to provide curved access is also the same (i.e. Three flat semi notches). LED/switch PCB panel is attached on the surface of these notches with the help of adhesive as shown in Figure 6-21.

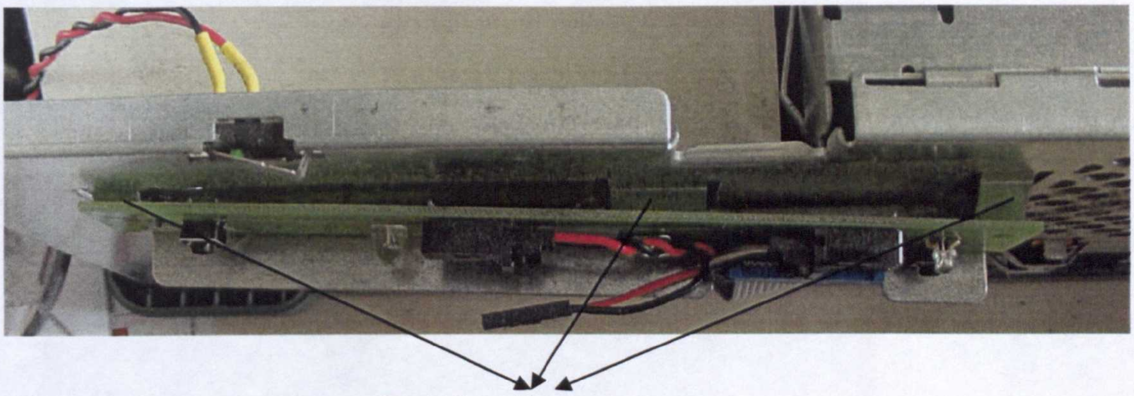


Figure 6-21: Current design of attaching LED plate with base plate of workstation

The case study has demonstrated that providing timely information to the designer about the design context information/consequences enables the designer in proactive decision making by selecting those solutions/PDEs, which have less preferred problematic consequences in the preferred design context knowledge categories.

6.4 Other Case Studies

Some more paper based case studies have been undertaken to illustrate the working of the Function to PDE mapping model in other mechanical design domains in addition to the previous example. They are illustrated in Appendix-E. The following sub sections give the summary of these case studies and illustrates that the conclusions drawn verify the Function to PDE mapping model, which has been successfully applied in different design domains/problems.

6.4.1 Case Study No. 1

The first case study has been developed by Mr. Arnaud Langle (an exchange undergraduate student from University of Technology Troyes, France) under the supervision of the author. It is an extensive case study related to the automotive sector. This case study reviews "car door" design using the proposed approach. The study investigates different functions performed by the car door such as *Accessibility, Provide Protection, Rust Resistant and Provide Comfort*. Detailed decomposition of these primary functions as well as possible solution means/PDEs are also highlighted and investigated in the exercise. A car door panel *material selection* problem is taken as a *functional requirement* to be fulfilled. Four types of materials namely *Conventional steel, Ultra light steel, Aluminium and SMC Composite* are considered in this case study as possible solutions, which are currently used in practice by different automotive companies to manufacture car doors.

Four context knowledge categories mentioned in section 5.3.2, 5.3.3, 5.3.5, 5.3.9 and three additional categories named as *Door cost*, *Complex sheet adaptability* and *Ease of recycling* are considered important and relevant to this decision making problem. Context knowledge is generated within these seven categories and the information exhibited in these categories is collected from literature and different Internet websites. After assigning degrees of suitability, based on the context knowledge consequences, relative ratings of four types of materials in terms of percentage weighting are calculated using AHP rules. The designer's preference in terms of percentage weighting is determined based on two view points (i.e. *customer and carmaker*) as both are of equal importance. After calculating the highest added normalized value, the best material from the *customer's* point of view is *SMC Composite.* While customers accord high priority to cost, safety, performance of the material and complex shape of design adaptability, they express no priority to the properties of the materials used, the easiness in manufacturing the doors and the achievable production rate. However, a moderate preference is accorded to weight and ease in recycling of material.

After similar calculations, the best material from a *carmaker's* point of view is *Ultra Light Steel.* In this case, car door manufacturer give high priority to the cost of the manufacturing process, ease of manufacturing, the achievable production rate, safety, rust resistance and ease in recycling of material. However, a moderate preference is accorded to weight, light impact resistance and complex shape of design adaptability by car manufacturers.

In another design scenario, the designer's preference is changed by considering the *"weight"* of the door as the most important factor from the *car-maker's* view point.

Based on this preference, *Aluminium* emerges as the best solution. Weight is considered to be as an important factor due to its impact on fuel consumption i.e. greater the weight, higher the fuel consumption, which in turn poses environmental concerns.

The designer's preferences can be changed for racing car design. In this case, the focus of the design consideration is on the performance of the car, implying that the car must be light in weight and at the same time should possess high power with good manoeuvrability. This result shows that *SMC composite* is the best material for car door panels in racing cars. Finally a comparison of results obtained from this case study with the actual material used by car makers in the door panels of different cars is given, which shows that in two out of three cases, material used currently in the car industry is the same as the one selected by this case study. However, in the third case, the material selected is *"Ultra Light Steel"* which contradicts the one used by car makers currently i.e. conventional steel. The reason for the use of *"Conventional Steel"* in the car industry as against the proposed *"Ultra Light Steel"* can be explained by the fact that the latter is relatively a new material and that car makers have already invested large capital and time in their production lines and therefore they are not willing to make any new investment to use this new type of material [ULSAC, 2000].

This case study leads to the conclusion that the designer can have different preferences from varying view points, which can be represented by creating different templates of preferences. This indicates the flexibility that the designer has during the process of decision making so as to achieve the best solution against each selected template.

6.4.2 Case Study No. 2

The second case study in Appendix-E relates to the structural elements design domain. The functional requirement is *"Support Uniformly Distributed Load Along Length of Beam"*. Five possible beams named as *Rolled I Beam, Fabricated I Beam, Fabricated Hollow Girder, Staggered Web Beam, Rolled Channel Beam* each having different cross section are presented as the initial generated solutions. The same ten categories of context knowledge as mentioned in section 5.3 are used to explore the context knowledge/information and corresponding consequences across different life cycle phases. Degrees of suitability are assigned to each alternative beam type based on the generation of good/problematic consequences and are converted to relative percentage weighting using AHP rules. The designer's preference is given in terms of percentage weighting to ten context knowledge categories with more preference given to *pre production, production and functional requirements* categories. The highest added normalized value suggests *Rolled I-Beam* as the best solution for the desired functional requirement.

This case study concludes that the Function to PDE mapping model can be successfully applied in structural elements design domain in addition to sheet metal design domain.

6.4.3 Case Study No. 3

The third case study, mentioned in the Appendix-E, is within the sheet metal domain and investigates the functional requirement for the supporting of storage media in a drive bay of a desktop computer. Therefore the functional requirements are defined as *"Supporting Storage Device in Computer Drive Bay"*. The conceptual design solutions generated are:

- *Eight 90^0 Bends* solution includes eight notches (four on each side) bent at ninety degrees along the depth of drive bay to support the storage device in the rectangular hollow drive bay.
- *Four Screw-Slot Assemblies* implies that four rectangular slots (two on each side) are stamped along the length of the drive bay, so as to enable fixing the storage device with the drive bay using four screws.
- *Four 90^0 Bends and Two Screw Slot Assemblies implies* that four notches bent at 90^0 opposite to each other and two rectangular slots stamped opposite to each other on the walls of the drive bay.

- *Four Lance Fit Assemblies* require four rectangular slots (two on each side) of the wall. A storage device with four lances stamped to its sides can be inserted using push fit into these slots.

The same ten categories of context knowledge as mentioned in section 5.3 are used to explore the context knowledge/information and corresponding consequences across different life cycle phases and other categories. The designer's preference is indicated in terms of percentage weighting with highest preference to *Quality of Means during Use (i.e. Degree of Fulfilling Intended Function in Different Conditions)* because of continuous/frequent running of motor in the storage device which affects the assembly of storage device in the drive bay, along with *Functional Requirements* and *Production Equipment Requirements* as second and third higher preferences. The best solution presented in this case study is *Eight* 90^0 *Bends.*

This case study reiterates the successful application of the Function to PDE mapping model in the selected sheet metal design domain.

6.4.4 Case Study No. 4

The final case study in the appendix highlights the applicability of the proposed Function to PDE mapping model to the machined component design problem by selecting the functional requirement of *"Convert Motion"* for investigation. The function is further decomposed into three functions and the function taken up for further investigation is "*Convert Rotary Motion into Translatory Motion*". Four solutions named as *Rack and Pinion Assembly*, *Belt and Pulley Assembly*, *Lead Screw Assembly* and *Cam and Follower Assembly* are generated as conceptual design alternatives. Five generic context knowledge categories from sections 5.3.1, 5.3.3, 5.3.4, 5.3.5, 5.3.6 and two more categories named as *Moving Load's Properties* and *Angle of Load Transportation* are considered to be important and relevant to this decision making problem. After assigning degrees of suitability based on generated context knowledge consequences, designer's preference is indicated in terms of percentage weighting to all the seven context knowledge categories with the highest preference accorded to functional requirements category, which includes (speed of moving load, weight of load, accuracy and distance of travel). The best solution presented in this case study is *Lead Screw Assembly*.

This case study concludes that the context knowledge categories presented in section 5.3 are generic in nature. However, some additional categories required for a specific domain need to be included alongside the generic categories in order to enable effective decision making.

6.4.5 Conclusions of Case Studies

- The case studies presented in this section demonstrate the successful application of the Function to PDE mapping model as a generic model. This can provide proactive decision support at the conceptual design stage across different design domains such as sheet metal components, machined components, structural elements and composites within mechanical engineering.

- The Function to PDE mapping model not only provides proactive decision support by generating and highlighting design decision consequences but also performs decision making by selecting the best solution among different alternatives.

- The context knowledge categories presented in section 5.3 are generic in nature and application as most of these categories are used in all the case studies. However, some more categories need to be included or excluded (i.e. as shown in case studies 1 and 4) so as to explore the context knowledge depending upon the domain and design problem under consideration.

- The developed approach in the Function to PDE mapping model provides flexibility to designers to indicate their preferences from different viewpoints (as illustrated in case study 1, i.e. from four different viewpoints). This demonstrates the role of the designer's authority and the flexibility present during the decision making process, whereby by creating a set of different templates from different viewpoints and indicating different preferences to context knowledge categories, different best solution alternatives corresponding to each template of preferences could be derived.

6.5 Chapter Summary

This chapter presented the development of the Function to Means mapping model. Product design elements (PDEs) are presented as solution means to functional requirements in the metal component design domain. The reasoning process illustrates the importance of the design context knowledge and its usefulness in supporting proactive decision making during the Function to PDE mapping process (i.e. at the conceptual design stage). Based on the reasoning mechanism, a generic design context knowledge based Function to PDE mapping model is proposed to support decision making at the conceptual design stage, which is explained by using a design example. The case studies presented highlight the successful application of the Function to PDE mapping model to provide a proactive decision support at the conceptual design stage across different mechanical engineering design domains. As argued in the main case study example, there could be n-number of consequences generated during the function to PDE reasoning and mapping process and as human beings have limited capacity to reason and remember a large number of consequences, therefore this model needs to be implemented as a computer based prototype system, which is illustrated in the next chapter.

7 Prototype Implementation

This chapter discusses the implementation of a Function to PDE mapping model to develop a computer based prototype system, which supports decision making at the conceptual design stage. The first section of the chapter highlights critical issues in prototype implementation such as the need for implementation and selection of the engineering design domain. The second section discusses about the expected functionalities that are required from the system followed by a discussion on the reasoning for selection of the hardware and software platforms. The third section discusses about the system development requirements followed by a discussion on the proposed system architecture in the fourth section. As part of this PhD research effort, the final section discusses the level of implementation achieved of the proposed architecture while developing the different modules and the functionalities within the prototype system.

7.1 Implementation Issues

Multiple interacting and non-interacting, good and bad consequences can be revealed and highlighted in order to support the designer's decision making process through the use of the reasoning mechanism. The reasoning mechanism can truthfully reveal violations of design principles and their causes so that designers can make informed decisions based on the assigned degrees of suitability of a solution against different context knowledge categories. This approach still gives designers freedom to make final decisions based on their preferences. It is a huge task to reason functional requirements and generated information manually under different context knowledge categories simultaneously for different PDEs/solutions. Moreover manual analysis and evaluation of different consequences generated by reasoning is also quite arduous. Therefore a computer-based environment is the most appropriate solution for this task and the proposed Function to PDE mapping model has been implemented in a computer-based prototype system called *PROCONDES* (Pro-Active Conceptual Design) [Rehman and Yan, 2004a] in this research.

electrical control enclosures (Figure 7-2) *etc.* These functions are achieved through different *manufacturing features*, which are inscribed on the metal sheet during the manufacturing process.

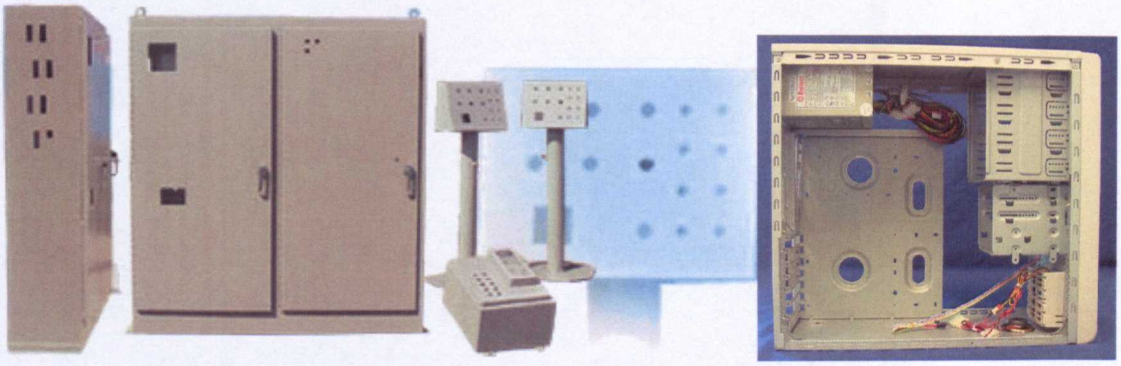


Figure 7-2: An example of industrial sheet metal products

7.2 Expected Functionalities of the Prototype System

The proposed functionalities of the prototype system are explained in the following sub sections.

7.2.1 User Interface

A good software system must be user friendly and must contain all relevant menu bars/icons/tool bars so that the user can choose easily from the available options. An adequate 'Help' function must be incorporated that allows the user to take a quick tour of the entire package thereby providing an overall idea of the package. Good textual/graphical user interface is a must for easy usage of the software. Solutions/PDEs generated during the conceptual design process should be displayed in detail both in textual as well as three dimensional graphical form together with necessary facilities like zoom, lighting, pan etc., so that the solution can be viewed easily and in detail from every aspect.

7.2.2 Context Knowledge Management

The proposed system should be able to represent context knowledge by taking input from the user/designer both in textual and graphical form (if required) as well as

7.1.1 Engineering Design Domain of Prototype Implementation

As the Function to PDE mapping model presented in Chapter 6 is generic in nature, it can be successfully applied to different design domains in mechanical engineering as shown in the paper based case studies. However, due to time constraints in coding, only the sheet metal engineering design domain has been selected to develop a computer based prototype system.

The application of sheet metal forming technology results in a wide range of sheet metal products, covering areas of automotive and aerospace on one end of the spectrum to computer casings and electronic circuitry housings on the other. The term sheet metal normally refers to a metal strip with a thickness ranging from 0.3 mm to 5mm. Sheet metal products are made up of different types of materials such as ferrous, non-ferrous and alloys. The common functions of sheet metal products are either of conveyance nature or assembly nature. For example, in the case of conveyance nature functions, the commonly used functions are to *convey, channel, direct, divide, guide*, etc. Various sheet metal residential & commercial products perform these types of functions such as those found in *Air Intakes, Dormer Vents, Static Louvers, Roof Vents, and Ducts* (Figure 7-1) etc.

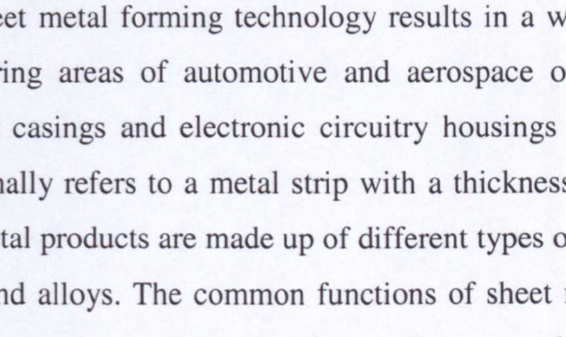


Figure 7-1: An example of residential sheet metal products

In the case of assembly type functions, the mostly commonly used functions are *assemble, constrain, enclose, fasten, fix, guide, join, link, locate, orient, position, support etc.* Industrial sheet metal products perform these types of functions [Rehman & Yan, 2002], which include *automotive body panels, computer casings,* displaying on request generated context knowledge under different categories for each conceptual design solution. The context knowledge should be adequately managed for easy storage, retrieval, modification and representation in textual form. The huge chunk of context knowledge should be reasoned in order to generate context knowledge consequences. Thus the proposed system should be able to perform reasoning as explained in the previous chapter.

7.2.3 Quantification of Designer's Preference

Designer's preference taken in the form of answers to certain questions should be quantified using Analytic Hierarchy Process decision making theory rules. The prototype system should be able to perform this process by taking designer's preference in a textual form and converting them into percentage weighting using decision making theory rules.

7.2.4 Decision Making

The software should be able to perform decision making and select the best/optimal design solution/PDE from a list of design alternatives using Analytic Hierarchy Process (AHP) decision making theory rules. The software should indicate why the given solution is presented as the best solution out of all the possible design alternatives.

7.3 System Development Requirements

A computer based software system requires the selection of an appropriate programming language (s) as well as a suitable hardware platform for its development and to adequately perform the required functionalities.

7.3.1 Selection of Programming Language

Selecting the right programming language is essential for the successful development of a system. The literature review carried out about different programming languages/packages suitable for the current research purposes is outlined below.

7.3.1.1 AutoLISP

AutoLISP [Sham, 1994] is based on *List in Processing* (LISP) programming language, which has been in existence for a long time. Though AutoLISP retains the syntax of LISP, it is streamlined to run inside AutoCAD and has many added functions so that it can interact with both the AutoCAD commands and the drawing database. An AutoLISP program can be written using any text editor and saved in a plain ASCII text file. This can then be loaded into the memory inside the AutoCAD program. Once loaded, the program can be run from the Command prompt or from a pull-down menu, just like any other AutoCAD command. The advantages of AutoLISP are:

- AutoLISP can perform advanced calculations.
- AutoLISP can interact with the user, prompting to get an input.
- AutoLISP can create entities in existing drawings, or even make complete drawings from scratch.
- AutoLISP can interact with the drawing database, performing both extraction and editing of information.
- AutoLISP can create, read, and revise files.

The disadvantages of AutoLISP are:

- AutoLISP programs can only be run within the AutoCAD environment.
- AutoLISP programs are difficult to debug, as the error messages are not comprehensive.
- AutoLISP is not an object-oriented language, but is a structured language.
- AutoLISP programs cannot be linked with external programs and databases.

7.3.1.2 Visual Basic

Microsoft Visual Basic development system is a productive tool for creating Windows and the Web based applications. Visual Basic is an object-oriented language, developed from BASIC, which was written by Microsoft. The user writes the program using a number of frames, into which the code is input and the frames are then linked together to form the whole program [Homes, 2003]. The advantages of Visual Basic are:

- It is easy to use and has a fairly comprehensive command set allowing the programmer to write programs for Microsoft Windows quickly and efficiently.
- One of the biggest advantages of Visual Basic is that it allows the programmer to quickly construct a user interface identical to the Windows interface.
- It is easy to learn and use.

The disadvantages of Visual Basic are:

- Visual Basic is not truly an object oriented language, because it displays problems of multiple inheritance of attributes.
- It has very poor graphical drawing capabilities.
- It cannot be interfaced with popular CAD tools.

7.3.1.3 Kappa PC

The KAPPA-PC application development system is a hybrid PC tool that combines critical technologies essential for the rapid development of low-cost, high-impact business applications and expert systems [Intellicorp, 1992]. The advantages of Kappa-PC are:

- Graphical application development can be performed using objects.
- It supports Windows Dynamic Data Exchange (DDE) and Dynamic-Link Libraries (DLL's).

- It uses compact code size and optimisation techniques for high performance.
- It uses efficient and consistent inheritance by reference of slots, values, methods, and slot options.
- It enables best performance through rules and object slots compiling into an inference network.
- It uses four powerful rule firing mechanisms i.e. depth-first, breadth-first, best-first, and selective.

The disadvantages are:

- It is appropriate only for symbolic reasoning and inadequate for performing mathematical functions.
- It is difficult to interface with CAD tools; external databases and other windows based applications.
- It is not possible to develop a stand-alone application that runs outside of the Kappa PC environment.

7.3.1.4 WxCLIPS

WxCLIPS is an extension of NASA's CLIPS expert system shell suitable for the windows environment. CLIPS provides a complete environment for the construction of rules and/or object based expert systems [Giarratano, 1998]. The advantages of WxCLIPS are:

- wxCLIPS provides a cohesive tool for handling a wide variety of knowledge, which support three different programming paradigms i.e. rule-based, frame-based and object-oriented.
- The standard version of wxCLIPS provides an interactive text oriented development as well as a windows environment, including debugging aids, on-line help, and an integrated editor.

- wxCLIPS includes a number of features to support the verification and validation of expert systems. This includes support for modular design and partitioning of a knowledge base, static and dynamic constraint checking of slot values and function arguments, and semantic analysis of rule patterns to determine if inconsistencies could prevent a rule from firing or generating an error.

The disadvantages are:

- wxCLIPS is not good for numerical reasoning. It does not have good mathematical functions.
- It is difficult to interface with popular CAD tools.
- wxCLIPS engine does not support backward chaining inference, which is useful for deep diagnostic procedures.
- wxCLIPS is an "empty" shell i.e. it does not include any predefined library of classes or rules.

7.3.1.5 Visual C++

Microsoft Visual C++ is the most productive object oriented C++ tool for creating the highest performance applications for Windows and the Web. Nearly all world-class software, ranging from the leading web browsers to mission critical corporate applications, are built using the C++ developing system. Visual C++ brings a new level of productivity to C++, without compromising on the flexibility, performance, or control [Sphar, 1999].

The advantages of Visual C++ are:

- It is powerful for use in programming DOS/Windows based applications.
- It provides a good user interface for the developed application.
- It is capable of developing applications, which can be integrated with all types of databases and popular CAD tools.

- It contains both object oriented and procedural programming techniques.

The disadvantages are:

- It is one of the most difficult languages to learn and program.

- It does not have good graphical functions/representations.

7.3.1.6 Open CASCADE Libraries

The Open CASCADE [Open CASCADE, 2003] Object Libraries are object-oriented C++ class libraries designed for rapid production of sophisticated domain-specific design applications. Open CASCADE Technology is a software development platform freely available in open source. It includes components for 3D surface and solid modelling, visualization, data exchange and rapid application development.

Open CASCADE Technology can be best applied in the development of numerical simulation software including CAD/CAM/CAE/GIS and PDM applications. A typical application developed using Open CASCADE deals with two or three dimensional geometric modelling in specialised design/analysis applications or illustration tools.

The advantages of Open CASCADE are:

- It enables good graphical user interface.

- It facilitates creation of a number of primitives using pre developed libraries.

- It can be seamlessly integrated with C++.

The disadvantages of Open CASCADE are:

- It does not have procedural programming techniques.

- It can only be integrated with C++ programming language.

7.3.2 Criteria for the Selection of the Programming Language

The main criteria set for the selection of the programming language to develop the proposed system are outlined below:

- Programming language should have both object oriented and rule based techniques because context knowledge is classified into different categories/classes, whereas consequence knowledge is generated due to selection of different values of attributes associated with these features. A feature can easily be defined using object oriented programming technique i.e. selection of a class, and instantiation of an object of that class with unique value of attributes for the selected class.

- Programming language should also have good mathematical capabilities to perform quantification of designer's requirements into percentage weighting using AHP decision making theory rules

- It should facilitate the development of a good interactive user interface.

- It should have good debugging facilities.

- It should have good interface with other windows based applications/databases especially CAD systems.

- It should have facilities for both symbolic as well as numerical reasoning.

- It should be easy to develop the system as an additional module in an existing CAD system or provide for smooth and seamless integration with other CAD tools.

All requirements in the above mentioned criteria are essential to select the right programming language for the development of the prototype system as shown later in section 7.5.

7.4 PROCONDES System Architecture

Based on the proposed functionalities and working of different stages of Function to PDEs mapping model discussed in Chapter 6, a system architecture is proposed for the prototype system and is shown in Figure 7-3.

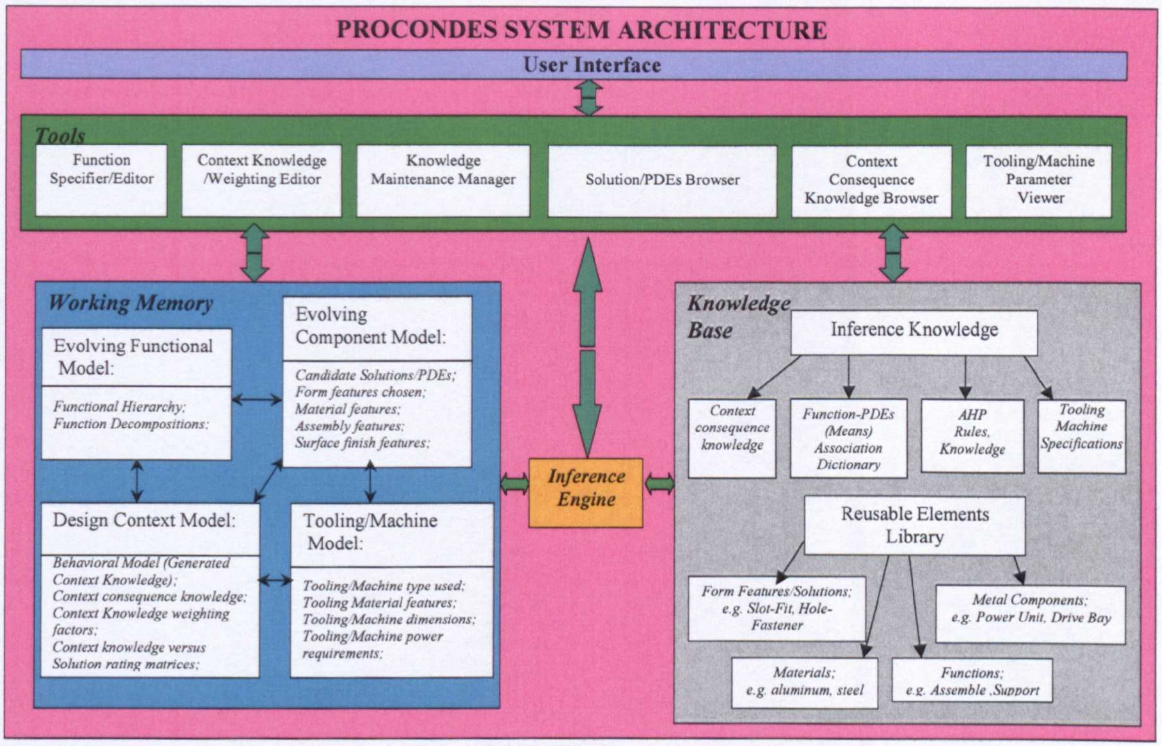


Figure 7-3: PROCONDES System Architecture

The main elements of the system architecture are described in the following subsections.

7.4.1 Knowledge Base

The *Knowledge base* contains detailed representation of the reusable element library. This library consists of different *solution elements* in the form of different *manufacturing features* like slot, hole, bend etc, different *material* elements used in sheet metal forming, different *industrial and commercial components* made up of sheet metal as well as different *functions* performed by the sheet metal products. The knowledge base further consists of Inference knowledge containing context design consequences knowledge, Function-PDEs association dictionary, AHP decision making rules and Tooling/Machine Specifications. Based on the understanding of the Manufacturing Consequences (MCs), it is possible to generate basic Machine and Tooling features from *Form* features of sheet metal component thus realising the concept of concurrent product and process design of sheet metal components [Rehman, 2000]. The process design involves the selection of the tool and the machine for the part to be manufactured.

7.4.2 Working Memory

Working Memory stores the resultant information about the different co-evolving models until the current stage of the design process at a given point in time. *Functional Model* is detailed in the form of function decomposition and a detailed functional hierarchy. *Context Model* consists of behavioural model (i.e. generated context knowledge), context consequences knowledge, and context knowledge weightings. *Component Model* consists of form, assembly, surface finish, material features etc of the selected solution components. Manufacturing life-phase model (tooling/machine model) derived from a concurrent synthesis of *Component Model* consists of tooling/machine type, dimensions, power consumption etc.

7.4.3 Inference Engine

The *Inference Engine* is the reasoning mechanism as explained in 6.2.4.1. It reasons the functions as well as the generated PDEs using rules of reasoning to elicit consequences. Rule based hybrid reasoning mechanism is proposed to represent the frame based context knowledge retrieval, which is stored in frames in the knowledge base in the form of *Functional, Component, and Design Context and Tooling/Machine* model.

7.4.4 Tools and User Interface

A set of tools has also been proposed to facilitate the communication between the user and the knowledge base. These include: a *Function Specifier/Editor* to select or change a desired function, *Solution/PDEs Browser* to visualise the generated solutions, a *Context Consequences Knowledge Browser* to display the probable consequences that would occur during the product development caused by the design decisions. Further, a *Context Knowledge Weighting Editor* is proposed to enable the designers to specify their weighting against different criteria, a *Tooling/Machine Parameter Viewer* to display the design parameters required to manufacture a form feature. These tools will be assessed by the designer through a user interface that contains menus, dialogue boxes, list controls, message boxes and icons.

7.5 Implementation of the System

Keeping in view the proposed functionalities required of the design decision support system, the author has chosen *Microsoft Visual C++ 6.0* [Sphar 1999] and *Open CASCADE* [Open CASCADE, 2003] for the purpose of the development of the computer based prototype system. This decision is based on the criteria for the selection as specified in section 7.3.2 and based on the review of the software engineering requirements [Sommerville, 1995]. Microsoft Visual C++ 6.0 has been adopted due to its open source architecture and its provision for easy knowledge maintenance. Open GL based Open CASCADE object libraries have been selected to provide easy interfacing to a CAD software system and to develop a good graphical user interface. The proposed architecture has been partially implemented in the PROCONDES prototype system on a Pentium 3 PC hardware platform, running the Windows 2000 (Professional) operating system. Some of the important features of the prototype system are shown in the following subsections.

7.5.1 Knowledge Representation

Different types of knowledge are represented and codified in the prototype system either in the form of *declarative* knowledge or *procedural* knowledge [Dym and Levitt, 1991]. Declarative knowledge is the representation of facts about objects, events and their relations. It is stored and represented in the system using Visual C++ class structure and relationships between different classes and their attributes in different Visual C++ data files.

An example of declarative knowledge could be

'Provide Support' is a type of Class *'Functions'*.

No Pre-Processing of components is required for Bolting Solution before Production.

Visual C++ supports object oriented technique for the representation of *declarative knowledge*. Objects have a uniform structure of attributes, which is very convenient for information maintenance. The hierarchical class structure of Visual C++ supports inheritance and data abstraction. Attributes of objects are represented by *data members* and *member functions.*

Procedural knowledge is concerned with knowledge that relates to *'what', 'when'* and *'how' to do*. Production rules are used normally to represent procedural knowledge in computer based implementation.

For example:

If *'Bolting'* is the solution then *Bolt and Nut* are required as *Additional Items* before production.

Procedural knowledge (DFX guidelines/rules and consequences) is represented by the IF-THEN facility of Visual C++.

7.5.2 Reasoning Mechanism

Rule based design context knowledge reasoning is performed in the PROCONDES system using the nested IF-THEN structure of the Microsoft Visual C++ language. The reasoning process elicits consequences caused by selecting a design solution. Degrees of suitability are assigned to each candidate design solution against different context knowledge categories based on the consequences generated.

7.5.2.1 Reasoning to Elicit Consequences

Design context knowledge consequences in each context knowledge category are elicited by reasoning knowledge/information generated due to the selection of a PDE design solution using the nested IF-THEN structure. The context knowledge consequences generated highlights the potential good and problematic implications of the selected solution. These consequences can be used to evaluate the impact of a solution on a particular life cycle phase of the product, the user of the product and the environment of the product.

An example of consequence is:

IF *'Bolting'* is selected as a solution then ***'Consequence'*** would be *'Retightening of nut and bolt'* is required as *'Post Manufacturing Operation'*.

IF *'Retightening of nut and bolt'* is required as *'Post Manufacturing Operation'* then ***'Consequence'*** would be *'Additional cost and time to perform this operation'*.

Implementation of the above mentioned generated consequences in the prototype system using Microsoft Visual C++ class, member function and data member structure is shown as follows:

if (str1 == "BOLTING" && str2 == "YES").

MessageBox ("Bolt, slotted nut and pin are required as additional items in this solution\n

This is violation of DFA principle as increase in number of parts\n

would increase cost of solution", "Consequences due to 'BOLTING' as solution").

Where *"str1"* is the data member (*Type of Solution*) of the '*Generated Solution List*' class and *"str2"* is the data member (*Additional Items Required For Solution*) of the *'Generated Context Knowledge'* class.

In this way, multiple interacting consequences are generated in the system by reasoning the selected design solution and the generated context knowledge under different context knowledge categories.

7.5.2.2 Reasoning to Assign Degrees of Suitability

As soon as these initial PDEs solutions are generated by the PROCONDES system, the context knowledge/information is generated regarding for every means/solutions in each one of the ten categories of the context knowledge. This information is analysed and compared by reasoning it with the context knowledge requirement for each design solution under each category. This is subsequently used to rate each design solution/means in terms of the degree of suitability for that particular context knowledge category as shown in figure 7-4. The scale and range of degrees of suitability set are as shown below:

Strength of Suitability	***Degree***
Absolutely High	5
Very High	4
High	3
Low	2
Very Low	1
Not suitable	0

An example of this could be:

IF *"Additional Items"* are *not* allowed in *"Pre production Context Knowledge Category"* and the selected design solution/PDE (Bolting) requires additional items (Nut, Bolt) THEN *"Degree of suitability assigned"* is ***'0'or 'Not Suitable'.***

This assignment is an indication of the suitability of a solution towards a particular context knowledge category against specific functional requirements.

7.5.3 User Interface of the PROCONDES System

The proposed set of tools in the system architecture has been implemented into the PROCONDES System by providing user interactive menus, dialogue boxes, message boxes, list controls and graphical display areas. The main window of PROCONDES prototype system is shown as screen dump in Figure 7-5.

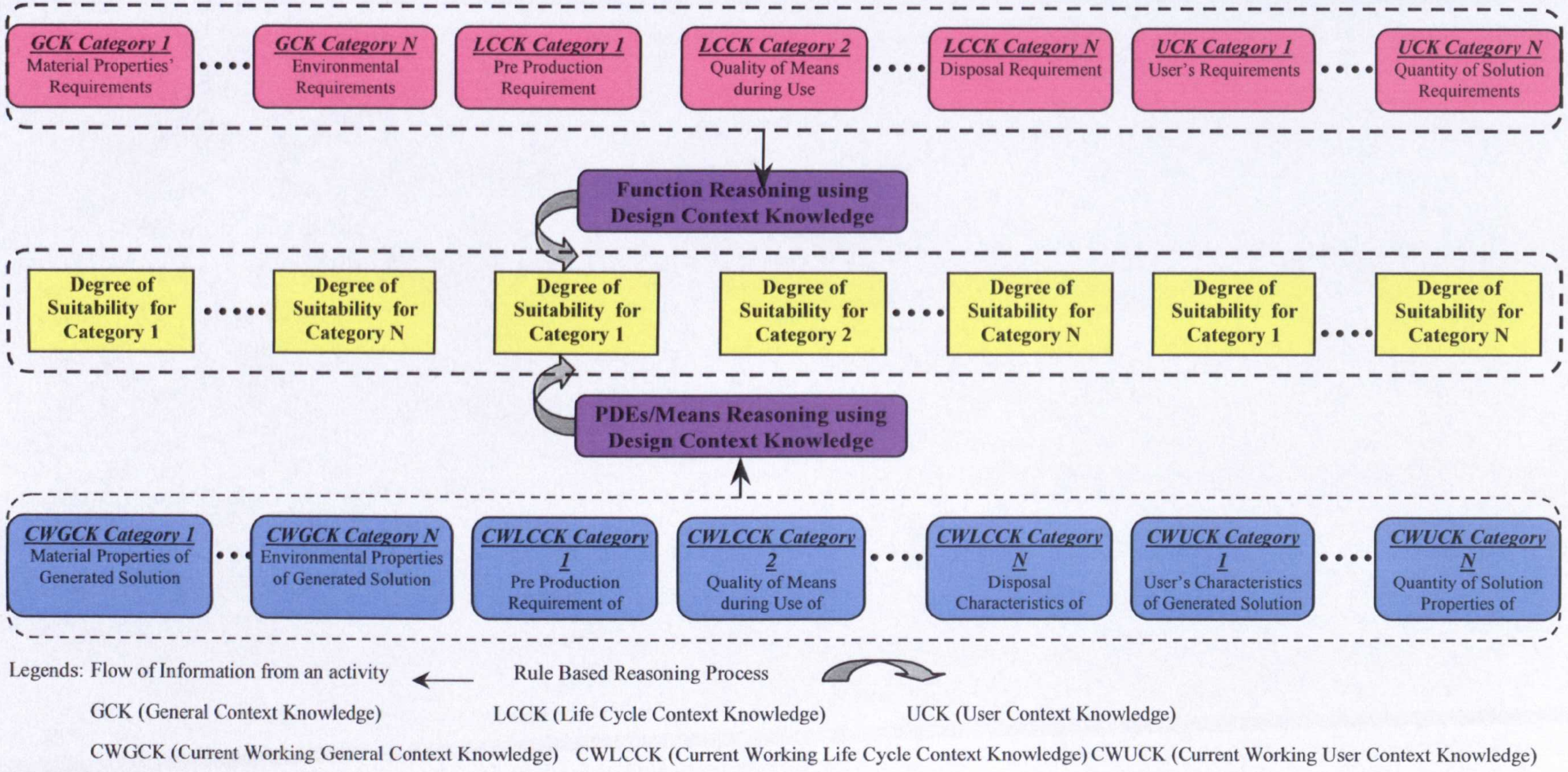


Figure 7-4: Reasoning Process to Assign Degrees of Suitability

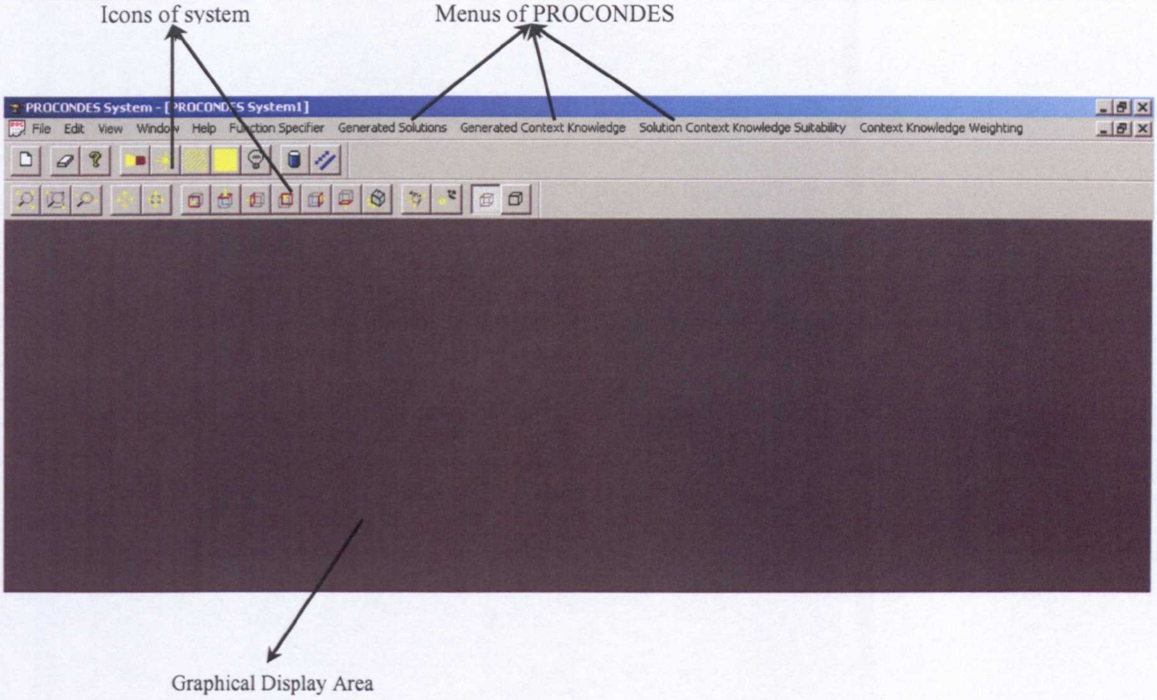
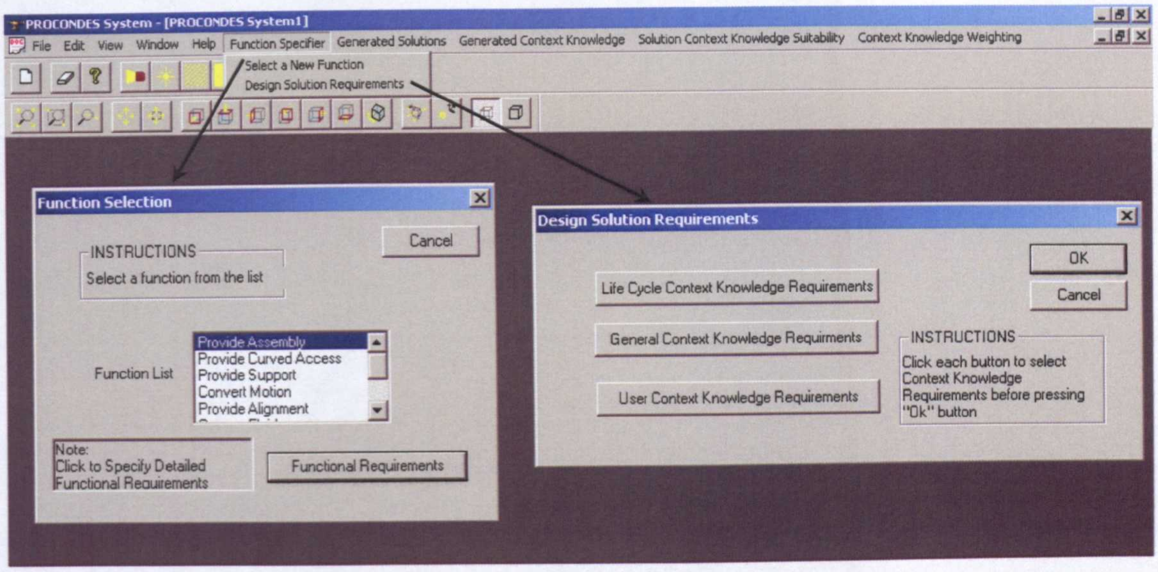


Figure 7-5: Screen dump of main windows of PROCONDES system

Subsequent dialogue boxes allowing user to select, input and manage knowledge/ information appear after pressing each menu item. For example *Function Specifier* allows the user to *'Select a New Function'* from the list of functions provided in the system. Once the function to be realized is selected, then the functional requirements can be input using the appropriate dialog box. *Design Solution Requirements* module allows the designer to input different requirements that are needed in a solution from three different perspectives i.e. life cycle, user related and general product related under different context knowledge categories as shown in Figure 7-6.

Similarly *Generated Context Knowledge* Menu displays three groups of context knowledge i.e. *'Life Cycle Context Knowledge', 'User Context Knowledge' and 'General Context Knowledge'* as shown in Figure 7-7. This enables designer to simultaneously browse through different pieces of information generated under different categories of context knowledge in order to compare different conceptual design solutions. There is a provision for checking consequences generated due to context knowledge so that a designer knows of the potential good or problematic implications/consequences associated with each piece of context knowledge.

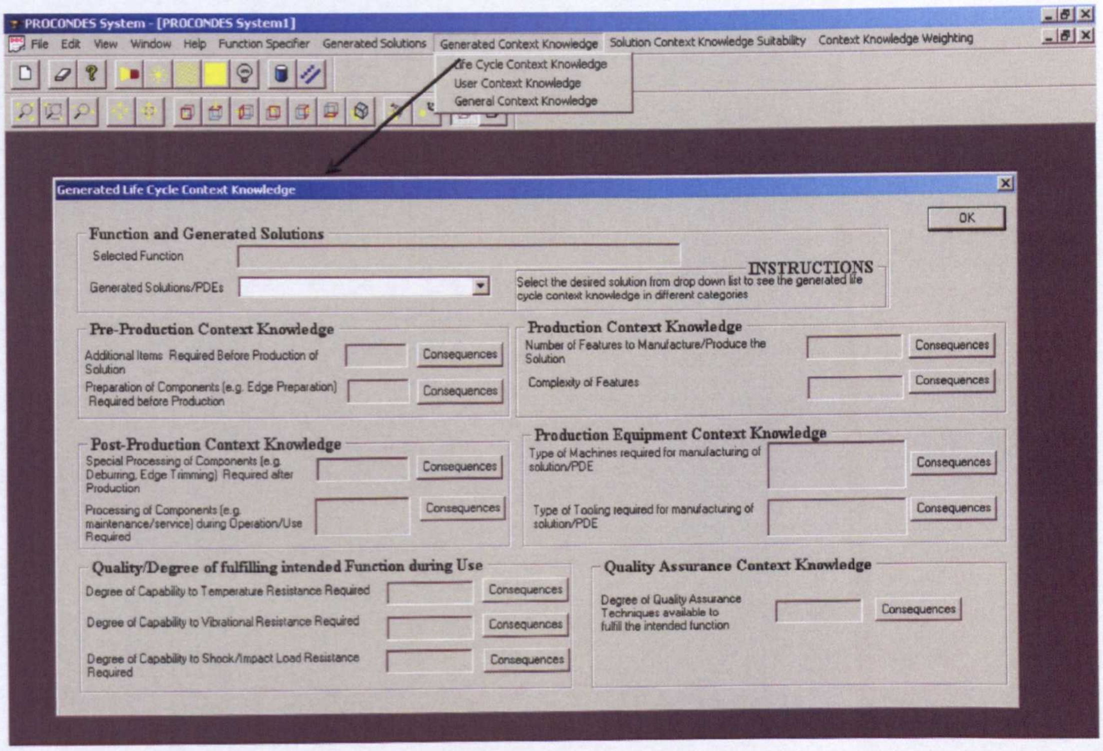


INSTRUCTIONS
Select a function from the list

Note:
Click to Specify Detailed Functional Requirements

INSTRUCTIONS
Click each button to select Context Knowledge Requirements before pressing "Ok" button

Figure 7-6: Screen dump of showing option selection of Function Specifier Menu



INSTRUCTIONS
Select the desired solution from drop down list to see the generated life cycle context knowledge in different categories

Figure 7-7: Screen dump of showing option selection of 'Generated Context Knowledge' Menu

The three dimensional graphical representation of the selected design solution is shown in the graphical area of PROCONDES system by using the '*Generate Solutions*' menu as shown in Figure 7-8.

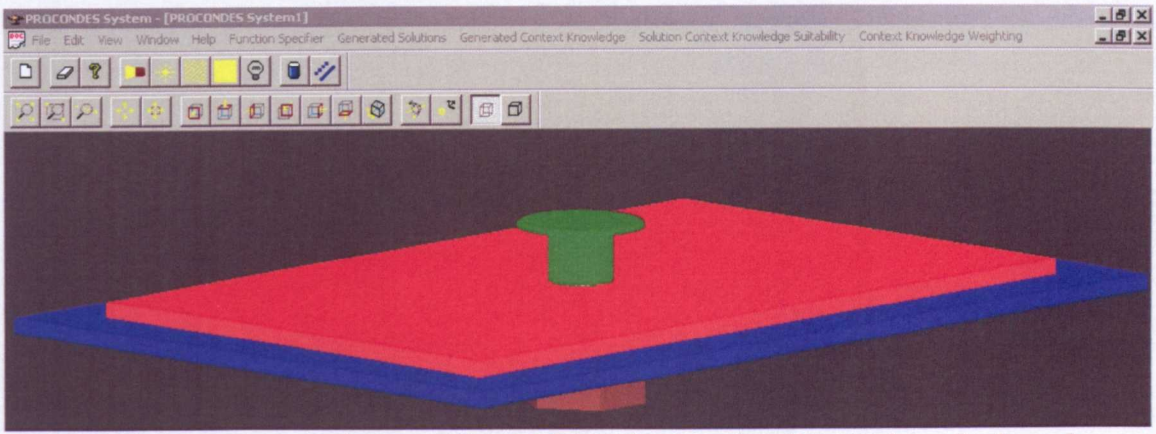


Figure 7-8: Screen dump of PROCONDES showing 3D display of selected solution

The degrees of suitability of a generated solution can be viewed on a scale of 1 to 5 under the *Suitability Indicator* module. These degrees of suitability are converted into percentage weighting using Analytic Hierarchy Process (AHP) rules and can be viewed using the *Context Knowledge Weighting* module. The designers can specify their own preferences in terms of percentage weighting to each context knowledge category. These preferences have an impact on the selection of the optimal design solution and are based on the designer's experience, market demands/trends and company policies.

7.5.4 Decision Making Process

The conceptual design decision making is performed by using different functionalities provided in the PROCONDES system in a particular sequence. This involves the following:

- Selection of a function and input/selection of detailed functional requirements.
- Input/selection of design solution requirements.

- Identification of the generated context knowledge and corresponding consequences.
- Assignment of degrees of suitability to selected design solutions and converting degrees of suitability into numerical rating/percentage weighting.
- Specification of designer's preference in percentage weighting.
- Calculation of the highest normalized value for the best solution.

The entire process of decision making using the PROCONDES system is shown as screen dumps in Appendix-F.

7.6 Chapter Summary

This chapter presents the implementation of the Function to PDE mapping model to develop a computer based prototype system named as PROCONDES. The implementation issues regarding representation/management of the context knowledge under different categories as well as display of the evolving conceptual design solutions/PDEs have been discussed. Different modules in the system architecture are presented to enable understanding about the functionality and application of the developed model. The next chapter presents the evaluation of PROCONDES as well as the overall Function to PDE mapping model using a case study.

8 Design Context Knowledge Based Decision Making Model and System Evaluation

This chapter evaluates the Function to PDE mapping model as well as the subsequent PROCONDES system. The first section elaborates the approach adopted for the evaluation. The second section uses a case study to evaluate the design context knowledge based decision making model as well as the PROCONDES prototype system. While the third section discusses about the evaluation procedure, the final section discusses the evaluation results in detail.

8.1 Evaluation Criteria

The Function to PDE mapping model developed in this research is evaluated by case studying a sheet metal component design problem. The purpose of this case study is to demonstrate in detail how the Function to PDE mapping model works in general using the design context knowledge based reasoning mechanism through the use of the PROCONDES system.

The main criteria for evaluating PROCONDES prototype system are given below:

- Does the PROCONDES system highlight the potential context knowledge consequences of selecting a particular design solution?
- Does it provide a decision support through evaluating all candidate design solutions against different context knowledge criteria?
- Does it support proactive decision making by allowing designers to give their preference to make an informed decision?

8.2 Case Study to Evaluate the Model and the PROCONDES

The criteria set out in previous section are evaluated by performing a sheet metal component design problem in this case study. The following design case example is used to evaluate the working of the model as well as the developed prototype system.

8.2.1 Design Case example to Evaluate Function to PDE Mapping Model

The PROCONDES system uses an effective methodology to perform the Function to PDE mapping process. For example, a function such as *(Provide Semi Permanent Assembly)* between two components can be realised by four possible means/ PDEs at the component building level of a sheet metal component as shown in Figure 8-1. This is derived from the mapping search algorithm, which performs a key word search in order to map possible means to a required function from the dictionary of functions and their associated means. Once the keyword is mapped onto a PDE, it will be identified as a suitable candidate and the search continues until all PDEs in the dictionary are evaluated. In this case study, *Slot-Fit, Bolting, Lance-Fit, Soldering and Wrapping* PDEs were nominated by the mapping algorithm for the designer's consideration. The potential solutions generated need to be evaluated further using design context knowledge based reasoning mechanism in order to support the designer to select the appropriate means.

With the context information available under three different groups and current working knowledge, the context information reasoning mechanism aims to detect any unfit/unfeasible PDEs from the initial mapped PDEs in order to reduce the initial set of PDEs to a reduced subset of PDEs. In this example the initial functional requirement i.e. ***"Provide Semi Permanent Assembly"*** has been matched with four possible PDEs/means to implement this requirement. To elucidate, if the search for the *General Product Related Context Knowledge* information reveals that low carbon steel material has been selected for joining both components, it activates a piece of knowledge i.e. *Wrapping* means cannot be used for the function as this solution is only suitable for non-metal/alloy made components. Timely prompting of this context information about material assists designers to eliminate this infeasible assembly option.

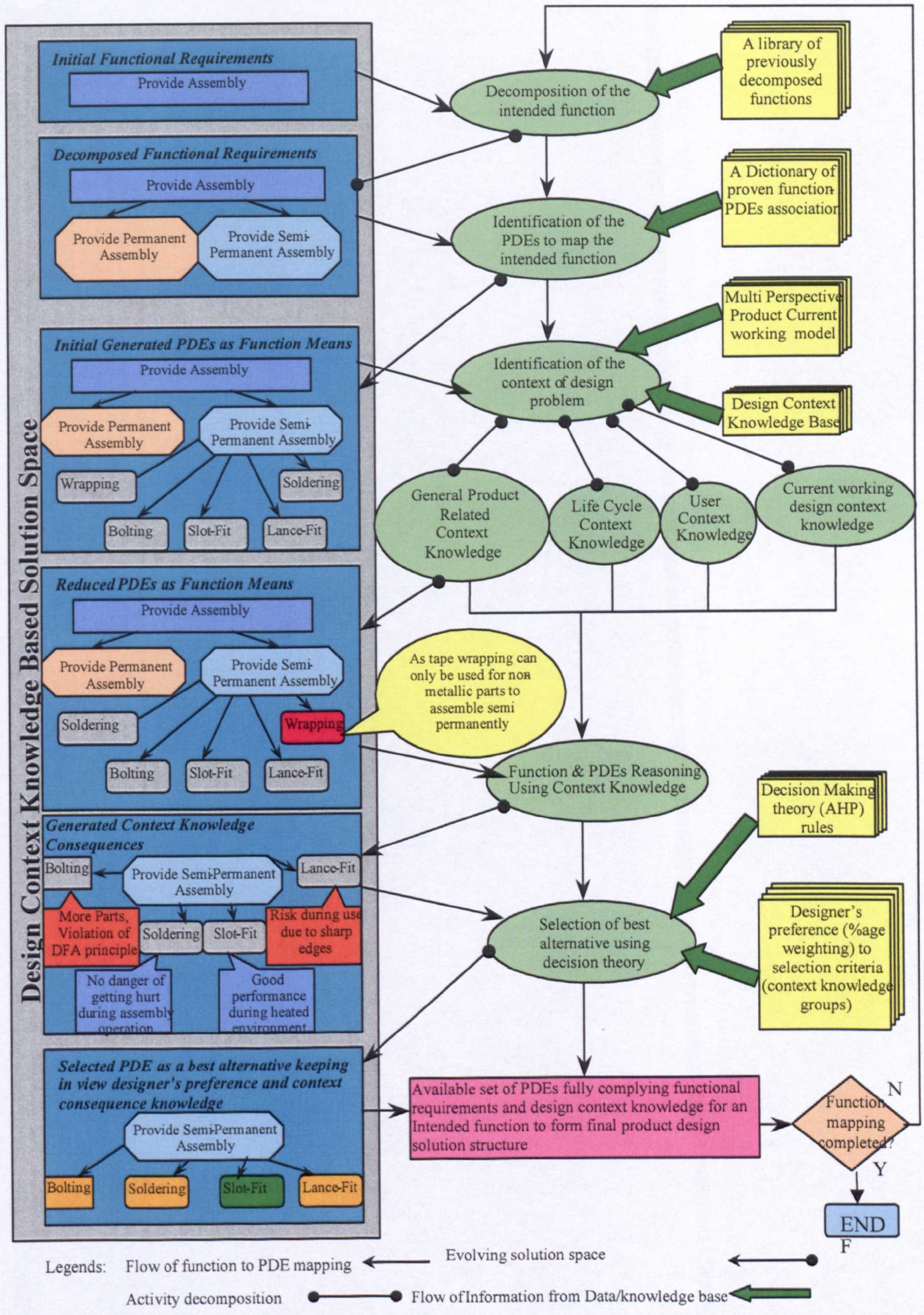


Figure 8-1: Function to PDE mapping and reasoning model with an example

Once there is a reduced set of PDEs available, then simultaneous functional reasoning of different categories of design context knowledge (i.e. requirements) as well as solution/PDEs reasoning (i.e. generated information during the course of design process and termed as current working knowledge) is performed to elicit design solution consequences. Selecting *Bolting* as the selected PDE would be a violation of design for assembly principle as this decision results in more parts for the design, which in turn adds up the time of assembly process and the cost of the product and hence this is a negative/problematic consequence. Similarly selecting *Slot-Fit* as a candidate solution will have a good performance in a high ambient temperature environment and there are less chances of the loosening of the assembly, resulting in a good consequence. Though Figure 8-1 depicts few selected consequences, there could be many more consequences for each design solution. After highlighting the consequences, the best possible solution could be selected by evaluating all PDEs/solutions using AHP theory rules and using the designer's preferences against all criteria (*Slot-Fit* is selected as the best PDE/solution in this example).

8.2.2 Demonstration of the Case Study using the PROCONDES System

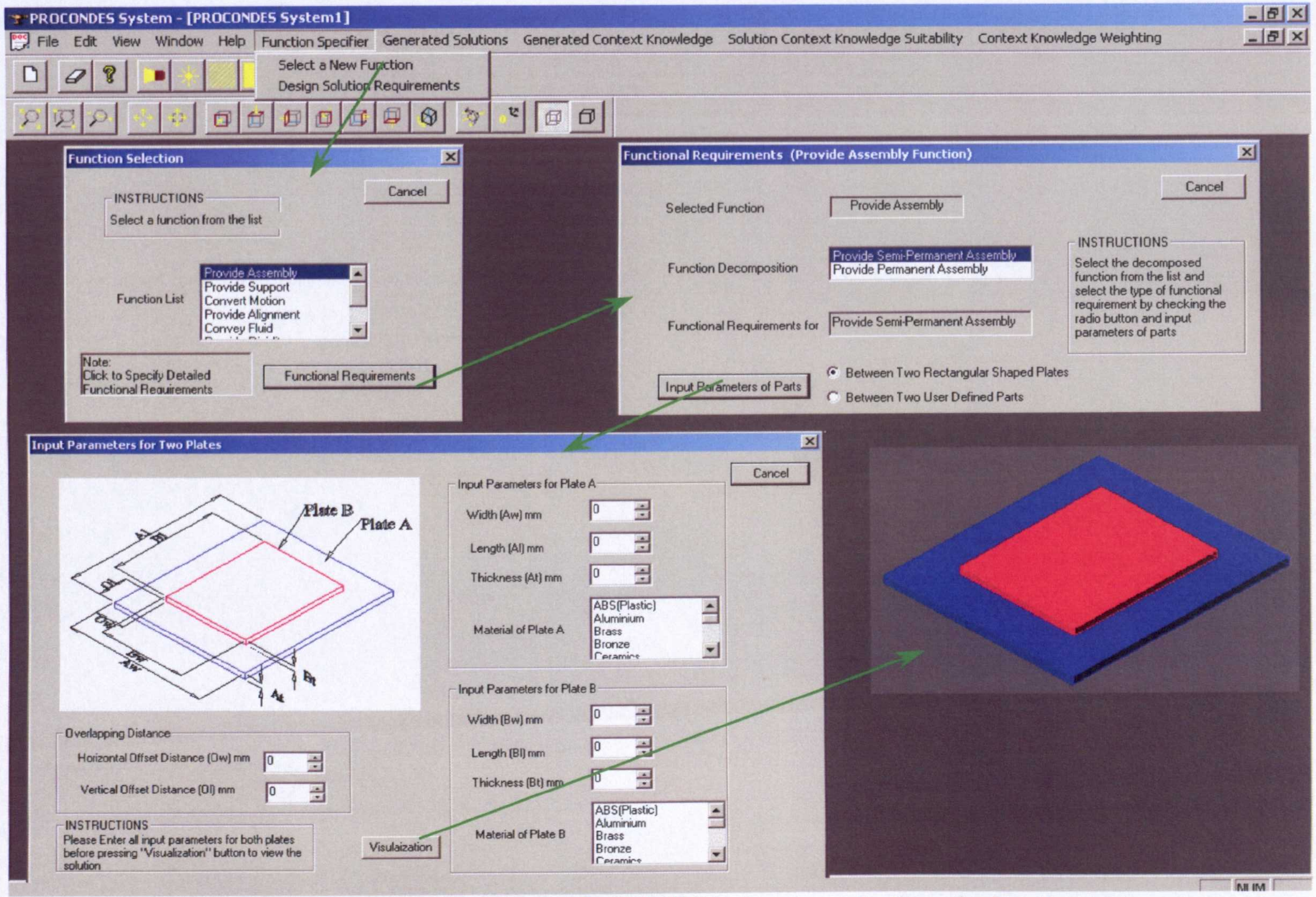
The case study discussed in the previous section is showcased to highlight the functionality of the PROCONDES prototype system. The following subsections demonstrate the use of the PROCONDES system in the context of the case study.

8.2.2.1 Function Selection

The main window of PROCONDES prototype system is shown as a screen dump in Figure 8-2. The first step is to select a new function from the *Function Selection* dialog box specified under the menu of *Function Specifier.* A *"Provide Assembly"* function is selected in this case study from the list of functions and functional requirements, which are specified in the *Functional Requirements* dialog box. *"Provide Semi-Permanent Assembly Between Two Rectangular Plates"* has been selected as a decomposed function in this dialog box for further exploration. Detailed parameters of these plates are input by using *Input Parameters of Parts* button, which displays a new dialog box. Different parameters of two plates like width, length, material etc. are selected and the two plates can be visualized using the *Visualization* option.

8.2.2.2 Inputting Functional Requirements

The next step in the case study is to specify the detailed functional requirements. These requirements are grouped under three different groups and each group has a certain number of context knowledge categories. The designer is asked to choose between different options under each question in a context knowledge category. Detailed functional requirements are input by using the *Design Solution Requirements* dialog box through which *Life Cycle, General and User Context Knowledge Requirements* are specified by selecting different parameters under the different knowledge categories as shown in Figure 8-3.



INSTRUCTIONS
Select a function from the list

Function List: Provide Assembly, Provide Support, Convert Motion, Provide Alignment, Convey Fluid

Note:
Click to Specify Detailed Functional Requirements

Selected Function: Provide Assembly

Function Decomposition: Provide Semi-Permanent Assembly, Provide Permanent Assembly

Functional Requirements for: Provide Semi-Permanent Assembly

INSTRUCTIONS
Select the decomposed function from the list and select the type of functional requirement by checking the radio button and input parameters of parts

● Between Two Rectangular Shaped Plates
○ Between Two User Defined Parts

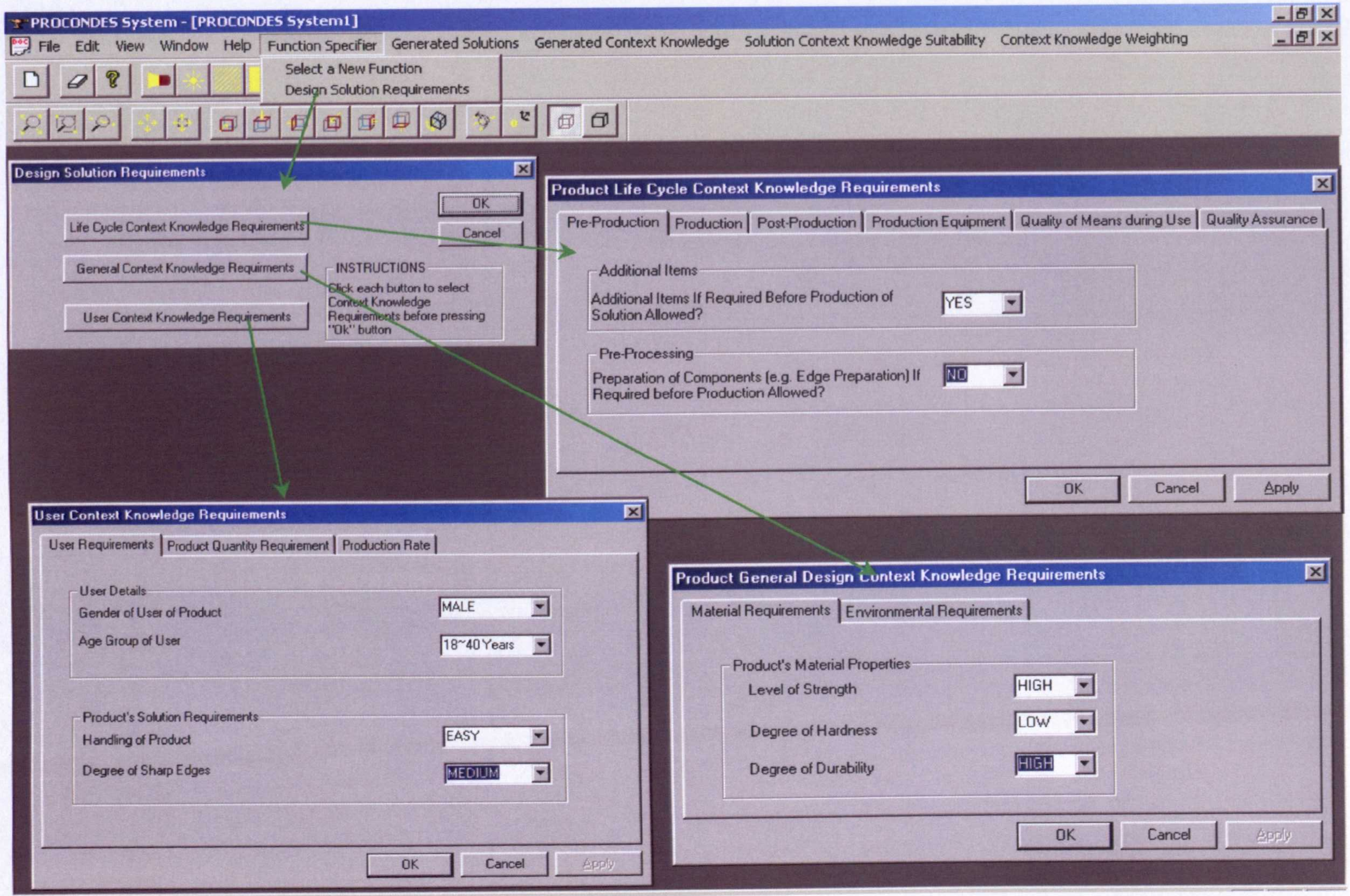
Overlapping Distance
Horizontal Offset Distance (Ow) mm: 0
Vertical Offset Distance (Ol) mm: 0

INSTRUCTIONS
Please Enter all input parameters for both plates before pressing "Visualization" button to view the solution

Input Parameters for Plate A
Width (Aw) mm: 0
Length (Al) mm: 0
Thickness (At) mm: 0
Material of Plate A: ABS(Plastic), Aluminium, Brass, Bronze, Ceramics

Input Parameters for Plate B
Width (Bw) mm: 0
Length (Bl) mm: 0
Thickness (Bt) mm: 0
Material of Plate B: ABS(Plastic), Aluminium, Brass, Bronze, Ceramics

Figure 8-2: Screen dump of PROCONDES showing selection of a function



INSTRUCTIONS

Click each button to select Context Knowledge Requirements before pressing "Ok" button

Additional Items

Additional Items If Required Before Production of Solution Allowed? YES

Pre-Processing

Preparation of Components (e.g. Edge Preparation) If Required before Production Allowed? NO

User Details

Gender of User of Product: MALE

Age Group of User: 18~40 Years

Product's Solution Requirements

Handling of Product: EASY

Degree of Sharp Edges: MEDIUM

Product's Material Properties

Level of Strength: HIGH

Degree of Hardness: LOW

Degree of Durability: HIGH

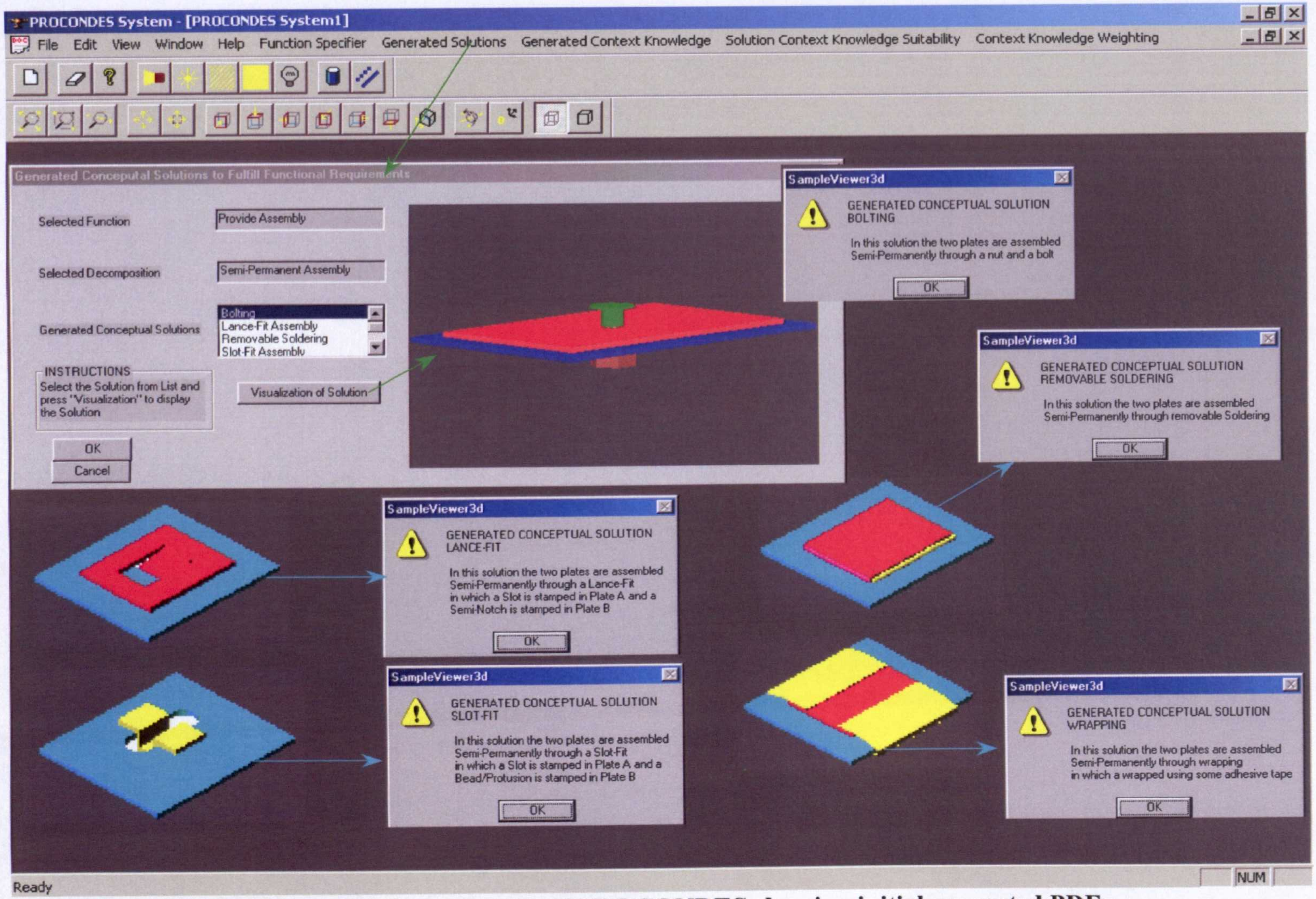
Figure 8-3: Screen dump of PROCONDES showing input of detailed functional requirements

8.2.2.3 Visualization of Solutions

Once the functional requirements are specified, the next step is to determine the initial generated solutions in terms of the PDEs. Different conceptual solutions/PDEs are stored in the PROCONDES system and these solutions are generated based on the Function to means/PDEs mapping algorithm. Selecting the *Generated Solutions* menu displays the *Generated Conceptual Solutions* dialog box, which highlights the solutions generated by the system. The three dimensional graphic images of the solution/PDEs are displayed in a dedicated graphical window created within the dialog box by using the *Visualization of Solution* button. It also simultaneously displays the generated solution in the general graphics area outside the dialog box. The textual detail of each one of these solution/PDEs is displayed in separate message boxes simultaneously by using the same button. Five initial PDEs i.e. *Bolting, Lance-Fit Assembly, Slot-Fit Assembly, Removable Soldering and Tape Wrapping* are identified as an initial list from the dictionary of Function-PDEs association. These have been illustrated graphically and textually as shown in a screen dump in Figure 8-4. Different graphical image manipulation functions like *zoom, pan, dynamic rotate, isometric-view, top view, bottom view, side views* as well as different lighting options *like shading, gouroud, hide* to view the generated solution from different angles and with different effects are provided in the PROCONDES system.

8.2.2.4 Generation of the Context Knowledge and the Consequences

Once a list of suitable PDEs is generated, then the context of design problem using the design context knowledge base and the multi perspective product current working model is identified. Thus the generated context knowledge for different solution PDEs can be viewed in different categories through three groups of dialog boxes i.e. *Generated Life Cycle Context Knowledge, Generated User Context Knowledge* and *Generated General Context Knowledge* by using the *Generated Context Knowledge* menu button as shown in Figure 8-5.



Selected Function: Provide Assembly

Selected Decomposition: Semi-Permanent Assembly

Generated Conceptual Solutions:
- Bolting
- Lance-Fit Assembly
- Removable Soldering
- Slot-Fit Assembly

INSTRUCTIONS
Select the Solution from List and press "Visualization" to display the Solution

GENERATED CONCEPTUAL SOLUTION
BOLTING

In this solution the two plates are assembled Semi-Permanently through a nut and a bolt

GENERATED CONCEPTUAL SOLUTION
REMOVABLE SOLDERING

In this solution the two plates are assembled Semi-Permanently through removable Soldering

GENERATED CONCEPTUAL SOLUTION
LANCE-FIT

In this solution the two plates are assembled Semi-Permanently through a Lance-Fit in which a Slot is stamped in Plate A and a Semi-Notch is stamped in Plate B

GENERATED CONCEPTUAL SOLUTION
SLOT-FIT

In this solution the two plates are assembled Semi-Permanently through a Slot-Fit in which a Slot is stamped in Plate A and a Bead/Protusion is stamped in Plate B

GENERATED CONCEPTUAL SOLUTION
WRAPPING

In this solution the two plates are assembled Semi-Permanently through wrapping in which a wrapped using some adhesive tape

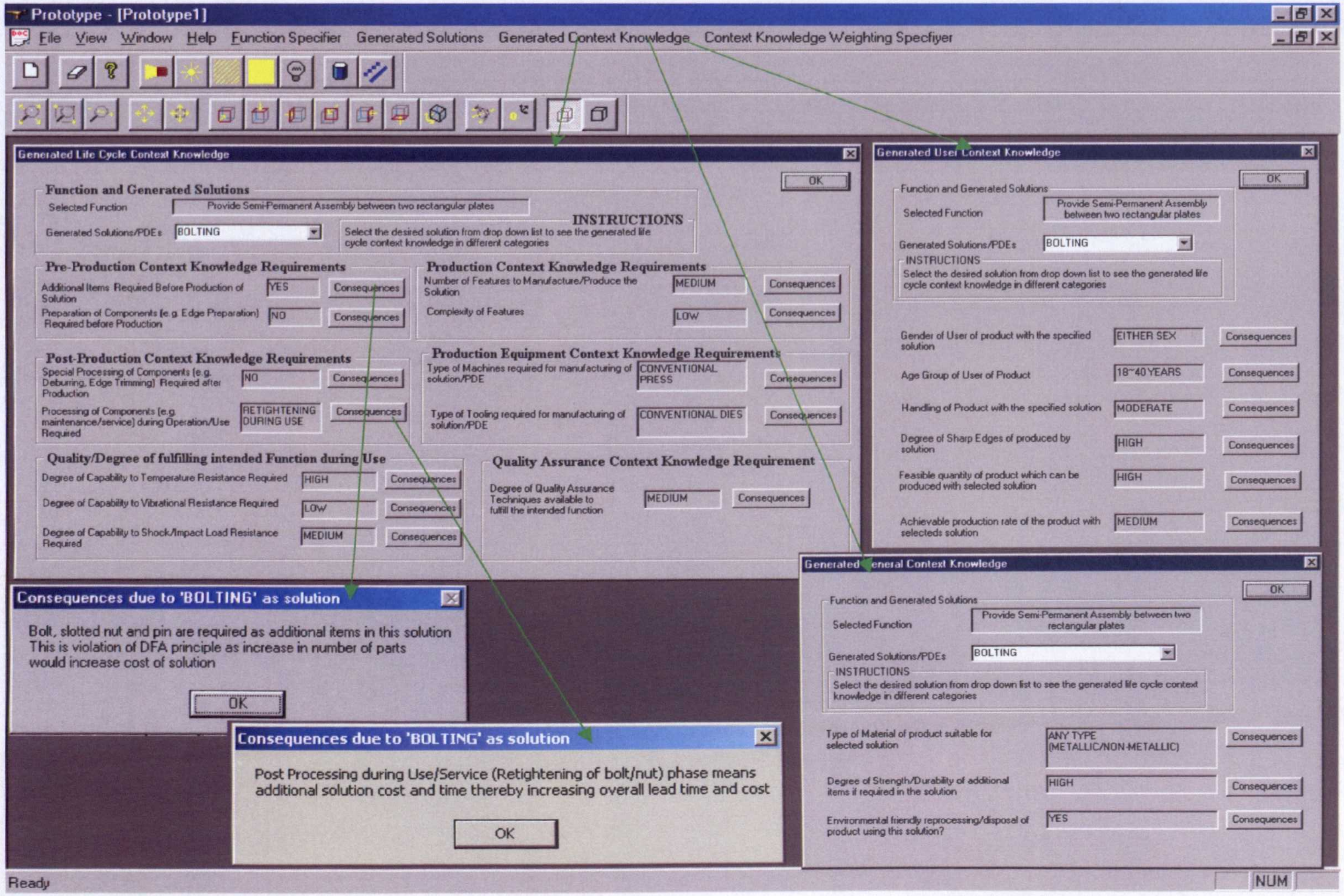
Figure 8-4: Screen dump of PROCONDES showing initial generated PDEs

Context consequences knowledge/information is generated regarding each one of these means/solutions for each of these categories. This information is generated by simultaneously reasoning the design solution requirements as well as the generated context knowledge for the design solution under consideration.

Proactive Decision Support

The early awareness pertaining to the later life cycle phases, the user of the product and the product itself provides proactive decision support to the designer when selecting a particular solution by highlighting the pros and cons of each solution. For example selecting a '*Bolting*' solution, the system shows a problematic consequence by indicating "YES" in the box corresponding to a requirement of '*Additional Items Required before Production of Solution*' under Life Cycle Context Knowledge Group in the *Pre-Production Context Knowledge Requirements* category as shown in Figure 8-5.

The reasoning process generates a consequence due to selecting '*Bolting*' as a solution, which is that a *Bolt, Slotted Nut and Pin* are required as additional items in this solution. This consequence shows that this solution is in violation of the DFA principle, as it would increase the number of parts involved in the solution thereby increasing the manufacturing cost and time of the solution. Similarly the '*Bolting*' solution generates 'RETIGHTENING DURING USE' consequence for the '*USE*' life cycle phase. This problematic consequence indicates that the retightening of the bolt and the nut would incur an additional cost and time during the '*Use*' phase. This type of awareness by the prototype system proactively supports the designer in decision making.



Generated Life Cycle Context Knowledge

Function and Generated Solutions

Selected Function: Provide Semi-Permanent Assembly between two rectangular plates

Generated Solutions/PDEs: BOLTING

INSTRUCTIONS

Select the desired solution from drop down list to see the generated life cycle context knowledge in different categories

Pre-Production Context Knowledge Requirements

Additional Items Required Before Production of Solution: YES

Preparation of Components (e.g. Edge Preparation) Required before Production: NO

Production Context Knowledge Requirements

Number of Features to Manufacture/Produce the Solution: MEDIUM

Complexity of Features: LOW

Post-Production Context Knowledge Requirements

Special Processing of Components (e.g. Deburring, Edge Trimming) Required after Production: NO

Processing of Components (e.g. maintenance/service) during Operation/Use Required: RETIGHTENING DURING USE

Production Equipment Context Knowledge Requirements

Type of Machines required for manufacturing of solution/PDE: CONVENTIONAL PRESS

Type of Tooling required for manufacturing of solution/PDE: CONVENTIONAL DIES

Quality/Degree of fulfilling intended Function during Use

Degree of Capability to Temperature Resistance Required: HIGH

Degree of Capability to Vibrational Resistance Required: LOW

Degree of Capability to Shock/Impact Load Resistance Required: MEDIUM

Quality Assurance Context Knowledge Requirement

Degree of Quality Assurance Techniques available to fulfill the intended function: MEDIUM

Generated User Context Knowledge

Function and Generated Solutions

Selected Function: Provide Semi-Permanent Assembly between two rectangular plates

Generated Solutions/PDEs: BOLTING

INSTRUCTIONS

Select the desired solution from drop down list to see the generated life cycle context knowledge in different categories

Gender of User of product with the specified solution: EITHER SEX

Age Group of User of Product: 18~40 YEARS

Handling of Product with the specified solution: MODERATE

Degree of Sharp Edges of produced by solution: HIGH

Feasible quantity of product which can be produced with selected solution: HIGH

Achievable production rate of the product with selecteds solution: MEDIUM

Generated General Context Knowledge

Function and Generated Solutions

Selected Function: Provide Semi-Permanent Assembly between two rectangular plates

Generated Solutions/PDEs: BOLTING

INSTRUCTIONS

Select the desired solution from drop down list to see the generated life cycle context knowledge in different categories

Type of Material of product suitable for selected solution: ANY TYPE (METALLIC/NON-METALLIC)

Degree of Strength/Durability of additional items if required in the solution: HIGH

Environmental friendly reprocessing/disposal of product using this solution?: YES

Consequences due to 'BOLTING' as solution

Bolt, slotted nut and pin are required as additional items in this solution This is violation of DFA principle as increase in number of parts would increase cost of solution

Consequences due to 'BOLTING' as solution

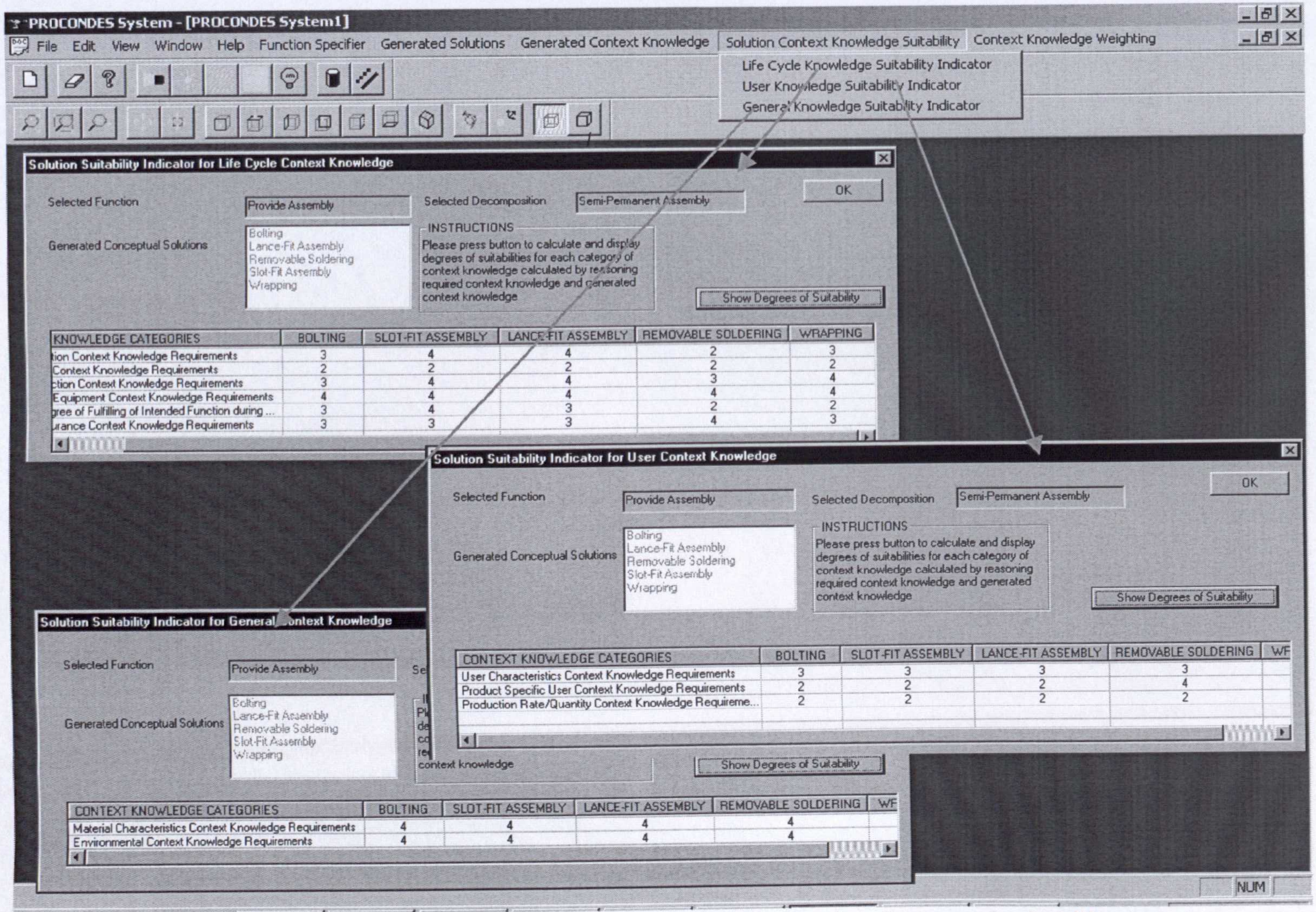
Post Processing during Use/Service (Retightening of bolt/nut) phase means additional solution cost and time thereby increasing overall lead time and cost

Figure 8-5: Screen dump of PROCONDES showing generated context knowledge of PDEs

8.2.2.5 Assignment of the Degrees of Suitability

Once the design solution/life cycle consequences are illustrated for different scenarios for each of the PDEs, it is possible to rate each design solution/means in terms of the degrees of suitability for that particular context knowledge category. This is done by the PROCONDES system using reasoning and comparing the design solution requirements and generated context knowledge in each of the context knowledge categories

The higher the degree, the fewer are the problematic consequences and hence more suitable is the solution under consideration. The assigned degrees of suitability are shown in Figure 8-6. The numerical rating to each of the design alternatives against each context knowledge criterion category is assigned by converting degrees of suitability into a percentage-weighting factor. This conversion uses the comparison scales (section 6.2.5.1) defined in the Analytic Hierarchy Process (AHP). These percentage weightings are shown in Figure 8-7 for different PDEs such as *Bolting, Slot-fit, Assembly* etc.



Solution Suitability Indicator for Life Cycle Context Knowledge

Selected Function: Provide Assembly

Selected Decomposition: Semi-Permanent Assembly

Generated Conceptual Solutions:
Bolting
Lance-Fit Assembly
Removable Soldering
Slot-Fit Assembly
Wrapping

INSTRUCTIONS
Please press button to calculate and display degrees of suitabilities for each category of context knowledge calculated by reasoning required context knowledge and generated context knowledge

KNOWLEDGE CATEGORIES	BOLTING	SLOT-FIT ASSEMBLY	LANCE-FIT ASSEMBLY	REMOVABLE SOLDERING	WRAPPING
ion Context Knowledge Requirements	3	4	4	2	3
Context Knowledge Requirements	2	2	2	2	2
ction Context Knowledge Requirements	3	4	4	3	4
Equipment Context Knowledge Requirements	4	4	4	4	4
gree of Fulfilling of Intended Function during ...	3	4	3	2	2
urance Context Knowledge Requirements	3	3	3	4	3

Solution Suitability Indicator for User Context Knowledge

Selected Function: Provide Assembly

Selected Decomposition: Semi-Permanent Assembly

Generated Conceptual Solutions:
Bolting
Lance-Fit Assembly
Removable Soldering
Slot-Fit Assembly
Wrapping

INSTRUCTIONS
Please press button to calculate and display degrees of suitabilities for each category of context knowledge calculated by reasoning required context knowledge and generated context knowledge

CONTEXT KNOWLEDGE CATEGORIES	BOLTING	SLOT-FIT ASSEMBLY	LANCE-FIT ASSEMBLY	REMOVABLE SOLDERING	WF
User Characteristics Context Knowledge Requirements	3	3	3	3	
Product Specific User Context Knowledge Requirements	2	2	2	4	
Production Rate/Quantity Context Knowledge Requireme...	2	2	2	2	

Solution Suitability Indicator for General Context Knowledge

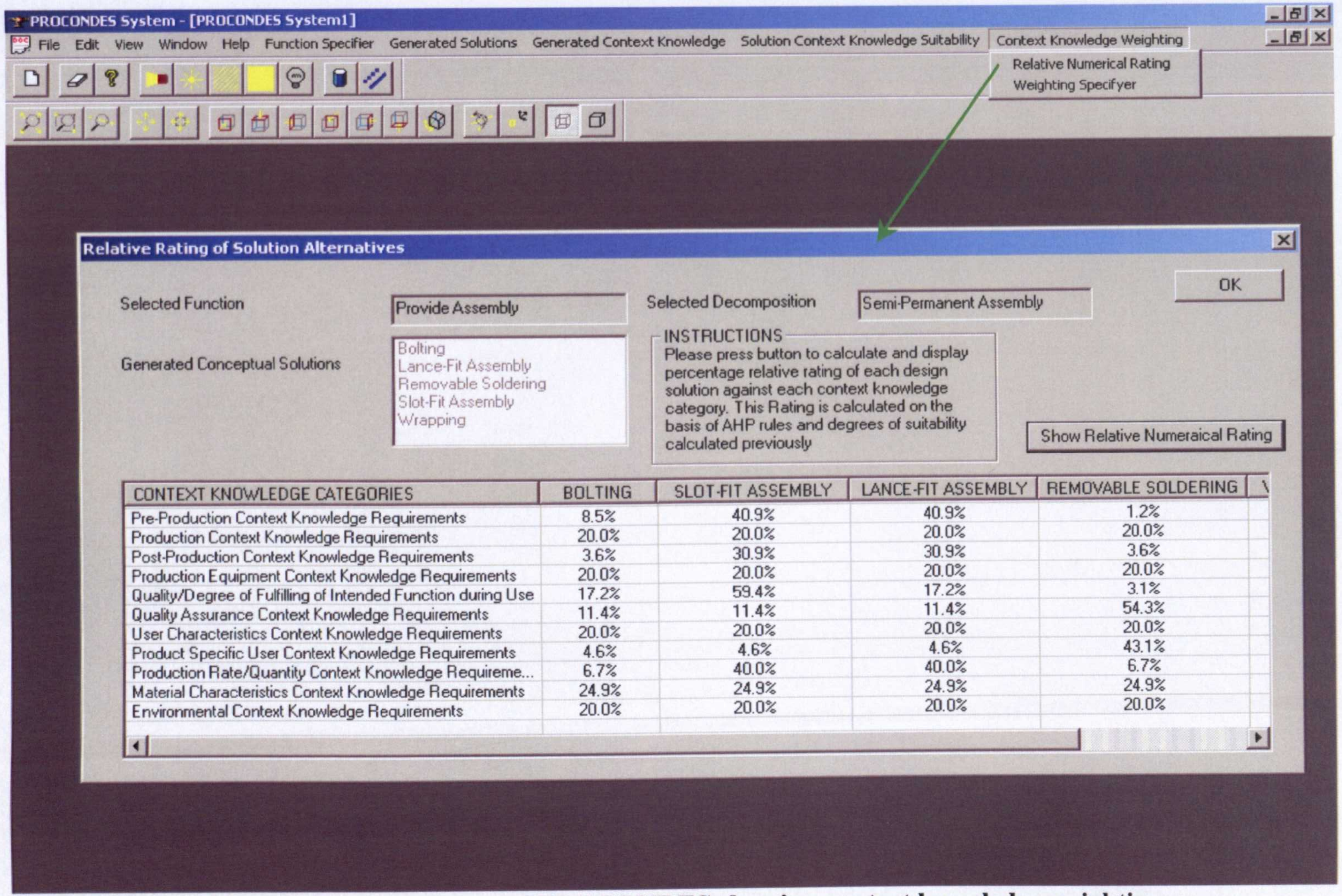
Selected Function: Provide Assembly

Generated Conceptual Solutions:
Bolting
Lance-Fit Assembly
Removable Soldering
Slot-Fit Assembly
Wrapping

context knowledge

CONTEXT KNOWLEDGE CATEGORIES	BOLTING	SLOT-FIT ASSEMBLY	LANCE-FIT ASSEMBLY	REMOVABLE SOLDERING	WF
Material Characteristics Context Knowledge Requirements	4	4	4	4	
Environmental Context Knowledge Requirements	4	4	4	4	

Figure 8-6: Screen dump of PROCONDES showing degrees of suitability



Selected Function: Provide Assembly

Selected Decomposition: Semi-Permanent Assembly

Generated Conceptual Solutions:
Bolting
Lance-Fit Assembly
Removable Soldering
Slot-Fit Assembly
Wrapping

INSTRUCTIONS
Please press button to calculate and display percentage relative rating of each design solution against each context knowledge category. This Rating is calculated on the basis of AHP rules and degrees of suitability calculated previously

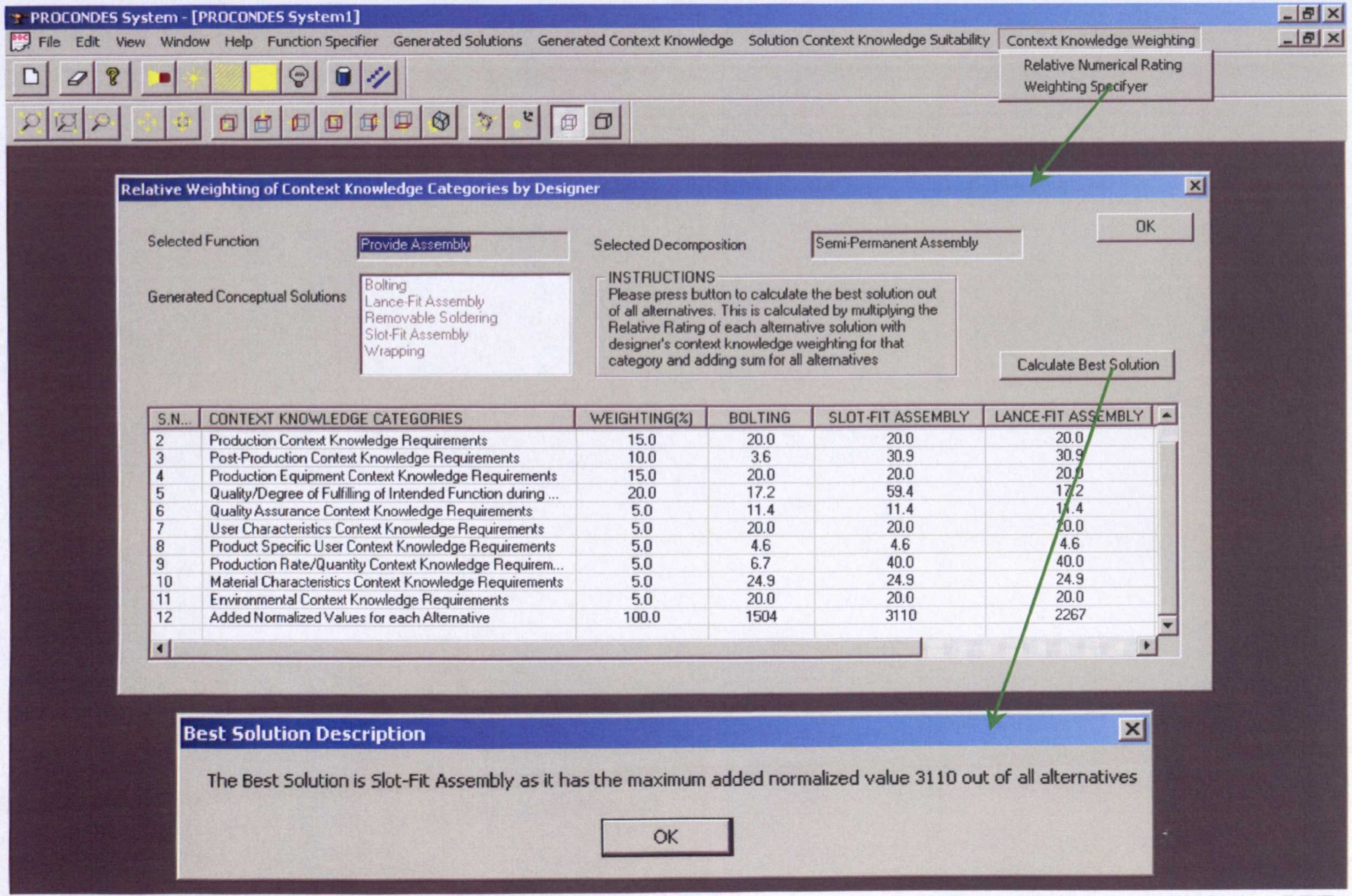
CONTEXT KNOWLEDGE CATEGORIES	BOLTING	SLOT-FIT ASSEMBLY	LANCE-FIT ASSEMBLY	REMOVABLE SOLDERING
Pre-Production Context Knowledge Requirements	8.5%	40.9%	40.9%	1.2%
Production Context Knowledge Requirements	20.0%	20.0%	20.0%	20.0%
Post-Production Context Knowledge Requirements	3.6%	30.9%	30.9%	3.6%
Production Equipment Context Knowledge Requirements	20.0%	20.0%	20.0%	20.0%
Quality/Degree of Fulfilling of Intended Function during Use	17.2%	59.4%	17.2%	3.1%
Quality Assurance Context Knowledge Requirements	11.4%	11.4%	11.4%	54.3%
User Characteristics Context Knowledge Requirements	20.0%	20.0%	20.0%	20.0%
Product Specific User Context Knowledge Requirements	4.6%	4.6%	4.6%	43.1%
Production Rate/Quantity Context Knowledge Requireme...	6.7%	40.0%	40.0%	6.7%
Material Characteristics Context Knowledge Requirements	24.9%	24.9%	24.9%	24.9%
Environmental Context Knowledge Requirements	20.0%	20.0%	20.0%	20.0%

Figure 8-7: Screen dump of PROCONDES showing context knowledge weighting

8.2.2.6 Selection of Best Alternative

The relative weighting among different knowledge criteria (i.e. preference of one criterion over other) can be done by giving percentage weighting for each context knowledge categories. Assignment of the relative weighting by the designer depends upon various factors like cost consideration, designer's preference based on experience, company policy etc. For example, some companies prefer a low cost product, which results in compromising the quality of the product. In this case study, the relative weightings taken as designer's preferences are shown in Figure 8-8 under *Weighting (%)* column.

After determining the relative weighting of each criterion and the numerical rating of different alternatives, the final task involves determination of the best design solution/alternative against the predefined weightings from the five selected alternatives *(i.e. Lance-Fit Assembly, Slot-Fit Assembly, Bolting, Removable Soldering, Tape Wrapping).* This is done by calculating the highest added normalized value for each design alternative PDE. Figure 8-8 shows the highest added normalized value (i.e. 3110) for the ***Slot-Fit Assembly***, which has therefore been chosen as the best alternative. The designer can change his/her decision and assign different percentage weightings to a context knowledge category at any time during the design session. This would change the highest added normalized value and subsequently the best solution.



Selected Function: Provide Assembly

Selected Decomposition: Semi-Permanent Assembly

Generated Conceptual Solutions:
- Bolting
- Lance-Fit Assembly
- Removable Soldering
- Slot-Fit Assembly
- Wrapping

INSTRUCTIONS
Please press button to calculate the best solution out of all alternatives. This is calculated by multiplying the Relative Rating of each alternative solution with designer's context knowledge weighting for that category and adding sum for all alternatives

S.N...	CONTEXT KNOWLEDGE CATEGORIES	WEIGHTING(%)	BOLTING	SLOT-FIT ASSEMBLY	LANCE-FIT ASSEMBLY
2	Production Context Knowledge Requirements	15.0	20.0	20.0	20.0
3	Post-Production Context Knowledge Requirements	10.0	3.6	30.9	30.9
4	Production Equipment Context Knowledge Requirements	15.0	20.0	20.0	20.0
5	Quality/Degree of Fulfilling of Intended Function during ...	20.0	17.2	59.4	17.2
6	Quality Assurance Context Knowledge Requirements	5.0	11.4	11.4	11.4
7	User Characteristics Context Knowledge Requirements	5.0	20.0	20.0	20.0
8	Product Specific User Context Knowledge Requirements	5.0	4.6	4.6	4.6
9	Production Rate/Quantity Context Knowledge Requirem...	5.0	6.7	40.0	40.0
10	Material Characteristics Context Knowledge Requirements	5.0	24.9	24.9	24.9
11	Environmental Context Knowledge Requirements	5.0	20.0	20.0	20.0
12	Added Normalized Values for each Alternative	100.0	1504	3110	2267

The Best Solution is Slot-Fit Assembly as it has the maximum added normalized value 3110 out of all alternatives

Figure 8:8: Screen dump of PROCONDES showing context knowledge weighting and best-selected solution PDE

8.3 Evaluation Procedure

The set of criteria mentioned in section 8.1 are evaluated using the previously mentioned case study of the sheet metal component design problem in the PROCONDES system. A group of nineteen people comprising of engineering design researchers, designers and engineering design students evaluated the functionalities of the PROCONDES system and the implemented model..

8.3.1 Evaluation Objectives

The main aim of the evaluation of the Function to PDE mapping model and the PROCONDES system is to determine as to the extent to which the developed model and its implementation fulfil the research aim and objectives identified in chapter 1 and also address the research questions identified in Chapter 4. Apart from the criteria defined in section 8.1, the other objective of the evaluation is to determine the extent to which the PROCONDES system's functionalities fulfil the following objectives: -

- Detailed description of the functional requirements as well as generated design solutions.
- Early design decisions' consequences awareness to the designer.
- Quantification of the design solution suitability to different context knowledge categories.
- Provision of proactive support to design decision making.

8.3.2 Evaluation Difficulties

The objective of demonstrating the PROCONDES capabilities was difficult due to the following factors:

- Due to the short time frame of this PhD research, only limited context knowledge categories as well as knowledge within these categories have been codified in the PROCONDES system. Although it serves the purpose for the evaluators to draw out the strengths and limitations of the model as well as the PROCONDES system, it does not perform exhaustive exploration of the Function to PDE mapping model.

- Being a PhD prototype system, the functionalities and interface (i.e. both graphical and textual) would not be as good as that of a typical commercial software in the same category, thereby making it difficult for the evaluators to fully appreciate the driving force behind it i.e. the Function to PDE mapping model and its effectiveness in supporting the decision making at the conceptual design stage.
- The number and the technical background of evaluators involved in the evaluation process were not as extensive and diverse as in an ideal evaluation to get a full evaluation of the system from a larger evaluation group of different people having a wide variety of technical knowledge.

8.3.3 Evaluation Questionnaire

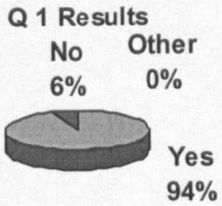
Due to the anticipated difficulties as explained in the previous section, the PROCONDES prototype system demonstration was conducted to highlight the strengths and weaknesses of the prototype system in the different areas. Due to varied nature of the technical background of the evaluators, a detailed power point based presentation was made for each evaluator, describing the PhD research, aim and objectives, development of the Function to PDE mapping model as well as the system architecture of the PROCONDES system to give them an overview of the project before conducting the case study. A detailed comprehensive questionnaire containing the main criteria set out in section 8.1 and the questions related to different functionalities of the PROCONDES system as well as the overall Function to PDE mapping model were presented to them after performing the case study in order to evaluate both the model and system in detail. A typical completed questionnaire is shown in Appendix-G.

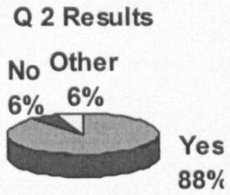
8.4 Critical Evaluation of Results

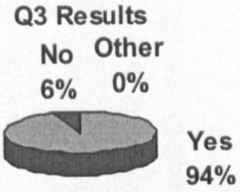
The response to each question in the questionnaire is compiled and presented in Appendix-H. Some of the critical evaluation results regarding the overall Function to PDE mapping model as well as the PROCONDES system are presented in this section.

8.4.1 Detailed Functional Requirements and Conceptual Design Solutions.

94% of the evaluators (Q1) said that the PROCONDES decomposed the functional requirements and explained them in detail in an appropriate manner for the case study. 88% of the evaluators supported the idea of splitting design solution functional requirements (Q2) into three groups. 94% of the evaluators (Q3) confirmed the idea of splitting functional requirements input under different categories into three groups i.e. life cycle group, user group and general product related knowledge group.





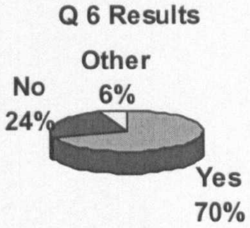


82% of the evaluators said that the conceptual solutions generated to realise the function selected in the case study was explained in enough detail (Q4a) through graphical representation. However some of them were of the view that it could be made aesthetically more appealing.

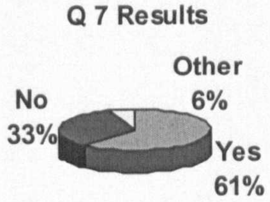
Explanation of a conceptual solution in textual form (Q4b) was detailed enough as indicated by 53% of the evaluators in the survey. Some evaluators (18%) said that explanation is sufficient but not clear in the textual form and it could be further improved, whereas 29% of the evaluators disagreed with the detail and the presentation of the textual form.

8.4.2 Context Knowledge and Consequences' Awareness

70% of the evaluators agreed that the context knowledge generated under three different groups in the different categories is detailed enough (Q6) to foresee the impact of selecting a particular solution on the different life cycle phases, the user of product and the environment of product. 61% of the evaluators (Q7) confirmed that they were made aware of all the consequences related to a chosen context knowledge category early at the design stage of selecting a particular conceptual design solution in detail.



Q 6 Results

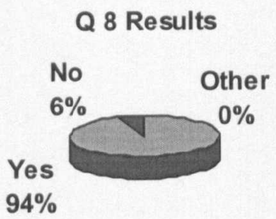


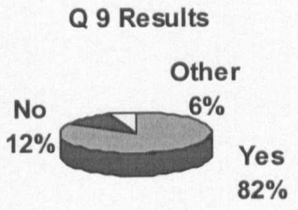
Q 7 Results

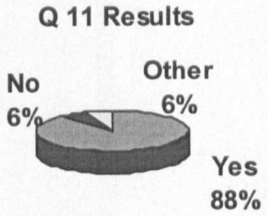
Some evaluators (24%) disagreed to Q6 and suggested that there could be more context knowledge categories that should be considered in the case study performed as well as in each category. Further, they felt the need for inclusion of more knowledge in each of the categories defined in the system. In addition, some evaluators (33%) disagreed to Q7 and suggested in the need for explaining a consequence in more detail while 6% of the evaluators suggested for additional consequences to be generated related to each context knowledge category.

8.4.3 Context Knowledge Suitability

94% of the evaluators agreed with the concept of assigning degrees of suitability (Q8) to a particular solution based on the context knowledge reasoning as a fair indication of the appropriateness of a conceptual design solution against a criterion. 82% of the evaluators agreed that the scale of suitability (Q9) from 0 to 5 set in the PROCONDES system is a fair indication of the appropriateness of a solution against a criterion. Moreover 88% of the evaluators agreed with the idea of allowing the designer's preference in percentage weighting instead of the linguistic rating scales (Q11).





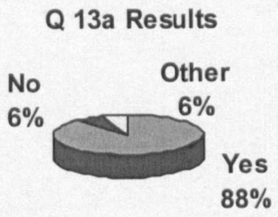


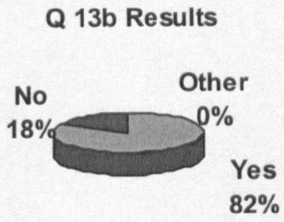
However 6% of the evaluators suggested for provision of inclusion of both these methods.

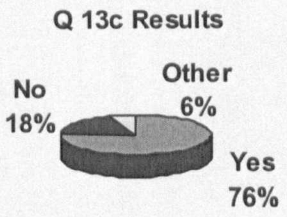
8.4.4 Decision Support

The response to question 13 indicated that the PROCONDES system adequately demonstrates its abilities in providing proactive decision support to a designer. The various attributes contributing to decision support along with the percentage of evaluators supporting the particular attribute have been highlighted below:

- Generating and highlighting the potential consequences of selecting a particular solution (88% of the evaluators).
- Evaluating all candidate design solutions against the different context knowledge criteria (82% of the evaluators).
- Selecting a best solution which not only fulfils the functional requirements, designer's preferences but is also suitable for the later life cycle stages thereby reducing the cost and time which would be incurred by selecting a particular solution without knowing its suitability for the later life cycle stages (76% of the evaluators).







8.4.5 PROCONDES System and the Overall Approach

As regards the recommendations/suggestions (Q14 & Q15) to the overall approach and the PROCONDES system, most of the evaluators appreciated the approach of proactively supporting decision making at the conceptual design stage using context knowledge reasoning. To elucidate, as one of the evaluators said:

> *"It is good for designers and helps in the course of designing".*

Some evaluators were of the opinion that additional context knowledge and consequences need to be included in each context knowledge category. Regarding the PROCONDES system's functionalities, most of the evaluators appreciated the graphical user interface of the system and the corresponding functionalities to view and display conceptual solutions. However as regards the textual interface and the explanation of the solutions, most of them were of the view that the text needs to be made more presentable as well as required more detail. Some evaluators suggested to the inclusion of the concurrent design process of the components (i.e. generation of basic tooling and machine parameters) along with the conceptual design solutions as originally proposed in the architecture of the system. Though this had been identified during the research process, it could not be accomplished due to lack of time. Some evaluators also suggested for codifying some of the more complex case studies in the PROCONDES system as well as to ensure that two of the existing case studies are made more understandable.

8.5 Chapter Summary

This chapter evaluates the Function to PDE mapping model as well as the evaluation of the PROCONDES prototype system using a case study. This was evaluated in the presence of a diverse group consisting of researchers, designers and students of engineering design. The evaluators were asked to give detailed responses to a comprehensive questionnaire regarding the overall approach as well as different functionalities of the PROCONDES system. The critical evaluation of the results have been compiled and presented in section 8.4. This shows that the Function to

PDE mapping model implemented in the PROCONDES system proactively supports decision making at conceptual design stage by:

1. *Generating and prompt highlighting of the context knowledge consequences (good/problematic) of selecting a particular solution.*
2. *Evaluating different design alternatives according to different design criteria comprising functional requirements, life cycle constraints and from the perspective of users and the environment.*
3. *Assisting decision making in selecting the best design alternative fulfilling functional requirements and avoiding problematic consequences.*

However, further work is needed to improve the different functionalities of the PROCONDES system in order to make it more acceptable for use in an industrial environment. The ways by which these can be achieved is discussed in the subsequent chapter.

9 Discussion and Future Work

This thesis details the research work carried out in order to develop a framework for conceptual design decision support, which proactively supports designers in making an informed decision at the conceptual design stage. This chapter discusses the overall research conducted as well as the contribution of the research to the existing knowledge. The first section discusses about the research results. Second section assesses the research results on the basis of the evaluation done in chapter 8. The final section of this chapter proposes and discusses the future work that needs to be carried out to extend this research in different directions.

9.1 Research Results

This research makes the following contributions to the existing engineering design knowledge:

1. Critical review of the existing methods and the corresponding tools and frameworks to support conceptual design decision making highlighting the strengths and weaknesses of the related work (Chapter 3).
2. Formalizing design context knowledge by characterizing it and classifying it into different groups and categories (Chapter 5).
3. Presenting Product Design Elements (PDEs) as means to realise functions in mechanical conceptual design by proposing a Function to PDE/means mapping model to support proactive decision making at the conceptual design stage using design context knowledge and Analytic Hierarchy Process (AHP) decision making theory (Chapter 6).
4. Implementation of the model to develop PROCONDES (*Pro*-Active *Con*ceptual *Des*ign) prototype computer based system (Chapter 7).

The main contribution is the development of Function to PDE/Means mapping model, which supports proactive decision making at the conceptual design stage. The following subsections highlight these contributions in detail.

9.1.1 Review of the Existing Methodologies and Frameworks

The review of the existing methodologies (section 3.1, 3.2, 3.3, 3.4) related to conceptual design decision making support shows that there is no existing method/technique, which presents and enables a holistic view of conceptual design decision making. There is not a single methodology, which provides knowledge/information for the consideration of the designer during decision making from the whole context of the design problem i.e. from life cycle view, designer's geo-socio-political environment as well as from product's use/working environment. Not only is there a need to identify the whole *context* or *contextualised information/knowledge* of design but also to formalise it in some structured form and present it for the designer's consideration early during the synthesis stage of design. This is when decision making takes place at the conceptual design stage and designers must require this information to foresee any life cycle consequences. The strengths and weaknesses of different prototype systems/tools implementing these methodologies are presented in Tables A-1, A-2 and A-3 in Appendix-C. These collectively form the state of the art review in the chosen research fields. The review results of the frameworks and the computer-based tools in Appendix-C are also a part of the contribution this PhD project makes. Although the tools analysed/reviewed in the tables have been critically analysed by others previously, no review has been conducted to study the research findings from the three key characteristics of decision making at the conceptual design stage i.e. *Detailed Functional Requirements, Decisions' Consequences Awareness and Selection of Criteria and Evaluation of Alternatives.*

9.1.2 Characterizing and Classifying the Design Context Knowledge

Design context knowledge is an important source of product background knowledge and it can and should influence design decision making, which result in design consequences. By exploring the design context knowledge, designers can gain insights into understanding of the design problem and the solutions generated with an increasing emphasis on the product life cycle performance. Design context knowledge can provide sophisticated keys to identify optimal life cycle solutions. Due to its dynamic nature, design context knowledge changes during every design problem solving situation. Adequately relating this knowledge and using it as a guide can lead to design solutions, which are most relevant and optimised for a given product application context. Failing this, designers' decisions will be imposed onto a particular application, which may lead to less optimised or even unsuitable design solutions. This research identifies *'Context'* as *the related surrounding knowledge of a design problem at a given moment in time for consideration* (section 5.1). *Design Context Knowledge* is formalized into six main groups. These groups are *Life Cycle Group, User Related Group, General Product Related Group, Legislations and Standards Group, Company Policies and Current Working Knowledge* (i.e. is partial solution information generated up to the current stage of the design process for a given problem). As the first three groups in the list are generic in design domain and can be applied in any company based design scenario, therefore this PhD research is focused on the first three groups of context knowledge. Based on the understanding of the design problem domain studied in this research, these three groups have been further classified into ten more refined context knowledge categories for general mechanical component design problems (section 5.3). It has been observed that these categories are by no means exhaustive and the number of the categories could increase or decrease depending upon the nature of a design problem under consideration. However it is argued that in the metal component design problem and specifically in sheet metal component design, the selected context knowledge groups can be and have been classified in ten different context knowledge categories in order to support designers at the conceptual design stage. Design context knowledge in these categories has been used to elicit design solution consequences through the reasoning process. These consequences would occur at the later life cycle stages of the product due to the selection of a particular conceptual design solution. The use of context knowledge categories allows the reasoning mechanism to derive the potential good and problematic consequences. This will enable the designer to foresee the implications of his/her decisions early at the conceptual design stage.

Additional context knowledge categories to these ten categories related to the other two groups of the design context knowledge should be considered in a company based real design environment. The methodology and approach developed in this research can be used successfully to extend the classification of more categories of knowledge in the other context knowledge groups.

9.1.3 Function to PDE/Means Mapping Model Development

Having classified context knowledge in different context knowledge categories the next step in the research was to make complete use of the defined categories of context knowledge. This has been realized by developing a framework to reason and generate consequence knowledge encompassing different stages of function based conceptual design in order to support decision making. Chapter 6 presents reasoning as an important mechanism in providing proactive support to decision making at the conceptual design stage. Function decomposing generates detailed and low-level function definition in order to map functional requirements to solution means. Function decomposition results in Product Design Elements (PDEs) i.e. a product break down structure at different hierarchical levels from the constructional view point. It has been shown that PDEs in metal component design at the *component level* are commonly known as manufacturing features, which can be used to realize different functional requirements of the product (section 6.1.4).

This thesis uses "*function based conceptual design*" as discussed in section 4.3. This approach refers to the process of generating a design solution using available well-understood function-PDE relationships to identify suitable means in the form of PDEs. Functional requirements are decomposed as design solution requirements in different context knowledge categories and are presented as a functional model. The generated PDEs are further decomposed into different attributes like *Material attributes* (Name, Physical properties), *Form attributes* (Shape, Structure) and *Surface Finish attributes* (Type of Finish, Degree of Finish). These different attributes together constitute the form/structural model of PDEs/solutions. Based on this information and using the design context knowledge base, the behaviour of each solution is assessed against ten different categories of the context knowledge. The generated information about the behaviour of each solution/PDE is presented as a behavioural model. A design context knowledge based reasoning mechanism has been proposed as a key method to generate context knowledge consequences in order to support the designer at the conceptual design stage (section 6.2.4.1). Thus simultaneous rule based reasoning of the functional and behavioural models is used to elicit the context knowledge consequences caused by selecting a particular design solution in each category.

Based on this reasoning mechanism, providing design decision consequences related to the different life cycle phases of the product, the user of the product and the product itself enables the designer at the conceptual design stage to foresee/anticipate any problems that may occur as well as the behaviour of a selected solution in the different life cycle phases and its impact on the user. Thus the proposed Function to PDE mapping model (section 6.2) provides proactive decision making support to the designer.

Consequences generated in each context knowledge category for the selected solution helps the designer to rate each design solution/PDE in terms of the numerical degrees of their suitability. These degrees of suitability must be then be converted into some percentage preference weightings. The model uses the Analytic Hierarchy Process (AHP) (a decision making theory used in the field of operational research) as a decision making method to convert degrees of suitability of a design solution and the designer's preferences into percentage weighting using its rating scales and normalization method. The model encompasses different stages of the function based conceptual design starting from the functional requirements and concluding by selecting the optimum design solution in terms of a PDE which not only satisfies functional requirements but also meets the design requirements from different perspectives.

9.1.4 PROCONDES System Development

Due to the limited human memorising capability and the inability of processing vast amounts of information simultaneously, the Function to PDE mapping model has been implemented to develop a computer based prototype system called

PROCONDES (chapter 7). Sheet metal components have been selected as the domain of implementation for the PROCONDES system and the context knowledge related to the sheet metal forming technology has been coded into the system. Whilst the proposed architecture of the PROCONDES system (section 7.4), shows the concurrent conceptual process design for the PDEs/solutions, however due to time constraint of the PhD project, all desired functionalities could not be fully realized in the implemented prototype system.

There are several modules provided within the PROCONDES system to interact effectively with the different functionalities of the software during the different stages of the conceptual design process. *Function Specifier/Editor* allows the designer to select a desired functional requirement to be fulfilled from the list of functions provided in the system. Once the function to be realized is selected, then the functional requirements can be input using the appropriate dialog box. *Design Solution Requirements* module allows the designer to input different requirements that are needed of a solution from the following three perspectives, i.e. life cycle related, user related and general product related. Different conceptual design solutions/PDEs generated by the system can be browsed both in textual as well as in three dimensional form using *Solution viewer* module. Different graphical image manipulation functions are also provided in the PROCONDES like *zoom, pan, dynamic rotate, isometric-view, top view, bottom view, side views* etc. as well as different lighting options *like normal shading, gouraud shading, hide* to view the generated solution from different angles and with different effects.

Design Context Knowledge generated in three different groups under different categories regarding each conceptual design solution/PDE can be viewed using Context knowledge browser. This enables designer to simultaneously browse through different pieces of information generated under different categories of context knowledge in order to compare different conceptual design solutions. There is a provision for checking consequences generated due to the context knowledge so that designer knows potential good or problematic implications/consequences associated with each piece of context knowledge triggered by a design decision.

Suitability of the generated context knowledge to a designer's requirements can be viewed using the *Suitability Indicator m*odule. The designer can view degrees of suitability of a generated solution for design solution requirements against a context knowledge category on a scale of 1 to 5. These degrees of suitability are converted into a percentage weighting using Analytic Hierarchy Process (AHP) rules and can be viewed using the facilities available from the *Context Knowledge Weighting* module. The designer can specify his/her own preference in percentage weighting against each context knowledge category in order to reflect his/her experience, market demands/trends and the company policies. This can lead to the selection of an optimal design solution, which not only meets the functional requirements but also accounts for the design context knowledge and the corresponding consequences related to different stages of the life cycle of the product.

9.2 Research Results Assessments

Chapter 8 evaluated the Function to PDE/Means mapping model by demonstrating a case study performed using the developed prototype PROCONDES system. This section assesses the overall research results in terms of their strengths and weaknesses.

9.2.1 Research Results Strengths

The strengths of this research are described in the following subsections:

9.2.1.1 Context Consequence Knowledge Awareness Early During Design Synthesis

Design context knowledge has been the main focus of this research and has been defined as the related background information of the design problem under consideration. Design context knowledge is an important source of product background knowledge and can contribute to and form design consequences. Function to PDE/Means mapping model developed in this research exhibits the timely and prompt generation of design context knowledge and associated consequences by virtue of reasoning during the synthesis of the conceptual design. Design context knowledge refers to the constraints imposed on design decisions of products by different life phase systems, users of the product and the product itself.

Designers are often unaware of these limitations due to their limited knowledge about these areas/issues. As design decisions become more related to other factors, it is very difficult, if not impossible, for designers to know about this huge repository of knowledge related to different issues that interact with the product during its life cycle. Thus the Function to PDE/Means mapping model makes the designer explicitly aware of the context and the consequence knowledge when a particular design solution is selected early at the conceptual design synthesis stage.

9.2.1.2 Proactive Support to Decision Making

The function to PDE/Means mapping model not only generates and highlights design context knowledge as well as related consequences but it also uses them in providing proactive support to the designer during decision making in conceptual design. The case study performed during evaluation of the PROCONDES system showed that simultaneous reasoning of the context knowledge under three different groups as well as current working knowledge in different categories generates potential consequences of selecting a particular solution. These consequences can be either good or problematic and have an impact on the later life cycle stages of the product, the potential users of the product and on the product itself. Designers are often unaware of these limitations and as design decisions are made based on various factors, it is very difficult, if not impossible, for designers to foresee these potential decision consequences. These also provide useful insights about the downstream implications of a design decision by proactively supporting early stage design decision making with timely prompts.

9.2.1.3 Support to Evaluation of Alternatives & Selection of Best Solution

The case study performed during the evaluation of the PROCONDES highlighted that the prototype system evaluates different alternative PDEs/solutions based not only on the functional requirements but also on different life cycle, user related and product related concerns using these as criteria to evaluate different alternative solutions. Each PDE based design solution is evaluated against different context knowledge categories and based on this evaluation degrees of suitability to the functional requirements are assigned. These degrees of suitability are converted into weighted percentages using the AHP theory rules. This gives the designer a clear indication of how suitable a PDE based design solution is with regard to a particular context knowledge category, in addition to fulfilling the functional requirements.

The PROCONDES system evaluation also depicted that while selecting a best solution, a designer is still given a choice to indicate his/her preference in terms of percentage weighting to a context knowledge category. This supports a designer to use his/her experience, personal preferences and company/departmental policies in the process of decision making while selecting the best solution out of different design alternatives. Thus the approach and the associated system provide an informed decision making support, rather than forcing a designer to pick the solution generated by the system.

9.2.2 Research Results Weaknesses

Certain inherent weaknesses of this research were highlighted by different evaluators during the evaluation process of the PROCONDES system. Most of the evaluators were of the view that it will not be possible to use the PROCONDES system in its present form in a commercial environment without further work and refinement.

One of the weaknesses highlighted by 38% of the evaluators was the level of user interface available within the PROCONDES system. They were of the view that the textual representation of the different phases of the case study was not quite clear specifically while providing explanation of the different design solutions generated during the conceptual design process.

The second criticism levied was with regard to the choice of the case study used for the purpose of study. They felt that the case study used is too simple and easy and that there is need to implement more complex case studies in order to check the validity of the Function to Means/PDE mapping model for more complex and difficult design tasks which would be reflective of the real world problems.

The third weakness of the PROCONDES system highlighted by 31% of the evaluators was with regard to the level of context knowledge categories used for defining the design problem in the case study. They felt that the amount of information under each context knowledge category is not exhaustive so as to explore all information and corresponding consequences while selecting a particular solution during the conceptual design. They argued that in real design scenarios, context knowledge categories related to other groups such as company specific guidelines and internationals standards/legislations/guidelines dictating the design of a specific product plays an important role in conceptual design decision making and the PROCONDES system has currently no facility to upgrade/maintain such context knowledge in the design context knowledge base.

Another weakness of the PROCONDES system is that it depicts a successful implementation of the Function to PDE mapping model only in the sheet metal domain, where assembly or conveyance type of functions are mostly employed. However, there are other types of functions employed in other mechanical engineering design domains and the implemented PROCONDES system currently does not support decision making in those domains. Examples of these components include those made of thermoplastics and other materials.

Whilst evaluators appreciated the approach of supporting decision making using the design context knowledge, they were of the view that significant improvements were needed in the PROCONDES system to fully implement the Function to PDE/Means mapping model for use in a commercial/industrial environment.

9.3 Future Research Directions

There are certain avenues where future research initiatives can be made. These include improvements in the Function to PDE mapping model as well as in the PROCONDES prototype system.

9.3.1 Improvements in the Function to PDE/Means Mapping Model

An improvement in the Function to PDE/Means mapping model entails further study and determination of the relationships of different parameters which influence the context based function and solution reasoning. For example, it needs to examine the relationship of the currently considered function with other functions of components, the impact the relationship has on the mapping of the considered function to those PDEs solutions, which have already been mapped. This will enable identification of conflicts if any that would arise by realizing a function with the currently considered PDE based solution and the solutions, which are already mapped to the previous functions. The study will also enable development of a conflict resolution mechanism to solve this research problem.

Another improvement is to extend this model to represent vagueness and uncertain information at the conceptual design stage. There is a need to find out how to model and analyse vague information and develop algorithm(s) to make it suitable for function and design solution reasoning. This will result in developing innovative and creative design solution selection by giving the designer a clear indication of the best solution alternative in spite of having vague/incomplete information about the functional requirements and the design solutions.

Another improvement could be to develop a mechanism, which can elicit, structure, represent and use context knowledge for reasoning purposes from the published work like books, journals and conference proceedings.

The approach of proactive decision making presented in this research could be extended from *function* based conceptual design to *component* based conceptual design in which the product model is constructed by assembling physical components selected from a database and then interface conditions and other constraints like spatial, physical etc so as to develop a conceptual solution.

9.3.2 Improvements in the PROCONDES System

As indicated by different evaluators, there is a need for improvement by incorporating suggested changes within the PROCONDES system in order to make it a commercially successful software system. Apart from improving the user interface specifically with regard to the textual interface, a provision of context knowledge maintenance facility is essential for upgrading the context as well as the consequence knowledge. This can be achieved by linking it to some external database sources.

While the current working of the PROCONDES system is suitable only for a single designer, it can be extended to include team based design. This implies that different designers located in different parts of world must be able to access the software located in a central server and indicate their selection of the design solution requirements as well as percentage preferences so that a consensus can be reached in mapping a single function to a PDE/solution or to work simultaneously in mapping different functions to PDEs on a single product in an interactive environment.

There was also a suggestion during the evaluation of the PROCONDES system to implement the concurrent process design of design solutions in terms of identifying the basic tooling and machine parameters required to manufacture a particular solution/PDE on the sheet metal component simultaneously with its selection as proposed in the architecture of the PROCONDES system. This would enable designers to have more knowledge about the realization phase as well as the corresponding realization systems required to manufacture a particular solution thereby reducing overall cost and lead time.

At present design solutions/PDEs are stored in the software as components or can be imported in different file formats from outside the program. Some evaluators also suggested integrating the PROCONDES system to online industrial catalogues of standard components through the Internet, so that more choices are available to the designer to explore more alternative design solutions/PDEs.

9.4 Chapter Summary

This chapter reviews the overall research work carried out during this PhD and discussed its original contributions to the existing knowledge base. Section 9.1 describes the results obtained in this research which are detailed below:

1. Characterization and classification of design context knowledge
2. Function to PDE/Means mapping model development to support proactive decision making at the function based conceptual design

3. Development of the PROCONDES prototype system to demonstrate the proof of the concept of the model.

Section 9.2 discusses the strengths and weaknesses of the research results collected on the basis of the questionnaire survey carried out as part of the evaluation of the PROCONDES system. Section 9.3 presents certain improvements and further work that can be carried out to refine the research in terms of the Function to PDE mapping model as well as in the PROCONDES system. The next chapter presents the conclusions of this research.

10 Conclusions

This chapter concludes the research presented in this thesis from three perspectives i) Proactive decision support for mechanical component design at the conceptual design stage ii) Development of the PROCONDES prototype system iii) Future research directions to extend the work undertaken during this research.

10.1 Overall Conclusion

This research has demonstrated that the *design context knowledge* is an important and useful surrounding knowledge/information of the product to be designed. Currently this knowledge has not been properly defined/structured for exploitation. This research has demonstrated that by formalizing and fully representing design context knowledge, a designer, with the help of a computer based system such as PROCONDES, can be empowered to foresee potential life cycle and other design decision consequences. This capability can change the way designing is carried out and enhance the existing design process considerably. Design context knowledge in the background of design process helps designers to process vast amounts of potentially related design information and prompts useful insights when they are available through reasoning. Reasoning using context knowledge can further assist designers to concentrate on exploring design alternatives and generate more innovative design solutions. All these help to reduce and eliminate the chances of redesign as life cycle implications have been considered earlier at the conceptual design synthesis stage due to the selection of a particular solution. With regard to this, the proposed design context knowledge based Function to PDE/solution Mapping Model and its implementation in the PROCONDES system in this research successfully highlights the potential good and problematic consequences to the designer earlier at the conceptual design stage. This provides proactive decision support as well as establishes a mechanism to select the best solution against the functional requirements and the different life cycle implications thus supporting conceptual design synthesis for Multi-X as well.

Detailed lower level conclusions are given in the following subsections.

10.2 Proactive Decision Support

Conceptual design is an early phase of the design process, which involves synthesis, generation and evaluation of design solutions, satisfying the functional requirements or life cycle requirements of a design problem. Chapter 2 explains the importance of conceptual design for the overall success of the product. To elucidate, once the conceptual design process has been finished, the majority of the product cost and quality has been committed and fixed by selecting particular concepts/solutions. These in turn have a bearing on the subsequent product life cycle activities (i.e. manufacturing, assembly, use, recycle/disposal) and on the chosen conceptual solutions. Designers therefore require complete understanding about three different interacting characteristics, which are essential for effective decision making. These are *Detailed Functional Requirements*, *Decisions' Consequences Awareness* and *Selection of Decision Criteria and Evaluation of Alternatives.*

Chapter 3 presents a review of the existing frameworks and methodologies that have been proposed by different researchers to support decision making at the conceptual design stage with respect to these three key areas. Chapter 4 illustrates the results of this review and highlights the lack of understanding about the artefact's behaviour and modelling. Most of the existing methodologies and frameworks developed either present segmented or late design consequences' awareness. None of the developed methods consider the dynamic nature of the conceptual design process. It is therefore necessary for the designers to be aware of the consequences of their decisions taken at the conceptual design stage not only on the later life phases of the product but also on the whole context of the design problem under consideration. For this purpose Chapter 5 characterizes *design context knowledge* as *the related surrounding knowledge of a design problem at a given moment in time for consideration.* By exploring design context knowledge, designers can gain insights and understanding of the design problem and the solutions generated with an increasing emphasis on the product life cycle performance. Chapter 5 formalizes design context knowledge in six different groups namely *Life Cycle Group, User Related Group, Product Related*

Group, Legislations & Standards Group, Company Policies Groups, and Current Working Knowledge Group. The first three groups being static in nature and domain and company independent are further classified into different categories. The number of categories in each group depends upon the design problem under consideration.

Chapter 6 presents Product Design Elements (PDEs) at component building level as a reusable design information unit (element) representing a potential solution means for a functional requirement. Design context knowledge based function and solution/PDE reasoning can be used to provide proactive support for decision making. The developed reasoning mechanism illustrates the importance of design context knowledge and its use to support decision making during function to PDE mapping process (conceptual design stage) by generating potential good or problematic consequences through simultaneous reasoning of the required context knowledge in one category and generated context knowledge of the PDE/solution under consideration for selection at that moment. Based on the reasoning mechanism a generic design context knowledge based Function to PDE mapping model is proposed to support decision making at the conceptual design stage and is explained through an example. Four more paper based case studies selected from different design domains within the mechanical engineering are conducted to highlight the successful application of the developed model as a generic framework to solve conceptual design decision making problems.

10.3 Development of the PROCONDES Prototype System

The reasoning mechanism showed that there could be 'n' number of consequences generated during the reasoning process. Due to the limited capability of the human beings to reason and remember a large number of consequences and incapability to handle large chunks of knowledge, Function to PDE mapping model is implemented in Chapter 7 to develop a computer based prototype system called *PROCONDES* (*Pro*-Active *Con*ceptual *Des*ign).

The system architecture demonstrates the use of different modules, which interact and facilitate the designer during mapping of the functional requirements to PDEs.

The interaction of different working models within the proposed system is also shown. In order to provide proof of the concept system, only two case studies related to sheet metal engineering design domain was implemented in the PROCONDES prototype system. The inability to implement the system on a broader domain encompassing several case studies has been mainly due to the lack of time and the complexity of the large number of context and corresponding consequence knowledge. However, through this implementation (i.e. restricted to two case studies related context knowledge) and subsequent evaluation, it has been proven that the PROCONDES system does provides proactive decision support. It is however argued that using the same method, the approach can be extended to other case studies.

Chapter 8 evaluates the developed Function to PDE mapping model using a paper based case study as well as the developed PROCONDES prototype system by performing the case study of mapping a functional requirement in a sheet metal component design problem to a PDE/solution. Different stages of the case study along with results in the form of input of functional requirements, selection of design solution requirements, generated solutions in graphical/textual form, generated context knowledge and corresponding consequences, assignment of the degrees of suitability and selection of the best solution is shown through screen dumps. The case study is performed before different researchers as well as students of engineering design. The feedback of the case study is gathered by doing a questionnaire survey.

The evaluation results indicated by the evaluators confirmed that both the Function to PDE mapping model as well as the PROCONDES prototype system provides proactive decision support to the designers at the function based conceptual design stage. However there are lot of improvements and suggestions highlighted by the evaluators during the survey, which need to be implemented in the PROCONDES prototype system in order to use it in a practical environment.

10.4 Future Research Directions

Apart from the weaknesses and limitations in PROCONDES identified during its evaluation in Chapter 8, Chapter 9 highlights certain areas where future research can be directed both in Function to PDE mapping model and in the PROCONDES prototype system so that it can be used successfully in a practical industrial environment.

These research directions are:

- Extending the model to represent vagueness and uncertain information in decision making.
- Determining the relationships of different parameters, which can influence the context based function and solution reasoning e.g. relationship of currently considered function with other functions of components previously realized.
- Improving user interface especially textual interface, provision of context knowledge maintenance facility by linking it to some external database source is essential for easy up gradation of context as well as consequence knowledge.
- Extending the model as well as the PROCONDES system to team based design approach.
- Including the concurrent process design of conceptual design solutions in terms of identifying the basic tooling and machine parameters required manufacturing a particular solution/PDE.

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Appendix-A: Glossary of Terms

Term	Definition
AHP	Analytic Hierarchy Process: A decision making method
AI	Artificial Intelligence: A branch of science
Artefact	An item made/manufactured by man as material object utilizing some resources
Awareness	Having Knowledge of
CBR	Case Based Reasoning
CN	Constraint Network
Component	A single material element manufactured without assembly operation
Consequence	An outcome of a decision commitment
Constraint	A restriction to a set of alternatives
Context	A related set of facts and circumstances
CSP	Constraint Satisfaction Problem
Decision Commitment	An option selected from different alternatives
Decision making	The cognitive process of reaching a decision
DFA	Design for Assembly
DFC	Design for Cost
DFD	Design for Distribution
DFM	Design for Manufacturing
DFX	Design for "X"
DOE	Design of Experiments
FBS	Function-Behaviour-Structure
Feature	An information unit (element) representing a 'region of interest' within a product
FMEA	Failure Modes Effect & Analysis
Functional Requirements	What a system/artefact/product should be able to do?
Knowledge	Data, information and experience, which support the inference of new facts from given facts
LCC	Life Cycle Consequence: A consequence influencing artefact's difference life phases
Life Phase	A time period in artefact's life during which artefact changes its state like design, manufacturing, assembly etc
Mapping	A process such that for every element of one set there is a at least one or more unique elements of another set
MAUT	Multi Attribute Utility Theory

OR	Operational Research: A branch of science
PDE	Product Design Element: An element that forms part of a mechanical artefact system
PDS	Product Design Specifications
QFD	Quality Function Deployment: A method developed to incorporate customer's voice in design process
Reasoning	The drawing of inferences or conclusions from known or assumed facts
Solution Means	A concept/object to realize a particular functional requirement
Synthesis	The process or result of building up separate elements, especially ideas, into a connected whole, especially into a theory or system

Appendix-B: Conceptual Design Definitions

This appendix explores about the conceptual design process by explaining different definitions of *conceptual design* process used by research community. These are:

- Adzhiev et al. [Adzhiev et al. 1998] describe *conceptual design* as a process of negotiation that is closely associated with the identification of an experimental context and involves developing concepts consistent with experience. *Conceptual design* activity is related with the development of mental conceptions through experiment with physical prototypes.

- Eder [Eder 1995] defines *Conceptual Design* evolves from *"starting to understand and develop a design specification"*, to *"starting to draw a dimensional layout*". This process should be carried out in a logical sequence that allows an engineer full and intuitive freedom to think about and comes up with ideas.

- French [French 1985] states that *Conceptual Design* is the phase that takes the statement of the problem and generates broad solutions to it in the form of schemes. It is in conceptual design where the greatest demand is made on the designer and where there is the most scope for making improvements.

- Navinchandra [Navinchandra 1992] defines *"Conceptual Design is that part of the design process in which: problems are identified, functions and specifications are laid out and appropriate solutions are generated through the combination of some basic building blocks"*. He also states that conceptual design unlike analysis has no fixed procedure and involves a mix of numeric and symbolic reasoning.

- Pugh [Pugh 1990] emphasises that the *Conceptual Design* is the core phase of design process and is primarily concerned with the generation of solutions to meet the state need; in other words, it involves generating solutions to meet the Product Design Specifications (PDS).

- Roozenburg and Eekels [Roozenburg and Eekels. 1995] states that *Conceptual Design* is commonly seen to be the most important phase of the design process, because the decisions made here will strongly bear upon all subsequent phases of the design process. A weak concept can never be turned into an optimum detailed design. In addition the main functions of the conceptual design stage are to generate and evaluate broad solutions, given the specification, which provides a suitable start up point for embodiment design and detail design.

- Sturges [Sturges et. al 1993] defines that *"A Conceptual Design process begins with questions and inexact design specifications, and then ends with detailed specifications"*. In this process, the inter-functional dependencies of a design can be identified by performing a systematic search.

- Welch & Dixon [Welch & Dixon 1992] defines that *Conceptual Design* is the transition between four different information states:

    - A set of required functions;
    - A set of behaviours that fulfil the functions; and
    - A set of preliminary systems that meet the behaviours

  They stress upon the role of behaviour in conceptual design and argue that to solve a conceptual design problem the explicit use of a behavioural reasoning is a key step instead of trying to map directly from function to form.

- Wolter & Chandrasekaran [Wolter & Chandrasekaran 1991] state that *Conceptual Design* is a top-down process beginning with a gross functional description of the system being designed and a decomposition of the system into an interrelated network of simpler functional units, and then selecting mechanical structures to perform each of these sub functions.

Appendix-C: Review of Tools/Frameworks

This Appendix details the review of tools/frameworks based on the methods discussed in sections 3.1, 3.2 and 3.3.

Table A-1: Review of existing work related with function, behaviour and form modelling

Research Work	Stages of Review				Review/Comments
	Functional Representation/ Decomposition	**Behavioural Representation**	**Form/Structure Modelling**	**Support for Design Decision Making**	
Schemebuilder [Bracewell & Sharpe 1996]	• Bond Graph technique used to represent the required functions. • A knowledge base of basic functions is provided to decompose the required function through previously defined relationships.	• Working principles are retrieved from the database on the basis of function reasoning to illustrate the behaviour of product through bond graphs.	• Textual representation is used to represent/model the form of product retrieved through functional embodiment knowledge base.	• The support for different design alternatives is limited to the simulation of different schemes generated by the system. • Expert system advice is also available in some cases.	*Strengths* • Good for inter disciplinary product design. • Good simulation of behaviour through the integrated use of MATLAB. • Automatic generation of different design alternatives. *Weaknesses* • Suitable only for functions related to energetic/motion relationships.

					• Display of final selected solution in textual form not able to display in graphical form, hence not allowing the designer to visualize the structure of selected means/solution. • Inter function relations are not clearly highlighted through bond graph techniques.
FuncSION [Chakrabarti & Bligh 1996]	• Vectors are used to represent the design problem such as different types of velocities. • Function is defined as a transformation between a set of input characteristics and set of output characteristics.	• The behaviour is illustrated through the constraint propagation using a knowledge base of spatial information about a set of primary functional elements. • The constraints are represented using constraint networks using nodes connected by different arcs.	• The form/structure of solution is represented by output vectors. • The solution structures are vector transformers, which transform a set of input vectors into a set of output vectors; these transformers are represented by length vectors.	• No description.	*Strengths* • A new description of functional requirements/solutions using vector based approach. • Clear description of topological and spatial configurations throughout the function-means evolution process. *Weaknesses* • The vector-based approach is suitable only for a specific class of functional requirements, which involve transmission, and transformation of mechanical forces and motion. • The system is limited to the generation of different design alternatives, there is no support provided to evaluate these alternatives against some criteria.

					• The system is domain specific, i.e. functional reasoning approach adopted cannot be used in other type of design domains like assembly problems.
Function to Form Mapping Model. [Roy et al. 2001]	• An object oriented textual representation has been used to describe functions. • Functions can be decomposed into sub functions using previously defined relationships in a database.	• Behaviour model is represented using a set of values of parameters of the function either at specified time or a series over a period of time. • Both artefact's functional behaviour and kinematic behaviour is depicted using textual representation	• Different Means and corresponding structures are retrieved from artefact library on the basis of functional and behavioural reasoning. • Text based natural language representation is used for modelling different means and corresponding structures.	• A comparison of values of different parameters associated with each design alternative is given.	*Strengths* • The proposed model of representation is extended in further stages of design process to include tolerance synthesis and analysis as well. • Well and detailed description of functional requirements throughout the design process-using object oriented technology. *Weaknesses* • The form/structure of artefact is limited to textual representation, which does not provide the clear idea about the structure of artefact to designer. • The model is suitable only for functions defined already in the library. The library of functions is limited to motion related functions. Addition of other type of functions such as Assembly/Support related functions couldn't be successfully modelled.

Function Design Model [Deng et al. 2000]	• The functions are represented using object oriented class hierarchies based on natural language representation. • The automatic decomposition of functions is generated using domain specific guidelines provided in functional knowledge base.	• A new input-output synthesis approach has been defined to illustrate the behaviour of product by generating graphs between different input and output state nodes.	• Meta level design knowledge, which includes both function decomposition design knowledge and function to physical means mapping knowledge, is used to generate the structures of artefact, which correspond the illustrated behaviour. • The different mapped physical structures are represented using two-dimensional graphical illustration as well textual description.	• No description has been provided.	*Strengths* • Easy to maintain and manage the knowledge due to classification in three different types of knowledge, i.e. meta-level knowledge, physical level knowledge and geometric level knowledge. • Good consistent representation of function throughout different stages of function-means evolution process providing clear idea of required function/sub functions. *Weaknesses* • No method/mechanism provided to evaluate all possible solutions/structures against some criteria. • In some cases it would be difficult to analyse completely the physical structure using two-dimensional representation such as spatial arrangement of complex assembly problems.
Function-Behaviour-State Modeller [Umeda et al. 1996]	• Object oriented textual representation is used to model functions. • Functional decomposition is	• Function-behaviour relationships are used to model the behaviour. • Behaviour is modelled using nodes	• Natural language based textual representation is used to represent the form/structure required achieving the corresponding	No support is provided.	*Strengths* • Good clear decomposition of required function into sub function. *Weaknesses*

	performed using pre-defined relationships between functions and sub functions.	connected with function through arcs/elements creating a behaviour network.	corresponding function.		• The approach is limited to those functions, which are registered, in its functional knowledge base; it is not possible to establish a functional structure of generic function. • No criteria defined to evaluate different alternatives suggested due functional/behavioural reasoning process. • Behavioural simulation is not clearly illustrated. • Text based description of physical structure/form is good only for energetic type of functions as in this case but not in other type of functions.

FDS [Kirschman 1996]	• Objective Function is selected from taxonomy of functions stored in a database. Function decomposition is also retrieved from database. • The taxonomy is based on the four primary function types (Power, Motion, Control & Enclosure). • Natural language representation is used to represent the function.	• Some description of behaviour for different forms is given along with constraints associated with each form.	• Basic Forms associated with the each type of objective function are retrieved from the database on the basis of function-form relationships already defined in the system.	• Different generated means/forms are evaluated on the rating of three matrices. • These matrices (Pleasure, Protection and Inverse Cost) are based on the voice of customer.	*Strengths* • Good database of functions, covers most type of mechanical artefact relating functions. • Clear and precise indication of use of matrices to evaluate design alternatives. *Weaknesses* • The relationship of behaviour with function and form is limited to a very abstract level thus restricting designer to make a decision. • The system is good for previously stored functions in the database. • Spatial constraints are not discussed.
[Simon et al. 1999]	• Standardised representation of functions related to energy in textual based format.	No description.	No description.	No description.	*Strengths* Good clear representation of function using textual based form. *Weaknesses* • No method is given about using the developed functional representation to link with artefact behaviour and form.

					• Textual representation works well only with functions related with energy/motion only.
[Welch & Dixon 1992]	• Mathematical equation based functional representation has been used. • User has to decompose him/herself a required function into sub functions.	• Behaviour graphs are used to illustrate the behaviour of artefact.	• Embodiment is represented as a function of behaviour, constraints, and evaluation criteria. • Text based representation of form of artefact.	No support is provided.	*Strengths* • Good for energy related problems and associated flows. *Weaknesses* • No support or information for design decision making. It is left to the discretion of designer to select a solution alternative. • The representation cannot work for functions other than transformation and transmission of energy. • Behaviour graphs cannot explain the kinematic and spatial relationships of structure of artefacts.
MOSES [Henson et al. 1994]	• Object oriented representation has been used in order to represent function using C++ class structure.	• The artefact behaviour is represented by its state. A part state has different set of variables, which either define the part state or transition between states.	• Assemblies/subassemblies and components are represented by class hierarchies with specified mating conditions between them.	• No support.	*Strengths* • Good clear functional description and decomposition of objective function using class hierarchies. *Weaknesses* • No criteria to evaluate different means for final selection. • Assembly constraints and mating

					conditions cannot be viewed until graphical three-dimensional illustrations.

Table A-2: Review of representative work related with providing Decisions' Consequences Awareness

Research Work/Tool	**Technique /Method**	**Stages of Review**		**Review/Comments**
		Single X or Multi X/ Representation	**Awareness during Synthesis or Analysis**	
Decision Capturer [Herzwurm et al. 2003]	QFD	Single X, Only during *Use* phase.	Only Analysis mode, the candidate solutions can be analysed, when they are submitted by designer/user.	*Strengths* • A good structured approach, which takes through decision making process. • A realistic set of product target values during use phase that guarantees customers make happy and prioritised list of the items that are critical to quality. • Domain independent generic software, which can be used for any mechanical design domain. *Weaknesses* • Reveals only *'Use'* life phase interactions. • Not suitable for Multiple Life Cycle interactions simultaneously. • Awareness is late that is when design solutions have already been generated, can be used only in analysis phase.
RelFMECA [RelFMECA 2004]	FMEA	Single X, Only during *Use* phase.	Only Analysis mode, the candidate solutions can be analysed, when they are submitted by designer/user.	*Strengths* • Can be used for any mechanical product design domain. • Powerful information management capability through database interface.

				• Failure mode library functions reducing the task on of input. *Weaknesses* • Only standardized failure modes/situations can be analysed using the library/database function, not suitable to a specific use phase problem/failure. • Can be used only to reveal life cycle problems/concerns that could arise during 'Use' or 'Maintenance' phase. • Awareness is late that is when design solutions have already been generated, can be used only in analysis phase. • No Multi-X support.
FuzzyDFA [Coma et al. 2002]	Feature based design	Single X	Analysis mode only as solutions are presented for feature recognition after they are completely synthesized.	*Strengths* • Supports DFA method by estimating DFA requirements like weight, dimensions and type of part (rotational or not). • Identifies the optimal orientation of part and recognizes the features as the requirements of DFA method. *Weaknesses* • DFA methodology is applied during analysis phase thus awareness is late as solutions are already synthesized. • The feature technology is not used to illustrate other life phase concerns like manufacturing cost etc. • Complete DFA analysis is not performed.
IKA [Zirkel et al. 2001]	Feature based design	Multi X	During Synthesis.	*Strengths* • Good open architecture to add design information/modules during the course of designing. • Analysis of complex assemblies

				Weaknesses • Only support evaluation of design solutions during 'Use' and 'Assembly' phase. • Analysis of only pressure vessel and related components is possible. • Awareness is segmented and no interaction between different life phase concerns.
[Pham & Dimov 1999]	Feature Based.	Single X	Synthesis stage	*Strengths* • Good extraction of downstream assembly/planning information. • Integration of knowledge base allows generation of assembly strategies using deductive reasoning. *Weaknesses* • Awareness is segmented and no interaction between different life phase concerns. • Suitable only for machined components. • No method to use features in extracting manufacturability, cost information.
[Changchien & Lin 1996]	Expert System	Multi X	Analysis stage	*Strengths* • Corrective remedial actions are provided to the designer in order to avoid assembly problems. • Easy and Integrated manufacturability and assembly evaluation of the components. *Weaknesses* • Suitable only for rotational parts. • Awareness is segmented and no interaction between assembly

				and manufacturing concerns. • Late awareness during analysis stage.
[Baragetti & Rovida 2001]	Expert System	Multi X	Synthesis stage	*Strengths* • Choice of assigning weights to different life cycle attributes like maintenance, reliability, manufacturing etc. • A complete catalogue of Mechanical functions to choose from. *Weaknesses* • Suitable only for mechanical system/machined parts. • Awareness is segmented and no interaction between life cycle attributes.
[Farrugia et al. 2002]	Expert System	Multi X	Synthesis stage	*Strengths* • Good extraction of different life cycle information at sketching stage. • Introduction of sketching knowledge to reduce misinterpretation. *Weaknesses* • No underlying method to evaluate different sketches qualitatively based on the life cycle consequences generated. • It is not possible to use sketch language to represent complex parts Suitable only for machined components.
[Swift et al. 2004]	DFX Guidelines	Multi X	Synthesis stage	*Strengths* • Proactive DFA tool using DFA method both at synthesis and analysis stage. • Optimised number of assembly parts, selection of appropriate

				joining process selection with high degree of assembly efficiency. *Weaknesses* • No revelation of other life phase concerns apart from manufacturing and cost. • Awareness is segmented as no interaction between assembly and manufacturing consequences.
[Ferrao et al. 2003]	DFX guidelines	Single X	Analysis stage	*Strengths* • Optimised disassembly activities for recycling of components. • Automatic separation of the reusable and recyclable components of assembly based on increased recycling efficiency. *Weaknesses* • Suitable only for automobile components. • Awareness regarding optimised disassembly and reusable components is late. • No interacting multiple life phase concerns.
RAEGIE [Pierini et al. 2003]	DFX guidelines	Single X	Analysis stage	*Strengths* • Good support for the Design for Environment scenarios. • Early identification of malfunction of components supporting reliability of design as well. *Weaknesses* • Suitable only for exhaust components of automobiles. • No generic methodology about reliable design or design for

				environment. • Awareness regarding reliability is late i.e. at the analysis stage. • No interacting multiple life phase concerns.
DECMAT [Zhihui & Johnson 1997]	Constraint Network	Single X	Analysis Stage	*Strengths* • Good technique of design constraints clustering for constraint satisfaction. • Enhanced and robust constraint satisfaction tool. *Weaknesses* • Late awareness at embodiment design stage. • No multiple life cycle concerns. • Segmented awareness about 'Use' phase only.
[Medland et al. 2003]	Constraint Network	Single X	Analysis Stage	*Strengths* • Formation of Constraint rules based on values of design variables for constraint satisfaction. • Integrated ACIS solid modeller to specify some standardised components graphically. *Weaknesses* • Suitable only for High-speed machinery like conveyors, cassette holders etc. • Late awareness at analysis of design stage. • No multiple life cycle concerns.
[Xu et al. 2002]	Constraint Network	Multi X	Analysis Stage	*Strengths* • Formulation of constraints from different perspectives like design, manufacturing, assembly.

				• Constraint decomposition for efficient constraint satisfaction. *Weaknesses* • Limitation of team based approaches like lack of domain knowledge among different team members, less frequent occurrence of team meetings. • Late awareness at analysis of design stage when design solutions are already formulated and presented by teams. • Unable to add, solving and satisfying other team's constraints dynamically.
[Ip & Kwong 2002]	Taguchi's Method	Single X	Synthesis stage	*Strengths* • Formulation of constraints from different perspectives like design, manufacturing, assembly. • Concurrent process design of mould and moulding process. *Weaknesses* • Suitable only for transfer/injection moulding domain. • Analysis and Identification of critical parameters is based on process simulation, which could lead to wrong identification due to simulation process efficiency. • Awareness is segmented and no revelation about other life cycle concerns.
[Design Expert 2004]	Taguchi's Method	Multi X	Analysis stage	*Strengths* • Multilevel factorial screening to identify critical factors of design. • Generate desirable parameter settings using numerical

				optimisation for different responses. *Weaknesses* • Statistical based method not knowledge based therefore not specifically for product development. • User has to input different parameters and different critical responses (situations) that are likely to occur during different life cycle phases. • Awareness is late.
CCSS [Xu et al. 1999]	Case Based Reasoning	Multi X	Synthesis stage	*Strengths* • Multiple searching model and indexing to retrieve a close case to requirement. • Constraint management and utility management tool for conflict resolution. *Weaknesses* • Segmented Multi X behaviour. • Only product and process (manufacturing) concerns can be highlighted. • Limited application due to team based approach i.e. user has to pass solutions to different team members for the response of resolved conflicts to select a particular case.
[Jerzy et al. 2002]	Case Based Reasoning	Single X	Analysis stage	*Strengths* • Good Integrated Software with modern CAD system like CATIA. • Parameterised case based reasoning approach connected with design rationale concept. *Weaknesses*

				• Suitable only for the design of gears of automobiles (vans). • Only use phase concerns can be highlighted. • Not suitable for complex and variant gearbox designs.

Table A-3: Review of representative work related with Selection of Decision Criteria and Evaluation of Alternatives

Research Work/Tool	**Technique /Method**	**Stages of Review**		**Review/Comments**
		Number of Criteria (Single/Multiple)	**Type of Analysis (Quantitative or Qualitative)**	
DE-ACE [Bayliss et al. 1997]	MAUT	Single Criteria	Qualitative Analysis	*Strengths* • Different design agents to aid decision making in different life cycle phases like *assembly*, *manufacturing etc.* • Conflict resolutions among different agents. *Weaknesses* • No quantitative analysis of alternatives and only single level of criteria can be considered. • No method to rank different design alternatives in terms of percentage weighting or other scale.
[Dejeu et al. 2004]	IBIS	Single or Multiple Criteria	Qualitative Analysis	*Strengths* • Supports and analyses criterion-solution interactions (evaluation activity) to help designers understand design rationale. • Database support to store alternatives-criterion interactions. *Weaknesses* • No quantitative analysis of alternatives is supported. • No method to rank different design alternatives in terms of

				percentage weighting.
CDFMC [Zha & Lu 2003]	Uncertainty Representation	Single criteria	Qualitative and Quantitative Analysis	*Strengths* • Use fuzzy ratings to support uncertainty and vagueness in decision making. • Knowledge based in the form of heuristic rules to evaluate design alternatives *Weaknesses* • Suitable only for decision making in mass customisation of products. • Trade off between different criteria is done by using only heuristics knowledge/rules; no life cycle considerations are taken into account. • No pair wise comparison of alternatives against a criterion.
[Ariel & Reich 2003]	AHP	Multiple	Qualitative Analysis	*Strengths* • Maximizing robustness of decision making utilizing resources. • Modelling and solving optimal resource allocation. *Weaknesses* • No dynamic interaction between different criteria. • Life cycle considerations are not taken into account during decision making. • No method to incorporate designer's preference of criteria.

Appendix-D: Working of AHP

This appendix describes the working of Analytic Hierarchy Process (AHP)-a decision-making method, which has been used in this PhD research.

Background

The Analytic Hierarchy Process (AHP) is a powerful and flexible decision making process to help people set priorities and make the best decision when both qualitative and quantitative aspects of a decision need to be considered. By reducing complex decisions to a series of one-on-one comparisons, then synthesizing the results, AHP not only helps decision makers arrive at the best decision, but also provides a clear rationale that it is the best. Designed to reflect the way people actually think, AHP was developed in the 1970's by Dr. Thomas Saaty, while he was a professor at the Wharton School of Business, and continues to be the most highly regarded and widely used decision-making theory.

Working of AHP

The analytic hierarchy process (AHP) is a comprehensive, logical and structural framework, which allows improving the understanding of complex decisions by decomposing the problem in a hierarchical structure. The incorporation of all relevant decision criteria, and their pair wise comparison allows the decision maker to determine the trade-offs among objectives. Such multi criteria decision problems are typical for R&D project selection. The application of the AHP approach explicitly recognizes and incorporates the knowledge and expertise of the participants in the priority setting process, by making use of their subjective judgments, a particularly important feature for decisions to be made on a poor information base. However AHP also integrates objectively measured information (e.g., yields) where this information is available.

The AHP is based on three principles:

1. Decomposition of the decision problem,
2. Comparative judgment of the elements, and
3. Synthesis of the priorities.

The first step is to structure the decision problem in a hierarchy as depicted in Figure A-1. The goal of the decision is at the top level of the hierarchy. The next level consists of the criteria relevant for this goal and at the bottom level are the alternatives to be evaluated.

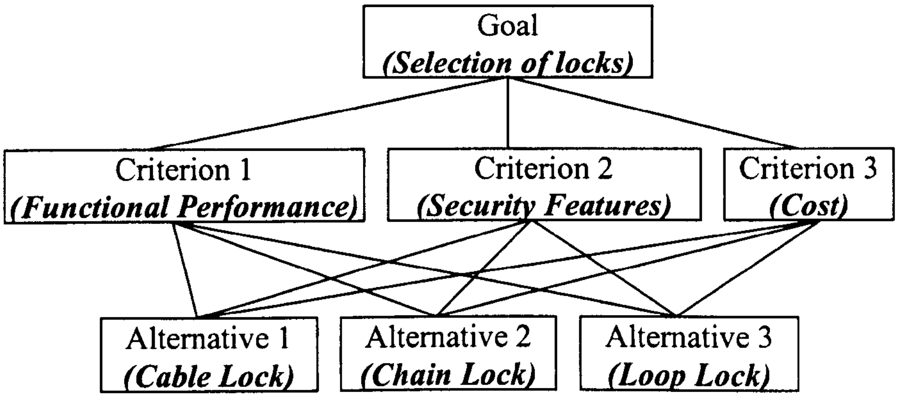


Figure A-1: Structure of AHP working

Example

This example has been developed by understanding the work done by Drake [Drake 1998]. The decision-making problem is "*Selection of a bicycle lock*". Five types of locks are available in the market named as *cable lock, chain lock, armoured lock, and loop lock.* Four selection criterion named as *Functional Performance* that is ease of operation of lock, *Physical Characteristics* which includes weight, appearance (colour) etc, *Security Features* includes strength of lock, type of locking mechanism and *Cost* includes purchasing cost and maintenance cost.

After defining the selection criteria, the next step is the pair-wise comparison of the different selection criteria. This comparison is performed by assigning different weights, which range between 1 (equally important) and 9 (absolutely more important) to the more important criterion in a pair of criterion. The reciprocal of these values is then assigned to the other criterion in the pair as shown in Figure A-2.

1 Objectives i (*Functional Performance*) and j (*Cost*) are of equal important.

3 Objective i (*Functional Performance*) is weakly more important than j (*Physical Characteristics*).

5 Objective i (*Cost)* is strongly more important than j (*Physical Characteristics*).

7 Objective i (*Security Features*) is very strongly more important than j (*Cost)*.

11 Objective i (*Security Features*) is absolutely more important than j (*Physical Characteristics*).

2,4,6,8 Intermediate values

Figure A-2: Rating Scale/values for pair wise comparison

The pair wise comparison of criteria is shown in Figure A-1, which shows that, for example, *functional performance* is *strongly more important* (5) than *physical characteristics*. The weightings of each criterion in Table A-4 are then normalized, by dividing each entry in a column by the sum of all the entries in that same column. Average value of weights for each criterion is calculated across each row after normalization as shown in Table A-5. These weights can also be described as percentage weighting (out of 100).

Criterion	Functional Performance	Physical Characteristics	Security Features	Cost
Functional Performance	1	5	1/7	1/5
Physical Characteristics	1/5	1	1/3	1/3
Security Features	7	5	1	4
Cost	3	3	1/4	1
Column Sum	11.2	14	1.73	5.53

Table A-4: Pair wise rating of selection criteria

Criterion	Functional Performance	Physical Characteristics	Security Features	Cost	Row Average
Functional Performance	0.09	0.36	0.08	0.04	0.14
Physical Characteristics	0.02	0.07	0.19	0.06	0.09
Security Features	0.63	0.36	0.58	0.72	0.57
Cost	0.27	0.21	0.14	0.18	0.20
Column Sum	1.00	1.00	1.00	1.00	1.00

{0.09=(1)/(1+1/5+7+3)}

Table A-5: Normalised Pair wise rating of selection criteria

Pair-wise comparison is also performed among different lock alternatives to determine how well they satisfy each of the criteria by quantifying their relationships. The method of assigning weight to different alternatives in a pair is same as that of comparing different criteria i.e. the better alternative is given a rating on a scale between 1 (equally important) and 9 (absolutely important), whilst the other alternative in the pairing is given a rating equal to the reciprocal of this value. This pair wise comparison of lock alternatives against the *'functional performance'* criterion are given in Table A-6. Each value in the table shows how well a lock alternative corresponds to other lock alternative in one particular row satisfying the *'functional performance'* criterion when compared to the other lock alternatives in different columns.

Lock Type	Cable Lock	Chain Lock	Armored Lock	Shackle Lock	Loop Lock
Cable Lock	1	2	1/3	1/3	1/6
Chain Lock	1/2	1	1/5	1/4	1/3
Armored Lock	3	3	1	1/5	1/4
Shackle Lock	5	4	3	1	1/2
Loop Lock	6	5	4	2	1
Column Sum	15.5	15	8.53	3.78	2.25

Table A-6: Pair wise rating of different lock alternatives with respect to *"Functional Performance"*

For instance, the *shackle lock* is found to be *strongly more important (5)* in 'functional performance' than *cable lock.* These pair wise ratings are normalized as before and averaged across the rows to give an average normalized rating of each lock alternative against a particular criterion, as shown in Table A-7 for 'functional performance'. Table A-8 presents a summary of average normalized ratings with respect to each of the lock selection criteria. These weights can also be described as percentage weighting (out of 100).

Lock Type	Cable Lock	Chain Lock	Armored Lock	Shackle Lock	Loop Lock	Row Average
Cable Lock	0.06	0.13	0.04	0.09	0.07	0.08
Chain Lock	0.03	0.07	0.02	0.07	0.15	0.07
Armored Lock	0.19	0.20	0.12	0.05	0.11	0.13
Shackle Lock	0.32	0.27	0.35	0.26	0.22	0.29
Loop Lock	0.39	0.33	0.47	0.53	0.44	0.43
Column Sum	1.00	1.00	1.00	1.00	1.00	1.00

Table A-7: Normalized pair-wise rating of lock type alternatives with respect to *'Functional Performance'*

Criterion	Rating of Lock Alternatives				
	Cable Lock	Chain Lock	Armored Lock	Shackle Lock	Loop Lock
Functional Performance	0.08	0.07	0.13	0.29	0.43
Physical Characteristics	0.15	0.10	0.05	0.23	0.48
Security Features	0.14	0.05	0.25	0.10	0.46
Cost	0.21	0.04	0.14	0.24	0.37

Table A-8: Average normalized ratings of Lock Alternatives with respect to each criterion

The last step in the AHP decision making method is to combine the average normalized Lock Alternative ratings (Table A-8) with the average normalized criterion weights (Table A-5) to generate an overall rating for each *Lock Alternative.* This combined normalized rating shows how much a selected type of lock satisfies different criteria. This is done as follows:

$$R_n = \sum_m (C_m A_{mn})$$

Where:

R_n. overall relative rating for lock alternative n

C_m. average normalized weight for criterion m

A_{mn}. average normalized rating for lock alternative n with respect to criterion m.

Table A-9 presents the combined normalized ratings. These results show that *Loop Locks* has the highest value (0.44) amongst all type of locks, therefore it is the best alternative among all five different types of locks.

Criterion	Weighting	Rating of Lock Alternatives				
		Cable Lock	Chain Lock	Armored Lock	Shackle Lock	Loop Lock
Functional Performance	0.14	0.08	0.07	0.13	0.29	0.43
Physical Characteristics	0.09	0.15	0.10	0.05	0.23	0.48
Security Features	0.57	0.14	0.05	0.25	0.10	0.46
Cost	0.20	0.21	0.04	0.14	0.24	0.37
Column Sum		0.14	0.06	0.20	0.17	0.44

Table A-9: Overall Lock Alternatives Ratings

Appendix-E: Case Studies

This appendix presents the paper-based case studies to evaluate the Function to Means/PDE mapping model presented in Chapter 6. These case studies present conceptual design problems in different mechanical engineering design domains.

Case Study No. 1

This case study is related to the mechanical engineering design domain and the product of interest is "Passenger Car Door". In order to have a better understanding of a car's door functions, a functional tree used to represent these functions is shown in Figure A-3 below.

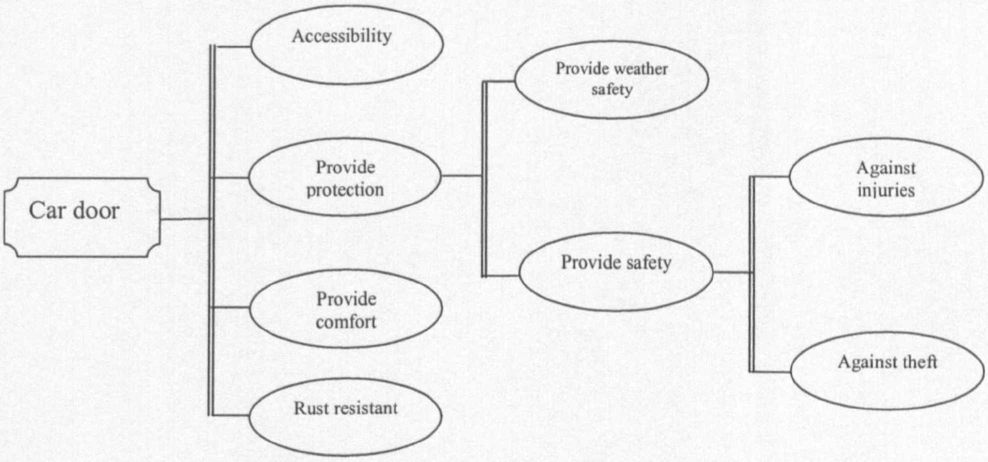


Figure A-3: Car Door Functions

There are therefore six functions in total. They are:

- Accessibility: This function makes it possible to access the car easily.
- Provide protection:
    - Keep weather out: Protects various elements in the car (i.e. equipments, passengers…) against the weather.
    - Provide safety: Protects various elements in the car against an external danger (i.e. robbers, tree during an accident…).

- Provide comfort: Gives maximum comfort to the passengers.
- Rust resistant: Makes it possible to withstand moisture.

A brief description of these functions is given here:

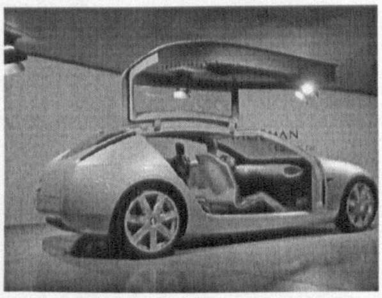
Provide accessibility

There are several possibilities by which accessibility to a car can be provided. These are:

1. **Pivot door**

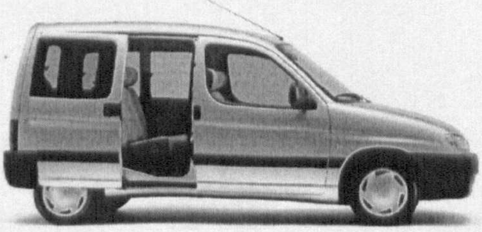
- Traditional hinged doors as shown in *"Aston Martin"*

- "Butterfly" hinged doors as shown in *"Renault Talisman"*



- Horizontally hinged doors as shown in *"Lamborghini Diablo"*

Push and pull door as shown in *"Peugeot Partner"*



The function "Accessibility" is possible if the door provides an opening either by a pivot door or a push and pull door. The function "Open door" can be related with this diagram.

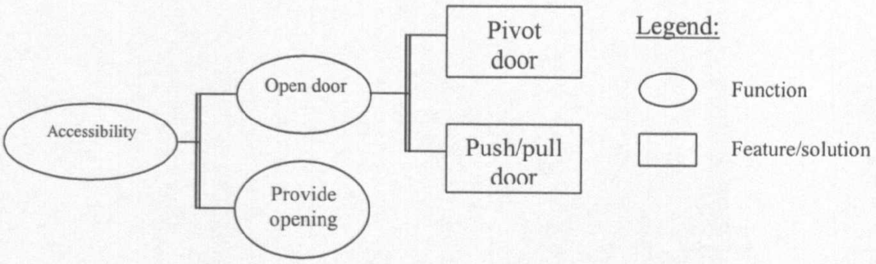


Figure A-4: Accessibility Function

Provide protection

Against Injuries

Injuries could be multiple. It could be from damage due to children who are playing next to the car or due to an accident against an object (for example: a tree). In those cases the car doors must resist the small shocks and protect the driver during an accident. In about 25 percent of all automobile accidents, the impact comes from the side. Another aspect is the possibility of injuries inflicted by someone who wants to attack drivers or passengers in order to rob the car. The features/solutions that provide protection to the car are explained below.

Safety Technology

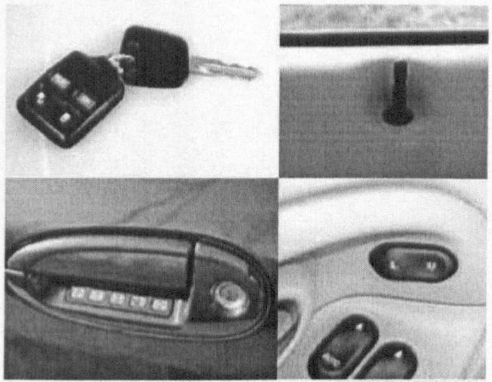
Safety will continue to dominate as a critical element during manufacture of cars. Cars are developed to ensure safety for occupants, and also for pedestrians. The two pillars of this development are active safety technologies to prevent accidents, and passive safety technologies to protect occupants in the event an accident occurs [Mitsubishi, 1999]. The means/solutions to provide safety are:

- *Safety Cell.*
- *Collision Beams.*
- *Airbag.*

Against Theft

The system used to protect the car from robbery is the door locks. Some of the ways that the car can be locked or unlocked are:

- With a key.
- By pressing the unlock button inside the car.
- By using the combination lock on the outside of the door.
- By pulling up the knob on the inside of the door.
- With a keyless-entry remote control.
- By a signal from a control centre.



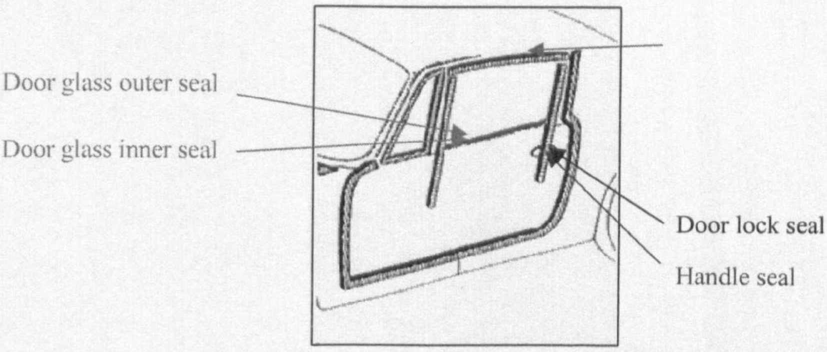
© 2000 How Stuff Works

Picture from [Nice 2003]

Some cars have power door locks; the lock/unlock switch actually sends power to the actuators that unlock the door. But in more complicated systems that have several ways to lock and unlock the doors, the body controller decides when to do the unlocking.

Provide Weather Safety

Seals are used to realize the function *"Provide Weather Safety"*. One of the principal door seals' functions is to keep water out of the interior of the car. Seals are produced by the extruding process.



Door Frame [Parts Locator 2003]

A tree diagram for "Provide protection" is shown below.

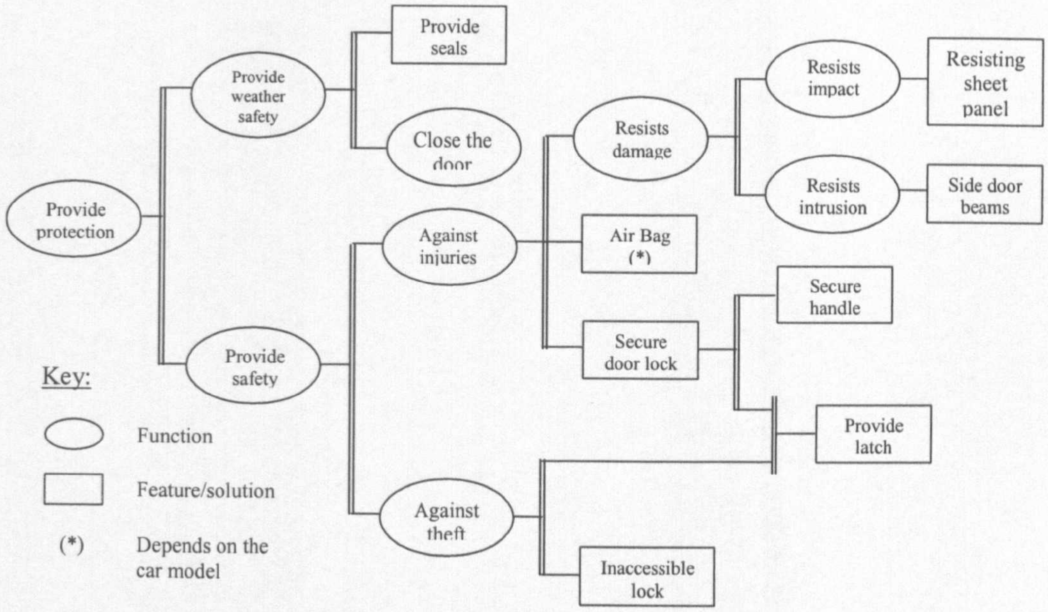


Figure A-5: Safety Function

Provide Comfort

Some accessories are available in car doors to increase the comfort of the passengers.

These elements are:

- Windows with its regulator system.

There are three kinds of regulator systems that can be found:

- Scissors style regulator.
- Goldie cable style regulator.
- Bowden cable style regulator.

These regulator systems could be mechanical or electrical.

- Rear view mirror.
- Sound insulation.

Sound insulation could be realized by using a butyl composite with aluminium constraining layer, sheet metal vibration damper. It is used throughout the vehicle interior to minimize intrusive noise from the engine compartment and road.

- Speakers.
- Armrest/handle.
- Adjustment systems for the rear-view mirrors *(depends on the model).*
- Pocket.
- Aeration system *(depends on the model).*

Provide Rust Resistant

In the automotive sector, the material most used is steel. It represents 98% of body applications. But the problem with this material is it is not resistant to rusting without treatment. The second material, after steel, is aluminium. One of the well-known proprieties of aluminium is its corrosion resistance. The third material used for car doors is a composite. As aluminium, composites do not need corrosion treatment.

A tree diagram with these features incorporating a global view of the characteristics for a car door is shown on the next page.

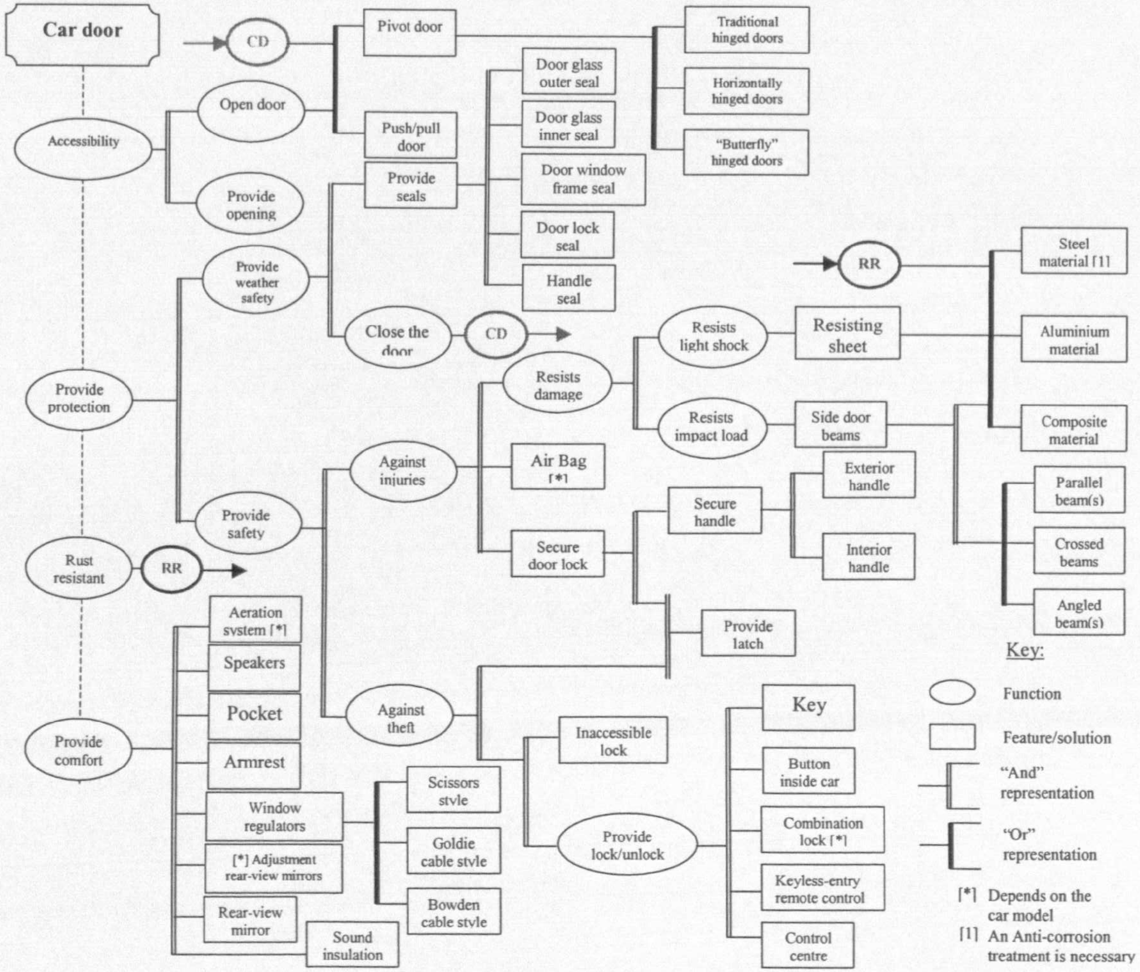


Figure A-6: Function and Solution Map for Car Door

Further work is concentrated on door panel analysis with the objective of determining the best material according to need/requirements. To date there are three types of materials used in door panels namely as Steel, Aluminium and Composites. Advantages/Disadvantages of these materials in different areas is given here.

Advantages/Disadvantages of the materials:

Steel

Conventional steel

Advantages:

- Amenable to high-speed fabrication technique.
- Inexpensive material.
- Good engineering properties.
- Many suppliers.

Disadvantages:

- High density.
- Corrosion: necessitates expensive processing.

Ultra light steel

Advantages

- Offers a light structure.
- Inexpensive material.
- Good engineering properties.
- Many suppliers.

Disadvantages:

- More expensive to produce than conventional steel.
- Corrosion: necessitates expensive processing.

Aluminium

Advantages :

- Offers a light structure.
- Easily recyclable.
- Glut in the market.
- Corrosion resistant.

Disadvantages:

- Difficult to form with traditional process.
- Difficult to join.
- High raw material cost.

Composite

Advantages:

- Weight saving.
- Increase design flexibilities.
- Relatively easy manufacture.

Disadvantages:

- Material and labour intensive processes.

- Long cycle time.
- Non-traditional manufacturing technology.

The comparison of four materials is given in Figure A-7.

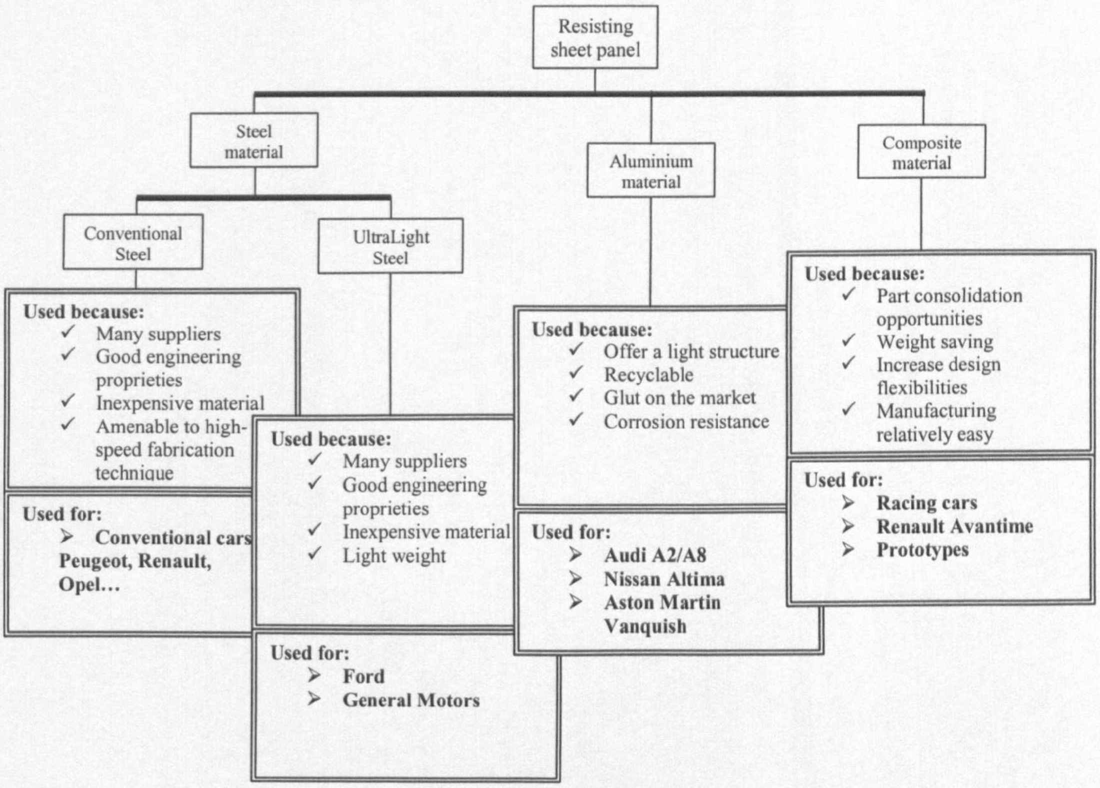


Figure A-7: Comparison of Four Materials

Context Knowledge Categories

Keeping in view the nature of problem that is selection of ideal material for car door panel, six categories have been identified for exploration.

1. Product/Components' Materials Properties

This category of contest knowledge is related to product's material properties. It includes the general material specifications of the components. In the case of the door panel, the important properties are:

- The Yield Strength, which gives of the material rigidity.
- Density, important to give an idea of weight.

2. Quality of Means/Solution During Use

This knowledge could be the adaptability of selected solution/Products Design Elements (PDE) to different working conditions. For a door panel, 4 elements are important:

- Resist light impact.
- Resist high impact.
- Rust Resistant.
- Weight.

3. Production requirement

It involves knowledge of actual manufacturing/production requirements for a solution/PDE to be manufactured into the component. This type of context knowledge is important for the designer to analyse not only the ease of manufacturing solutions/PDEs on the component but also the precision and the complex shape adaptability of the material used.

4. Cost

It is a context knowledge category that deals with knowledge about the cost of manufacturing a particular solution/PDE on a component. This part includes:

- Process cost: Laboratory, energy, fixed overhead, maintenance, sub-assembly, and painting.
- Material cost.
- Equipment cost: Machine cost and the tooling cost.

5. Achievable Production Rate

This category allows us to evaluate the achievable production rate of each solution.

6. Recycling

This context knowledge is more and more important in our society and must be taken into consideration by the designer in order to evaluate the potential of his product to be recycled.

Splitting Context Knowledge Categories

Categories presented here are further split to have a detailed analysis and degrees of suitability are assigned as shown below.

1. Product/Components' Materials Properties

Yield Stress

The measure of an object's strength is directly to its yield stress and mass moment of inertia. Yield Stress is defined as *"The critical stress that must be applied to a material before it begins to deform permanently"*.

Calculation of the Moments of Inertia:

(In order to simplify the calculations, the door panel will be considered as a panel).

$$\text{Ics} = \frac{1}{12}M(A^2+B^2) \longrightarrow \boxed{\frac{(A^2+B^2)}{12}}M$$

M: masse (Kg).

Constant: C

A: Length (m).

B: Width (m).

The dimension of a door panel being the same for every material, only the weight will influence the characteristic of the material to be strong or not. The material has to be strong and light weight at the same time.

Materials	Context/Consequence Knowledge	Degree of suitability
Conventional Steel	Yield Strength 220 Mpa / Moment 16.70 Kg.m-3	2
UltraLight Steel	Yield Strength 250 Mpa / Moment 15.25C Kg.m-3	4
Aluminium	Yield Strength 185 Mpa / Moment 12.50C kg.m-3	3
SMC composite	Yield Strength 150 Mpa/ Moment 13.75C kg.m-3	2

Strength of Material and Density Factor (Strength & Light Weight Considered)

2. Quality of Means/Solution during Use

Resist light impact

To resist light impact, the material must be strong enough not to bend under its own weight but flexible enough to absorb the maximum energy. The flexibility is opposite to stiffness, which depends on modulus of elasticity. The Modulus of Elasticity and the Yield Strength will give this notion to identify the best material for this function.

Materials	Context/Consequence Knowledge
Conventional Steel	Modulus of Elasticity 210 000 Mpa/Yield Strength 220 Mpa
UltraLight Steel	Modulus of Elasticity 210 000 Mpa/Yield Strength 250 Mpa
Aluminium	Modulus of Elasticity 69 500 Mpa/Yield Strength 185 Mpa
SMC composite	Modulus of Elasticity 1250 Mpa/Yield Strength 150 Mpa

Materials	Context/Consequence Knowledge	Degree of suitability
Conventional Steel	Material strong and very stiff	**2**
UltraLight Steel	Material very strong and very stiff	**2**
Aluminium	Material strong and stiff	**3**
SMC composite	Material strong and flexible	**4**

Resist Light Impact Factor (Flexibility Considered)

Resist high impact

To resist at a high impact and absorb the maximum energy, the material must have a strong structure and be stiff enough to absorb energy deformation. A structure, which is too flexible, can be dangerous for passengers, as it would not protect them from high impact.

Materials	Context/Consequence Knowledge	Degree of suitability
Conventional Steel	Material strong and very stiff	**3**
UltraLight Steel	Material very strong and very stiff	**4**
Aluminium	Material strong and stiff	**3**
SMC composite	Material strong and flexible	**2**

Resist High Impact Factor (Strength Considered)

Rust Resistant

A material naturally resistant to rust is the most interesting because it gives the certainty of its capability to resist moisture.

Materials	Context/Consequence Knowledge	Degree of suitability
Conventional Steel	Need a treatment	**3**
Ultra Light Steel	Need a treatment	**3**
Aluminium	Rust resistant	**4**
SMC composite	Rust resistant	**4**

Weight

One important characteristic for car elements is to save the maximum amount of weight in order to reduce the cars weight, thus to consume less energy. The number used, as an example does not takes into consideration the weight of the equipment (paint, trim…) on the door but only the weight of the panel.

Materials	Context/Consequence Knowledge	Degree of suitability
Conventional Steel	16.70 Kg	**1**
Ultra Light Steel	15.25 Kg	**2**
Aluminium	12.50 Kg	**4**
SMC composite	13.75 Kg	**3**

3. Production requirement

Ease of the manufacturing part

In this context knowledge, it is possible to compare the simplicity of the process to produce the door panel using the different materials. In this part it is interesting to compare the potential of each material (between conventional steel, Ultra Light steel and aluminium) to be stamped. In order to know the ease of stamping some criteria must be studied:

	Conventional steel	**UltraLight steel**	**Aluminium**	**SMC**	**Criterion must be**
A%: Facture Elongation (%)	**32**	**34**	**13**	**MOULDING**	HIGH
YS: Yield Stress (Mpa)	**240**	**250**	**185**		LOW
YS/UTS *(1)*: Ratio	**0.65**	**0.65**	**0.84**		LOW
r: The plastic strain ratio *(2)*	**1.6**	**1.2**	**0.65**		HIGH
n: Strain hardening coefficient *(3)*	**0.15**	**0.17**	**0.2**		HIGH

1. Ultimate Tensile Stress (Mpa).
2. It reflects the aptitude of the steel to undergo severe deep drawing strains.
3. A high value of n corresponds on a good aptitude for forming in the expansion (stretching) mode.

Explanation:

By comparing the criteria it is easy to understand the characteristics of each material. Indeed, the criteria between conventional steel and Ultra Light steel are very similar. Thus it is possible to affirm that both are simple to stamp compared with aluminium. But the plastic strain ratio is more important for conventional steel and means it has the best aptitude to undergo deep drawing strains. In view of its ability to be formed in expansion mode, aluminium gives the best result and is in this way very ductile.

The table on next page shows, which is the easiest material to stamp.

Materials	Context/Consequence Knowledge	Degree of suitability
Conventional Steel	Easy to stamp and aptitude to undergo deep drawing strains	**3**
Ultra Light Steel	Quite similar to conventional steel with a worse aptitude to severe deep drawing strains	**2**
Aluminium	Difficult to stamp but good ductility *(*)*	**1**
SMC composite	Easy process does not need long experience	**4**

(*) Property of the material to be easily deformed and particularly to be easily stretched.

Complex shape adaptability

Car design is more and more important nowadays and the carmakers use more complex forms to conceive a car. Design is also an important part in the conception of a car model, because customers are sensitive to it.

Materials	Context/Consequence Knowledge	Degree of suitability
Conventional Steel	Difficult to form for complex 3D forms	**3**
Ultra Light Steel	Difficult to form for complex 3D forms	**3**
Aluminium	Difficult to form for complex 3D forms	**3**
SMC composite	Capability of complex design geometries	**4**

Precision of the process

In the car industry, the robotized assembly of elements for manufacture of a car requires precise parts with ± 0,3 mm of tolerance.

Materials	Context/Consequence Knowledge	Degree of suitability
Conventional Steel	Tolerance between 0.2 and 0.6 mm (depends on the dimensions)	**4**
Ultra Light Steel	Tolerance is similar to conventional steel	**4**
Aluminium	Tolerance between 0.2 and 0.6 mm (depends on the dimensions)	**4**
SMC composite	Linear withdrawal from 0 to -0.1%	**4**

The precision of the process depends more on the machine used for production than the product itself.

4. Cost

From the perspective of costumers, they want the best product and the cheapest. So the most expansive the panel door will be, the worst.

Total door cost

Total cost per door for a series of 300 000 parts, which include the:

- Manufacturing part.
- Sub-assembly.
- Painting.
- Trim.

Materials	Context/Consequence Knowledge	Degree of suitability
Conventional Steel	44.63 $	**4**
Ultra Light Steel	46.17 $	**3**
Aluminium	62.41 $	**2**
SMC composite	66.36 $	**1**

Material cost

Material cost per door for a series of 300 000 parts.

Materials	Context/Consequence Knowledge	Degree of suitability
Conventional Steel	21.11 $	**4**
Ultra Light Steel	21.18 $	**3**
Aluminium	36.66 $	**1**
SMC composite	22.30 $	**2**

Equipment cost

Now, this only represents the cost of the equipment used to produce a door panel. It includes the **machine cost and the tooling cost** per door for a series of 300 000 parts.

Materials	Context/Consequence Knowledge	Degree of suitability
Conventional Steel	7.55 $	**4**
Ultra Light Steel	21.18 $	**3**
Aluminium	36.66 $	**2**
SMC composite	22.30 $	**1**

Process cost

For this context, included are the costs of the:

- Laboratory.
- Energy.
- Fixed overhead.
- Maintenance.
- Sub-assembly.
- Painting.

These prices are the price per door for a series of 300 000 parts.

Materials	Context/Consequence Knowledge	Degree of suitability
Conventional Steel	31.95 $	**2**
Ultra Light Steel	30.77 $	**3**
Aluminium	21.72 $	**4**
SMC composite	33.53 $	**1**

5. Achievable Production Rate

The production rate is evaluated by the capability of the material to be manufactured at a high production rate.

Materials	Context/Consequence Knowledge	Degree of suitability
Conventional Steel	Can be used for high production rate	**4**
Ultra Light Steel	Can be used for high production rate	**4**
Aluminium	Can be used for high production rate	**4**
SMC composite	Can be used for medium production rate	**3**

6. Recycling

Recycling of automobiles can reduce costs for both manufacturers and consumers, and can vastly reduce the flow of material into the solid waste stream, thus helping to protect our environment.

Materials	Context/Consequence Knowledge	Degree of suitability
Conventional Steel	Very easy to recycle	**4**
UltraLight Steel	Very easy to recycle	**4**
Aluminium	Easy to recycle	**3**
SMC composite	Difficult to recycle	**2**

Assignment of Numerical Rating and Weighting Factors

The next step in this case study is the assignment of numerical rating and percentage weighting factors. Numerical rating is assigned to each material by converting degree of suitability of each material for sub context knowledge category into percentage weighting using AHP decision making theory rules.

Assignment of weighting factor to each sub context knowledge category depends two factors. In the automotive industry, two points of view exist. The first is that of the customers and the second, is that of the manufacturer. Indeed, customers do not care about the properties of the materials or the ease of the manufacture.

The most important for them is:

- *The Cost:* The cheaper the product, the better.
- *Safety (resist high impact):* Customers want the safest product possible in order to protect their life during an accident.
- *Performance of the material (resist light impact, rust resistant):* The performance of the material allows them to be sure of having the best product for as long as possible.
- *Best design (complex design adaptability):* Customers are attracted by good design. The more complex and unusual the product, the better.

Desirable features:

- *Weight:* Customers do not really care about the weight of the door. It is not a priority when they buy a car.

- *Ease of recycling*: Customers are sensitive to environmental problems. However, whether a material is easily recycled or not, may not be a customers first priority.

Not important:

- *Ease of the process:* Customers do not care about the ease of manufacture.
- *Achievable production rate:* This criterion is not important to customers. Customer wants the product in the shortest period of time.

Car manufacturers have a different point of view. They need to take into account all criteria to realize a product with the best features and as cheaply as possible. It is possible to determine the priorities in this way:

The most important is:

From the point of view of manufacturing:

- *Cost of the process:* This is probably the most important criterion. Indeed, if manufacturers produce a door with high cost, they would not have taken into account what the customers wants and therefore could have problems selling customers their products.
- *Ease of the process:* This criterion is important for two reasons. Firstly, it will have implications for the cost of the product and secondly for the speed of manufacturing the door panel. Therefore, ease of manufacture contributes to a cheaper and faster solution.
- *Achievable Production rate.*
- *Ease of recycling:* A materials ability to be recycled allows us to protect the environment. This is important to manufacturers, especially with recent environmental laws.

From the point of view characteristics:

- *Safety:* In order to reduce the number of deaths in the car accidents, safety is important. Moreover a safe car gives a good image to customers.

- *Rust resistant*: If a car has rust problems, it could influence customers not to buy a car model. It is therefore an important criterion.

Desirable features:

- *Resist light impact:* This criterion is not a priority for manufacturers. They prefer to take into consideration the resistance against high impact.
- *Weight:* The weight is, of course, important because it influences the total weight of the car.
- *Complex sheet adaptability:* In order to have the best design and to do better than their competitors, the adaptability of the sheet may be important as the better the design, the more attractive it is. However a complex design increases the complexity of manufacture and hence the cost of door.

In order to give a notion of importance, the following factors are used:

- **0:** *not important*
- **5:** *quite important*
- **10:** *important*
- **15:** *very important*
- **20:** *priority*

The cost must be studied in two different ways. Indeed, carmakers and customers do not have the same point of view. Customers pay great attention to the cost of the finished product. The tooling costs or machine costs are not important to them, whereas it is for manufacturers, in order to produce the cheapest product with the best features. For this reason the cost will not be considered in the same way. In one way, there is the total cost of the door for customers, but different part costs for the manufacturers (material cost, equipments cost, process cost). Using this method, the result is more precise for manufacturers. Here the priorities of customers and manufacturers are transformed into factors of importance with the numbers seen above. Here the Weighting factors for both customers and manufacturers:

		Costumers	Car Makers
N	Criterion	Weighting factor (%)	Weighting factor (%)
1	*Product/components' Material Properties*		
	Module of Elasticity	**0**	**5**
2	*Quality of Means/Solution during use*		
	Resist light impact	**15**	**5**
	Resist high impact	**15**	**10**
	Rust Resistant	**15**	**10**
	Weight	**10**	**5**
3	*Complex Sheet adaptability*	**15**	**5**
4	*Production Requirement*		
	Ease of the manufacturing part	**0**	**10**
5	*Cost*	**20**	
	Material's Cost		**10**
	Equipment Cost		**10**
	Process Cost		**10**
7	*Achievable Production Rate*	**0**	**10**
8	*Ease Recycling*	**10**	**10**
	TOTAL	**100**	**100**

Selection of Best Alternative Solution/Material

After determining relative weighting for each criterion and numerical ratings for alternatives, the final task is to find the best material out of the four materials by comparing the total scores for each material. The material that has the best score is the best solution. The results of these calculations are presented on next page.

First of all, for Customers:

2334.54= Σ column

		Costumers	MATERIALS							
N	Criterion	Weighting factor (%)	Conv. Steel		UltraL. Steel		Aluminium		SMC	
1	*Product/components' Material Properties*									
	Strength & Density	**0**	9.67	**0**	55.49	**0**	25.16	**0**	9.67	**0**
2	*Quality of Means/Solution during use*									
	Resist light impact	**15**	11.0	**165.00**	12.4	**186.00**	24.2	**363.00**	52.50	**787.5**
	Resist high impact	**15**	20.1	**301.5**	51.9	**778.5**	20.1	**301.5**	7.9	**118.5**
	Rust Resistant	**15**	12.50	**187.50**	12.50	**187.50**	37.50	**562.50**	37.50	**562.50**
	Weight	**10**	5.69	**56.89**	12.19	**121.87**	55.79	**557.89**	26.33	**263.35**
3	*Complex Sheet adaptability*	**15**	9.67	**145.05**	9.67	**145.05**	25.16	**377.47**	55.49	**832.42**
4	*Production Requirement*									
	Ease of the manufacturing part	**0**	26.33	**0**	12.19	**0**	5.69	**0**	55.79	**0**
5	*Door Cost*	**20**	55.79	**1115.78**	26.33	**526.69**	12.19	**243.75**	6.58	**131.64**
	Process Cost									
	Material's Cost									
	Equipment Cost									
6	*Achievable Production Rate*	**0**	30.00	**0**	30.00	**0**	30.00	**0**	10.00	**0**
7	*Ease Recycling*	**10**	38.89	**388.93**	38.89	**388.93**	15.35	**153.45**	6.87	**68.69**
	TOTAL	**100**		**2360.67**		**2334.54**		**2559.56**		**2764.6**

It is now possible to see both the criteria and the weighting factors used for customers, the best material to satisfy the customers' needs is the **SMC composite**. By comparing the most important material scores for each criterion it is possible to see which criteria made the difference.

The highest scores are:

- ✓ Resist light impact.
- ✓ Rust resistant.
- ✓ Complex sheet adaptability.

Indeed, this material allows freedom in the design stage and has good mechanical characteristics. Moreover SMC is rust resistant. From the customers' point of view all these characteristics give SMC a great advantage.

But, from the point of view of the manufacturers, is SMC the best option for them? Automakers have to take into consideration all parameters to produce a door panel. It is interesting to know which material is the best for automakers in terms of **cost, manufacturing and mechanical properties.**

		Carmakers	MATERIALS							
N	Criterion	Weighting factor (%)	Conv. Steel		UltraL. Steel		Aluminium		SMC	
1	*Product/components' Material Properties*									
	Strength & Density	**5**	9.67	**48.35**	55.49	**277.47**	25.16	**125.82**	9.67	**48.35**
2	*Quality of Means/Solutio during use*									
	Resist light impact	**5**	11	**55**	12.4	**62**	24.2	**121**	52.5	**262.5**
	Resist high impact	**10**	20.1	**201.0**	51.9	**519**	20.1	**201**	7.9	**79**
	Rust Resistant	**10**	12.50	**125.00**	12.50	**125.00**	37.50	**375.00**	37.50	**375.00**
	Weight	**5**	5.69	**28.44**	12.19	**60.94**	55.79	**278.95**	26.33	**131.67**
3	*Complex Sheet adaptability*	**5**	9.67	**48.35**	9.67	**48.35**	25.16	**125.82**	55.49	**277.47**
4	*Production Requirement*									
	Ease of the manufacturing part	**10**	26.33	**263.35**	12.19	**121.87**	5.69	**56.89**	55.79	**557.89**
5	*Door Cost*									
	Material's Cost	**10**	55.79	**557.89**	26.33	**263.35**	5.69	**56.89**	12.19	**121.87**
	Equipment Cost	**10**	55.79	**557.89**	26.33	**263.35**	12.19	**121.87**	5.69	**56.89**
	Process Cost	**10**	12.19	**121.87**	26.33	**263.35**	55.79	**557.89**	5.69	**56.89**
6	*Achievable Production Rate*	**10**	30.00	**300.00**	30.00	**300.00**	30.00	**300.00**	10.00	**100.00**
7	*Ease Recycling*	**10**	38.89	**388.93**	38.89	**388.93**	15.35	**153.45**	6.87	**68.69**
	TOTAL	**100**		**2656.09**		**2693.59**		**2474.59**		**2136.24**

With these weighting factors, the **UltraLight steel** is therefore the best solution. This result can be explained by the excellent characteristics of this material. This new generation of steel has appeared since the automotive sector used to use aluminium. The UltraLight Steel Auto Body (ULSAB) Consortium was formed to answer the challenge of carmakers around the world: reduce the weight of steel auto body structures while maintaining their performance and affordability.

With current environmental problems, the car weight must be reduced in order to decrease fuel consumption. For that reason, importance has been given to the car's weight. With this new data, the weighing factors must change. In total, it will be the same but the weighting factor of the criterion "weight" will increase in order to take into account the new priority. But if a factor increases the designer must decrease one or several factors to keep the balance between them.

Using the factor of importance, the designer can decide the priority of each criterion. The weighting factors used by the carmaker in the last example can be used. Indeed, in this example the priority was the cost of the process in order to have the best material with the lowest price. But in this second example the priority is the weight, so the factor of the criterion "Weight" must be changed and be increased from 5 (quite important) to 15 (means: very important) and the factors "Material cost" and "Equipments cost" can be reduced if the designer decides to invest in a good material and good equipment.

		Carmakers	MATERIALS							
N	Criterion	Weighting factor (%)	Conv. Steel		UltraL. Steel		Aluminium		SMC	
1	*Product/components' Material Properties*									
	Strength & Density	**5**	9.67	**48.35**	55.49	**277.47**	25.16	**125.82**	9.67	**48.35**
2	*Quality of Means/Solution during use*									
	Resist light impact	**5**	11.0	**55**	12.4	**62.00**	24.2	**121.00**	52.5	**262.5**
	Resist high impact	**10**	20.1	**201.0**	51.9	**519.00**	20.12	**201.00**	7.9	**79**
	Rust Resistant	**10**	12.50	**125.00**	12.50	**125.00**	37.50	**375.00**	37.50	**375.00**
	Weight	**15**	5.69	**85.33**	12.19	**182.81**	55.79	**836.84**	26.33	**395.02**
3	*Complex Sheet adaptability*	**5**	9.67	**48.35**	9.67	**48.35**	25.16	**125.82**	55.49	**277.47**
4	*Production Requirement*									
	Ease of the manufacturing part	**10**	26.33	**263.35**	12.19	**121.87**	5.69	**56.89**	55.79	**557.89**
5	*Door Cost*									
	Material's Cost	**5**	55.79	**278.95**	26.33	**131.67**	5.69	**28.44**	12.19	**60.94**
	Equipment Cost	**5**	55.79	**278.95**	26.33	**131.67**	12.19	**60.94**	5.69	**28.44**
	Process Cost	**10**	12.19	**121.87**	26.33	**263.35**	55.79	**557.89**	5.69	**56.89**
6	*Achievable Production Rate*	**10**	30.00	**300.00**	30.00	**300.00**	30.00	**300.00**	10.00	**100.00**
7	*Ease Recycling*	**10**	38.89	**388.93**	38.89	**388.93**	15.35	**153.45**	6.87	**68.69**
	TOTAL	**100**		**2195.08**		**2552.11**		**2943.11**		**2310.29**

The best alternative solution if the weight is a priority is **aluminium**. It is possible to observe in the automotive industry, aluminium is used more and more because of its properties. Indeed, since 1990, the use of aluminium has doubled in cars and has tripled in the lucrative light truck market. Aluminium use is still growing, largely due to its environmental, safety and driving performance advantages.

Many of the world's tops performing cars are made of aluminium:

- Aston Martin Vanquish,
- Audi A8,
- BMW Z8,
- Ferrari Modena 360,
- Mercedes CL Coupe.

Despite the cost of producing an aluminium door panel, all the characteristics put together give an advantage for this material. It is probably for this reason that the largest manufacturers are investing in this material in order to offer to their customers the best solution. Aluminium performs all the functions of a door panel and reduces the weight of the car.

Another sector in the automotive industry is the racing car. Indeed, the weighting factors will not be the same in this sector because of their needs and priorities. Thus, the door panel priorities will be determined in the following way:

The most important is:

From the point of view of manufacturing:

- *Ease of process:* the people who are doing this kind of sport need the most simple process to produce the door panel because they have generally not many opportunities to use traditional methods.
- *Cost:*
  - Material cost
  - Process cost

  Both these cost are high, so the lowest possible would be better.

From point of view characteristics:

- *Safety/Resist light impact:* During a race the car can receive heavy or light impact. For this reason the door panel must resist both.
- *Weight:* In order to reduce weight, each part of the car must be as light as possible. Indeed each gram lost means diminution of the total weight, thus betters performance.
- *Complex sheet adaptability:* With this criterion the manufacturers are free to choose a design for the car, which will give the best performance.

Desirable features:

- *Equipment cost:* This cost is the lowest of the three categories; its importance can be reduced.
- *Achievable Production rate*: As this kind of car has a limited series, the manufacturers do not need a process with a high production.
- *Ease recycling:* A material's ability to be recycled allows us to protect the environment, which is important for carmakers especially with the recent environment laws.
- *Rust resistant:* Racing cars do not have a long life; therefore rust problems are not a priority.

With these priorities, and by using the factors of importance, from 0 for criteria that are not important to 20 for the criteria that are a priority, it is possible to know which material is best for this sector of activity in the automobile industry.

		Carmakers	**MATERIALS**							
N	Criterion	Weighting factor (%)	Conv. Steel		UltraL. Steel		Aluminium		SMC	
1	*Product/components' Material Properties*									
	Strength & Density	**5**	9.67	**48.35**	55.49	**277.47**	25.16	**125.82**	9.67	**48.35**
2	*Quality of Means/Solution during use*									
	Resist light impact	**10**	11.0	**110**	12.4	**124.00**	24.2	**242.00**	52.5	**525.00**
	Resist high impact	**10**	20.1	**201.0**	51.9	**519.00**	20.1	**201.00**	7.9	**79.00**
	Rust Resistant	**5**	12.50	**62.50**	12.50	**62.50**	37.50	**187.50**	37.50	**187.50**
	Weight	**10**	5.69	**56.89**	12.19	**121.87**	55.79	**557.89**	26.33	**263.35**
3	*Complex Sheet adaptability*	**10**	9.67	**96.70**	9.67	**96.70**	25.16	**251.65**	55.49	**554.95**
4	*Production Requirement*									
	Ease of the manufacturing part	**15**	26.33	**395.02**	12.19	**182.81**	5.69	**85.33**	55.79	**836.84**
5	*Door Cost*									
	Material's Cost	**10**	55.79	**557.89**	26.33	**263.35**	5.69	**56.89**	12.19	**121.87**
	Equipment Cost	**5**	55.79	**278.95**	26.33	**131.67**	12.19	**60.94**	5.69	**28.44**
	Process Cost	**10**	12.19	**121.87**	26.33	**263.35**	55.79	**557.89**	5.69	**56.89**
6	*Achievable Production Rate*	**5**	30.00	**150.00**	30.00	**150.00**	30.00	**150.00**	10.00	**50.00**
7	*Ease Recycling*	**5**	38.89	**194.46**	38.89	**194.46**	15.35	**76.73**	6.87	**34.35**
	TOTAL	**100**		**2273.64**		**2387.18**		**2553.65**		**2786.53**

In this case, **SMC** composite is the best solution for racing cars or for prototypes. Indeed, with its good resistance to deformation and its low weight, SMC offers the best-cost ratio for this sector of activity (especially for medium production). Moreover, producing this composite is relatively easy and does not need a great deal of experience. Some manufacturers such as Renault have produced some cars in the past and still produce a few models with SMC composite. Generally these models are at the top of the range (Renault Espace) or limited series (Renault 5 SMC, Renault Avantime).

It is possible to observe with the help of all these results that the reason for which a designer uses a specific material depends upon his/her needs and priorities. The most important is to fix on the criteria and to know which criteria are important. It is by the weighting factor that the designer will be able to decide the importance for each criteria in order to have the best solution adapted to his/her needs.

It would be interesting to compare the results of each material in the actual car industry and the results found with the method, in order to know if there is a big difference between the theory and the industrial reality as shown in Figure A-7 earlier and in the following table.

Criterions	Used in car Industry	***This Research Method results***	Car sector
High Production/Low cost	Conventional steel	UltraLight steel	Familial cars (most important)
High Production/Low weight	Aluminium	Aluminium	Top of the rang cars
Medium Production/ Design flexibility	SMC	SMC	Limited series, prototypes, racing cars

The above table shows that the results are the same for each criterion with the exception of steel. Indeed, in this case conventional steel is used most often in the car industry compared to UltraLight steel. This difference could be explained by the recent appearance of this new generation of steel and carmakers are not ready to change all their production lines. It would be too expensive and it would change their methods of production, which have been well established for tens of years.

By this research thesis methodology it is possible to understand the choice of materials in the automobile sector according to the designers' needs and the materials' characteristics. But with the steel example, it is possible to observe that the method takes into consideration all criteria and gives the best solution for designers. It is finally the manufacturers who take the final decision depending the materials and tools they have got in their possession. In the automotive industry the most important factors are to have high volume and easy production methods at the lowest cost. If we consider the different materials' possibilities we observe that steel is the best. But because of environmental issues aluminium and composites are used more and more. With their use, the total weight of a car can be reduced enormously in order to reduce fuel consumption.

Case Study No. 2

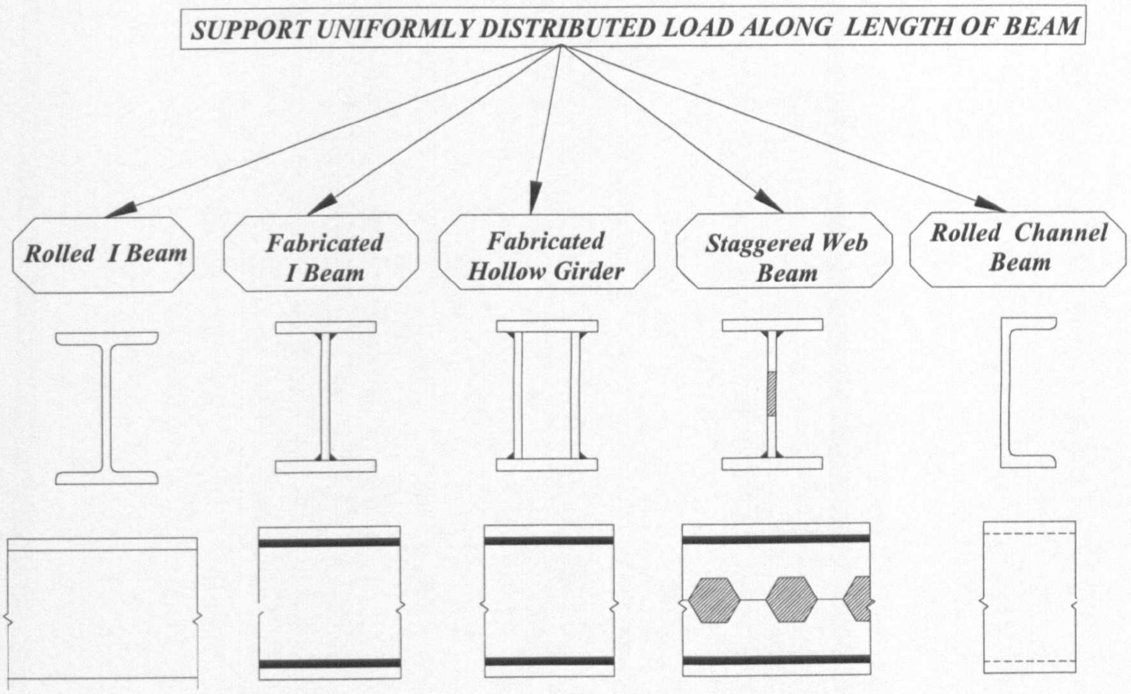
This case study is related to structural engineering design domain. The conceptual design problem is related to *"Beam Design"*.

Functional Requirement

The functional requirement is to *"Support Uniformly Distributed Load Along Length of Beam"*.

Conceptual Solutions

Based on the functional requirements following five conceptual solutions are generated/proposed.



These are different types of beams and with different cross sectional shapes and manufactured through different processes. A brief description of these solutions is

- *Rolled I-Beam* is manufactured through rolling process and a stock/ingot of material is fed through consecutive rolling mills to achieve the required shape.
- *Fabricated I-Beam* is manufactured by welding two flange plates with web plate using either continuous or intermittent fillet welding.
- *Fabricated Hollow Girder* is manufactured by welding two flange plates with two web plates using welding.
- *Staggered Web Beam* is manufactured by cutting the web plate in a staggered fashion and then welding the opposite edges of web plate to increase the depth of web plate and subsequently welding it with flange plates.
- *Rolled Channel Beam* is manufacture through rolling process and has Channel C cross sectional shape.

Generated Context Knowledge and Reasoning

Context knowledge for the design problem under consideration is generated for each of the ten categories of context knowledge. As soon as these five means/solutions selected, context consequence knowledge/information is generated regarding each one of these means/solutions in each one of the ten categories of context knowledge. The context knowledge generated in this case study is taken from different sources of beam/structural design references.

The information generated in each context knowledge category is analysed and reasoned to assign degrees of suitability from 0 to 5 as shown below in ten different categories.

1- USER REQUIREMENT

- Support Uniformly distribute load of 200 kg/M
- Length should be 10 M

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rolled I Beam	*Can be used for all types of loading*	5
Fabricated I Beam	*Can be used for all types of loading*	5
Fabricated Hollow Girder	*Can be used for all types of loading*	5
Staggered Web Beam	*Can be used for all types of loading*	5
Rolled Channel Beam	*Can be used for all types of loading*	5

2- COMPONENT MATERIAL PROPERTIES/CONSUMPTION

- ASTM A-36 Structural Steel as material of Beam

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rolled I Beam	*Can be used for all types of materials, Low material consmuption*	5
Fabricated I Beam	*Can be used for all types of materials, High material consumption*	4
Fabricated Hollow Girder	*Can be used for all types of materials, Very high material consumption*	3
Staggered Web Beam	*Can be used for all types of materials, low material consumption*	5
Rolled Channel Beam	*Can be used for all types of materials, low material consumption*	5

3- QUALITY OF MEANS DURING USE (DEGREE OF FULLFILLING INTENDED FUNCTION IN DIFFERENT CONDITIONS)

- Capable of withstanding/absorbing shock load due to earthquake
- Capable of withstanding/absorbing lateral wind load
- Capable of withstanding load in high temperature conditions

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rolled I Beam	*Medium shock load resistant, high temperature resistant*	4
Fabricated I Beam	*Medium shock load resistant, low temperature resistant*	3
Fabricated Hollow Girder	*Very High shock load resistant, low temperature resistant*	4
Staggered Web Beam	*Very High shock load resistant, low temperature resistant*	4
Rolled Channel Beam	*Low shock load resistant, high temperature resistant*	3

4- PRE-PRODUCTION REQUIREMENT [PREPARATION OF MATERIAL (S)]

- Cost/Ease of preparing components (Less time to prepare)

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rolled I Beam	*No preparation is required*	5
Fabricated I Beam	*Edge preparation of sheets is required*	4
Fabricated Hollow Girder	*Edge preparation of sheets is required*	4
Staggered Web Beam	*Edge preparation as well as cutting of sheets is required*	2
Rolled Channel Beam	*No preparation is required*	5

5- PRODUCTION REQUIREMENT (ADDITIONAL ITEMS/COMPONENTS)

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rolled I Beam	*No additional item required*	5
Fabricated I Beam	*Low quantity of welding rods and filler material is required*	4
Fabricated Hollow Girder	*High quantity of welding rods and filler material is required*	3
Staggered Web Beam	*Very high quantity of welding rods and filler material is required*	2
Rolled Channel Beam	*No additional item required*	5

6- POST PRODUCTION REQUIREMENT [SPECIAL PROCESS (S) REQUIRED]

- Less costly post processing

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rolled I Beam	*Quenching in oil is required*	5
Fabricated I Beam	*Longitudinal Straightening under press is required*	4
Fabricated Hollow Girder	*Longitudinal Straightening under press is required*	4
Staggered Web Beam	*Longitudinal as well as lateral Straightening under press is required*	3
Rolled Channel Beam	*Quenching in oil is required*	5

7- PRODUCTION EQUIPMENT REQUIREMENT/COST (TOOLING /MACHINE COST REQUIRED)

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rolled I Beam	*Medium costly rolling machines required*	5
Fabricated I Beam	*High costly submerged arc welding machines required*	4
Fabricated Hollow Girder	*High costly submerged arc welding machines required*	4
Staggered Web Beam	*High costly submerged arc welding machines required*	4
Rolled Channel Beam	*Medium costly rolling machines required*	5

8- QUANTITY OF PRODUCT REQUIRED

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rolled I Beam	*Can be used for any quantity*	5
Fabricated I Beam	*Can be used for medium quantity*	4
Fabricated Hollow Girder	*Can be used for low quantity*	3
Staggered Web Beam	*Can be used only for very low quantity*	2
Rolled Channel Beam	*Can be used for any quantity*	5

9- ACHIEVABLE PRODUCTION RATE OF SELECTED MEANS

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rolled I Beam	*High production rate*	5
Fabricated I Beam	*Medium production rate*	4
Fabricated Hollow Girder	*Low production rate*	3
Staggered Web Beam	*Very low production rate*	2
Rolled Channel Beam	*High production rate*	5

10- DEGREE OF AVAILABLE QUALITY ASSURANCE TECHNIQUES

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rolled I Beam	*Visual anticipation of deflection as well as strain gauges are available*	5
Fabricated I Beam	*Visual anticipation of deflection as well as strain gauges are available*	5
Fabricated Hollow Girder	*Visual anticipation of deflection as well as strain gauges are available*	5
Staggered Web Beam	*Visual anticipation of deflection as well as strain gauges are available*	5
Rolled Channel Beam	*Visual anticipation of deflection as well as strain gauges are available*	5

Relative Weighting and Numerical Rating

The relative weighting among ten-design knowledge criterion (preference of one criteria over other) can be done by giving percentage weighting out of 100 for each categories. In this case study the relative weightings as designer's preference is shown below.

CRITERIA	WEIGHTING (%)
User Requirement	15
Component Material Properties/Consumption	10
Quality of Means During Use (Degree of Fullfilling Intended Function in Different Conditions)	10
Pre-Production Requirement {Preparation of Component(s)}	20
Production Requirement (Additional Items/Components)	15
PostProduction Requirement {Special Process(s) Required}	10
Production Equipment Requirement/Cost (Tooling/Machine Cost Required)	10
Quantity of Product Required	2.5
Achievable Production Rate of Selected Means	5
Degree of Available Quality Assurance Techniques	2.5
Consolidated Rating of Each Alternative	***100***

The assignment of numerical rating to each of design alternatives under each context knowledge criterion category is done by converting degree of suitability of each alternative into weighting factor as described in chapter 8. This is done by using the comparison scales defined in decision making theory Analytic Hierarchy Process. Degrees of suitability matrices are generated for all ten categories of context knowledge and these matrices are shown on next page.

Rating of Alternatives on User Requirement

ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	1	1	1	1	ROLLED I-BEAM	0.200	0.200	0.200	0.200	0.200
FABRICATED I-BEAM	1	1	1	1	1	FABRICATED I-BEAM	0.200	0.200	0.200	0.200	0.200
FABRICATED HOLLOW GIRDER	1	1	1	1	1	FABRICATED HOLLOW GIRDER	0.200	0.200	0.200	0.200	0.200
STAGGERED WEB BEAM	1	1	1	1	1	STAGGERED WEB BEAM	0.200	0.200	0.200	0.200	0.200
ROLLED CHANNEL BEAM	1	1	1	1	1	ROLLED CHANNEL BEAM	0.200	0.200	0.200	0.200	0.200

Rating of Alternatives on Component Material Properties/Consumption

ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	3	5	1	1	ROLLED I-BEAM	0.283	0.290	0.263	0.283	0.283
FABRICATED I-BEAM	1/3	1	3	1/3	1/3	FABRICATED I-BEAM	0.094	0.097	0.158	0.094	0.094
FABRICATED HOLLOW GIRDER	1/5	1/3	1	1/5	1/5	FABRICATED HOLLOW GIRDER	0.057	0.032	0.053	0.057	0.057
STAGGERED WEB BEAM	1	3	5	1	1	STAGGERED WEB BEAM	0.283	0.290	0.263	0.283	0.283
ROLLED CHANNEL BEAM	1	3	5	1	1	ROLLED CHANNEL BEAM	0.283	0.290	0.263	0.283	0.283

Rating of Alternatives on Quality of Means During Use (Degree of Fullfilling Intended Function in Different Conditions)

ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	3	1	1	3	ROLLED I-BEAM	0.273	0.273	0.273	0.273	0.273
FABRICATED I-BEAM	1/3	1	1/3	1/3	1	FABRICATED I-BEAM	0.091	0.091	0.091	0.091	0.091
FABRICATED HOLLOW GIRDER	1	3	1	1	3	FABRICATED HOLLOW GIRDER	0.273	0.273	0.273	0.273	0.273
STAGGERED WEB BEAM	1	3	1	1	3	STAGGERED WEB BEAM	0.273	0.273	0.273	0.273	0.273
ROLLED CHANNEL BEAM	1/3	1	1/3	1/3	1	ROLLED CHANNEL BEAM	0.091	0.091	0.091	0.091	0.091

Rating of Alternatives on Pre-Production Requirement {Preparation of Component(s)}

ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	3	3	7	1	ROLLED I-BEAM	0.356	0.366	0.366	0.280	0.356
FABRICATED I-BEAM	1/3	1	1	5	1/3	FABRICATED I-BEAM	0.119	0.122	0.122	0.200	0.119
FABRICATED HOLLOW GIRDER	1/3	1	1	5	1/3	FABRICATED HOLLOW GIRDER	0.119	0.122	0.122	0.200	0.119
STAGGERED WEB BEAM	1/7	1/5	1/5	1	1/7	STAGGERED WEB BEAM	0.051	0.024	0.024	0.040	0.051
ROLLED CHANNEL BEAM	1	3	3	7	1	ROLLED CHANNEL BEAM	0.356	0.366	0.366	0.280	0.356

Rating of Alternatives on Production Requirement (Additional Items/Components)

ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	3	5	7	1	ROLLED I-BEAM	0.374	0.398	0.349	0.304	0.374
FABRICATED I-BEAM	1/3	1	3	5	1/3	FABRICATED I-BEAM	0.125	0.133	0.209	0.217	0.125
FABRICATED HOLLOW GIRDER	1/5	1/3	1	3	1/5	FABRICATED HOLLOW GIRDER	0.075	0.044	0.070	0.130	0.075
STAGGERED WEB BEAM	1/7	1/5	1/3	1	1/7	STAGGERED WEB BEAM	0.053	0.027	0.023	0.043	0.053
ROLLED CHANNEL BEAM	1	3	5	7	1	ROLLED CHANNEL BEAM	0.374	0.398	0.349	0.304	0.374

Rating of Alternatives on Post Production Requirement {Special Process (s) Required}

ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	3	3	5	1	ROLLED I-BEAM	0.349	0.360	0.474	0.294	0.283
FABRICATED I-BEAM	1/3	1	1	3	1/3	FABRICATED I-BEAM	0.116	0.120	0.158	0.176	0.094
FABRICATED HOLLOW GIRDER	1/3	1	1	3	1	FABRICATED HOLLOW GIRDER	0.116	0.120	0.158	0.176	0.283
STAGGERED WEB BEAM	1/5	1/3	1/3	1	1/5	STAGGERED WEB BEAM	0.070	0.040	0.053	0.059	0.057
ROLLED CHANNEL BEAM	1	3	1	5	1	ROLLED CHANNEL BEAM	0.349	0.360	0.158	0.294	0.283

Rating of Alternatives on Production Equipment Requirement/Cost (Tooling/Machine Cost Required)

ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	3	3	3	1	ROLLED I-BEAM	0.333	0.333	0.333	0.333	0.333
FABRICATED I-BEAM	1/3	1	1	1	1/3	FABRICATED I-BEAM	0.111	0.111	0.111	0.111	0.111
FABRICATED HOLLOW GIRDER	1/3	1	1	1	1/3	FABRICATED HOLLOW GIRDER	0.111	0.111	0.111	0.111	0.111
STAGGERED WEB BEAM	1/3	1	1	1	1/3	STAGGERED WEB BEAM	0.111	0.111	0.111	0.111	0.111
ROLLED CHANNEL BEAM	1	3	3	3	1	ROLLED CHANNEL BEAM	0.333	0.333	0.333	0.333	0.333

Rating of Alternatives on Quantity of Product Required

ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	3	5	7	1	ROLLED I-BEAM	0.374	0.398	0.349	0.304	0.374
FABRICATED I-BEAM	1/3	1	3	5	1/3	FABRICATED I-BEAM	0.125	0.133	0.209	0.217	0.125
FABRICATED HOLLOW GIRDER	1/5	1/3	1	3	1/5	FABRICATED HOLLOW GIRDER	0.075	0.044	0.070	0.130	0.075
STAGGERED WEB BEAM	1/7	1/5	1/3	1	1/7	STAGGERED WEB BEAM	0.053	0.027	0.023	0.043	0.053
ROLLED CHANNEL BEAM	1	3	5	7	1	ROLLED CHANNEL BEAM	0.374	0.398	0.349	0.304	0.374

Rating of Alternatives on Achievable Production Rate of Selected Means

ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	3	5	7	1	ROLLED I-BEAM	0.374	0.398	0.349	0.304	0.374
FABRICATED I-BEAM	1/3	1	3	5	1/3	FABRICATED I-BEAM	0.125	0.133	0.209	0.217	0.125
FABRICATED HOLLOW GIRDER	1/5	1/3	1	3	1/5	FABRICATED HOLLOW GIRDER	0.075	0.044	0.070	0.130	0.075
STAGGERED WEB BEAM	1/7	1/5	1/3	1	1/7	STAGGERED WEB BEAM	0.053	0.027	0.023	0.043	0.053
ROLLED CHANNEL BEAM	1	3	5	7	1	ROLLED CHANNEL BEAM	0.374	0.398	0.349	0.304	0.374

Rating of Alternatives on Degree of Available Quality Assurance Techniques

ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM	ALTERNATIVES	ROLLED I-BEAM	FABRICATED I-BEAM	FABRICATED HOLLOW GIRDER	STAGGERED WEB BEAM	ROLLED CHANNEL BEAM
ROLLED I-BEAM	1	1	1	1	1	ROLLED I-BEAM	0.200	0.200	0.200	0.200	0.200
FABRICATED I-BEAM	1	1	1	1	1	FABRICATED I-BEAM	0.200	0.200	0.200	0.200	0.200
FABRICATED HOLLOW GIRDER	1	1	1	1	1	FABRICATED HOLLOW GIRDER	0.200	0.200	0.200	0.200	0.200
STAGGERED WEB BEAM	1	1	1	1	1	STAGGERED WEB BEAM	0.200	0.200	0.200	0.200	0.200
ROLLED CHANNEL BEAM	1	1	1	1	1	ROLLED CHANNEL BEAM	0.200	0.200	0.200	0.200	0.200

Selection of best PDE/design solution

After determining relative weighting of each criteria and numerical rating of alternatives, the final task in this case study is to find the best design solution/alternative out of these five alternatives *(Rolled I-Beam, Fabricated I-Beam,* *Fabricated Hollow Girder, Staggered Web Beam, Rolled Channel Beam,).* The highest added normalized value is *3089* for *Rolled I-Beam* as shown in the table below. Therefore Rolled I-Beam is the best solution out of all five alternatives.

CRITERIA	**WEIGHTING (%)**	**RATING OF SUITABILITIY OF ALTERNATIVES**				
		ROLLED I-BEAM	**FABRICATED I-BEAM**	**FABRICATED HOLLOW GIRDER**	**STAGGERED WEB BEAM**	**ROLLED CHANNEL BEAM**
User Requirement	15	20.0	20.0	20.0	20.0	20.0
Component Material Properties/Consumption	10	28.1	10.8	5.1	28.1	28.1
Quality of Means During Use (Degree of Fullfilling Intended Function in Different Conditions)	10	27.3	9.1	27.3	27.3	9.1
Pre-Production Requirement {Preparation of Component(s)}	20	34.5	13.6	13.6	3.8	34.5
Production Requirement (Additional Items/Components)	15	36.0	16.2	7.9	4.0	36.0
PostProduction Requirement {Special Process(s) Required}	10	35.2	13.3	17.1	5.6	28.9
Production Equipment Requirement/Cost (Tooling/Machine Cost Required)	10	33.3	11.1	11.1	11.1	33.3
Quantity of Product Required	2.5	36.0	16.2	7.9	4.0	36.0
Achievable Production Rate of Selected Means	5	36.0	16.2	7.9	4.0	36.0
Degree of Available Quality Assurance Techniques	2.5	20.0	20.0	20.0	20.0	20.0
Consolidated Rating of Each Alternative	**100**	***3089***	**1430**	**1406**	**1237**	**2844**

Case Study No. 3

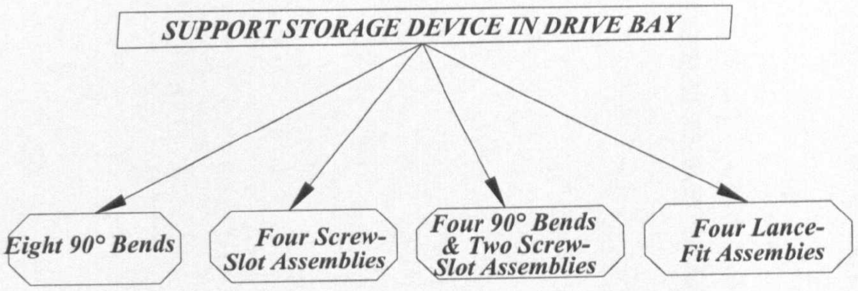
This case study is related to sheet metal engineering design domain. The conceptual design problem is related to *"Supporting Storage Device in Computer Drive Bay"*. The storage device could be an optical (CD/DVD) drive, hard drive or floppy drive in a typical desktop computer.

Functional Requirement

The functional requirement is to *"Support Storage Device"*.

Conceptual Solutions

Based on the functional requirements following five conceptual solutions are generated/proposed.



A brief description of these solutions is given below:

- *Eight 90^0 Bends* solution includes eight notches (four on each side) bent at ninety degrees along the depth of drive bay to support the storage device in rectangular hollow drive bay.
- *Four Screw-Slot Assemblies* means that four rectangular slots (two on each side) are stamped along the length of drive bay to fix the storage device with drive bay using four screws.
- *Four 90^0 Bends & Two Screw Slot Assemblies* means that four notches bent at 90^0 opposite to each other and two rectangular slots stamped opposite to each other on the walls of drive bay.
- *Four Lance Fit Assemblies* require four rectangular slots (two on each side) of wall are required. A storage device with four lances attaché to its sides can be push fit into these slots to make a lance fit assembly.

Generated Context Knowledge and Reasoning

The context knowledge along with consequences generated are shown on next page

1- *USER REQUIREMENT (SPECIFIC AGE GROUP/GENDER)*

- Both Men and Women (20 – 45 years age) will use
- No sharp edges while use/assembly
- Modular (Must be able to support any design of storage device)
- Easy to insert storage device (Less time required for insertion/holding)

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Eight 90° Bends	Few edges, Modular (Can be used for any type of storage device) Very less time for insertion/holding	5
Four Screw-Slot Assemblies	Few sharp edges of screw head, Can be used only for tapped hole provided storage device, Considerable time is required to remove the casing cover from both sides and for insertion/holding of storage device	2
Four 90° Bends & Two Screw-Slot Assemblies	Very Few sharp edges of screw head, Can be used only for tapped hole provided storage device, Less time is required for insertion/holding of storage device	4
Four Lance-Fit Assemblies	Highly Sharp Edges, Can be used only for lance feature provided type of storage device, Very less time for insertion/holding	2

2- *COMPONENT MATERIAL PROPERTIES*

- Aluminium alloy as material of Drive Bay
- Aluminium alloy/ABS (a type of plastic) as material of storage device

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Eight 90° Bends	Can be used	5
Four Screw-Slot Assemblies	Can be used	5
Four 90° Bends & Two Screw-Slot Assemblies	Can be used	5
Four Lance-Fit Assemblies	Can only be used for aluminium alloy type storage device	3

3- *QUALITY OF MEANS DURING USE (DEGREE OF FULLFILLING INTENDED FUNCTION IN DIFFERENT CONDITIONS)*

- Capable of withstanding/absorbing vibrations caused due to running of motors of storage devices
- Capable of holding storage device firmly in its condition during heat dispiation caused to long use of storage device

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Eight 90° Bends	Very low vibrational resistant, Low temperature resistant	2
Four Screw-Slot Assemblies	Very High vibrational resistant, High temperature resistant	5
Four 90° Bends & Two Screw-Slot Assemblies	High vibrational resistant, High temperature resistant	4
Four Lance-Fit Assemblies	Very low vibrational resistant, High temperature resistant	3

4- *PRE-OPERATION REQUIREMENT (PREPARATION OF COMPONENT (S))*

- Ease of preparing components (Less time to prepare)

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Eight 90° Bends	No additional item required	5
Four Screw-Slot Assemblies	Four screws with washers required	2
Four 90° Bends & Two Screw-Slot Assemblies	Two screws with washers required	2
Four Lance-Fit Assemblies	No additional item required	5

5- *OPERATION REQUIREMENT (ADDITIONAL ITEMS/COMPONENTS)*

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Eight 90° Bends	Eight notches bend at 90° are required on drive bay opposite side walls	7
Four Screw-Slot Assemblies	Four slots are required on drive bay walls Four tapped holes are required on sides of storage device	5
Four 90° Bends & Two Screw-Slot Assemblies	Two notches bend at 90° are required on one side wall of drive bay Two slots are required on the other side of drive bay wall Two tapped holes are required on one side of storage device	4
Four Lance-Fit Assemblies	Four rectangular slots are required on opposite side walls of drive bay Four lance features are required at a fixed distance on side walls of storage device	5

6- *POST OPERATION REQUIREMENT (SPECIAL PROCESS (S) REQUIRED)*

- Less costly post processing

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Eight 90° Bends	No post processing required	5
Four Screw-Slot Assemblies	No post processing required	5
Four 90° Bends & Two Screw-Slot Assemblies	No post processing required	5
Four Lance-Fit Assemblies	No post processing required	5

7- *PRODUCTION EQUIPMENT REQUIREMENT/COST (TOOLING /MACHINE COST REQUIRED)*

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Eight 90° Bends	Low costly simple mechanical/hydraulic presses can be used to create bend	7
Four Screw-Slot Assemblies	Low costly simple mechanical/hydraulic presses can be used to create slot and hole whereas expensive fasteners are used increasing the cost of operation	5
Four 90° Bends & Two Screw-Slot Assemblies	Low costly simple mechanical/hydraulic presses can be used to create slot, bend and hole whereas expensive fasteners are used increasing the cost of operation considerably	3
Four Lance-Fit Assemblies	Low costly simple mechanical/hydraulic presses can be used to create lance and slot	6

8- *QUANTITY OF PRODUCT REQUIRED*

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Four 90° Bends	Can be used for any number of drive bays	5
Four Screw-Slot Assemblies	Can be used for very high number of drive bays in order to justify the cost of dies/punch	4
Four 90° Bends & Two Screw-Slot Assemblies	Can be used for very high number of drive bays in order to justify the cost of dies/punch	4
Four Lance-Fit Assemblies	Can be used for any number of drive bays	5

9- *ACHIEVABLE OPERATION RATE OF SELECTED MEANS*

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Eight 90° Bends	Can be used for very high operation rate	5
Four Screw-Slot Assemblies	Can be used only for low operation rate	2
Four 90° Bends & Two Screw-Slot Assemblies	Can be used for medium operation rate	3
Four Lance-Fit Assemblies	Can be used for very high operation rate	5

10- *DEGREE OF AVAILABLE QUALITY ASSURANCE TECHNIQUES*

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Eight 90° Bends	Vibration of computer during use of storage device indicates the quality of supporting means	4
Four Screw-Slot Assemblies	Vibration of computer during use of storage device indicates the quality of supporting means	4
Four 90° Bends & Two Screw-Slot Assemblies	Vibration of computer during use of storage device indicates the quality of supporting means	4
Four Lance-Fit Assemblies	Vibration of computer during use of storage device indicates the quality of supporting means	4

Relative Weighting and Numerical Rating

The relative weighting among ten-design knowledge criterion (preference of one criteria over other) can be done by giving percentage weighting out of 100 for each categories. In this case study the relative weightings as designer's preference is shown below.

CRITERIA	WEIGHTING (%)
User Requirement (Specific Age Group/Gender)	20
Component Material Properties	5
Quality of Means During Use (Degree of Fullfilling Intended Function in Different Conditions)	30
Pre-Operation Requirement {Preparation of Component(s)}	5
Operation Requirement (Additional Items/Components)	10
Post Operation Requirement {Special Process(s) Required}	5
Production Equipment Requirement/Cost (Tooling/Machine Cost Required)	15
Quantity of Product Required	2.5
Achievable Operation Rate of Selected Means	5
Degree of Available Quality Assurance Techniques	2.5
Consolidated Rating of Each Alternative	**100**

Degrees of Suitability of each alternative to each context knowledge category is converted into relative numerical rating using AHP comparison scales and these are converted into percentage weighting as shown in the matrices on the next page:

Rating of Alternatives on User Requirement (Specific Age Group/Gender)

ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	Average
EIGHT 90° BENDS	1	7	3	7	EIGHT 90° BENDS	0.618	0.500	0.682	0.500	57.5
FOUR SCREW-SLOT ASSEMBLIES	1/7	1	1/5	1	FOUR SCREW-SLOT ASSEMBLIES	0.088	0.071	0.045	0.071	6.9
FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	1/3	5	1	5	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	0.206	0.357	0.227	0.357	28.7
FOUR LANCE-FIT ASSEMBLIES	1/7	1	1/5	1	FOUR LANCE-FIT ASSEMBLIES	0.088	0.071	0.045	0.071	6.9

Rating of Alternatives on Component Material Properties

ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	Average
EIGHT 90° BENDS	1	1	1	5	EIGHT 90° BENDS	0.313	0.313	0.313	0.313	31.3
FOUR SCREW-SLOT ASSEMBLIES	1	1	1	5	FOUR SCREW-SLOT ASSEMBLIES	0.313	0.313	0.313	0.313	31.3
FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	1	1	1	5	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	0.313	0.313	0.313	0.313	31.3
FOUR LANCE-FIT ASSEMBLIES	1/5	1/5	1/5	1	FOUR LANCE-FIT ASSEMBLIES	0.063	0.063	0.063	0.063	6.3

Rating of Alternatives on Quality of Means During Use (Degree of Fulfilling Intended Function in Different Conditions)

ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	Average
EIGHT 90° BENDS	1	1/7	1/5	1/3	EIGHT 90° BENDS	0.063	0.085	0.044	0.036	5.7
FOUR SCREW-SLOT ASSEMBLIES	7	1	3	5	FOUR SCREW-SLOT ASSEMBLIES	0.438	0.597	0.662	0.536	55.8
FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	5	1/3	1	3	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	0.313	0.199	0.221	0.321	26.3
FOUR LANCE-FIT ASSEMBLIES	3	1/5	1/3	1	FOUR LANCE-FIT ASSEMBLIES	0.188	0.119	0.074	0.107	12.2

Rating of Alternatives on Pre-Operation Requirement {Preparation of Component(s)}

ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	Average
EIGHT 90° BENDS	1	5	7	5	EIGHT 90° BENDS	0.648	0.682	0.500	0.682	62.8
FOUR SCREW-SLOT ASSEMBLIES	1/5	1	3	1	FOUR SCREW-SLOT ASSEMBLIES	0.130	0.136	0.214	0.136	15.4
FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	1/7	1/3	1	1/3	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	0.093	0.045	0.071	0.045	6.4
FOUR LANCE-FIT ASSEMBLIES	1/5	1	3	1	FOUR LANCE-FIT ASSEMBLIES	0.130	0.136	0.214	0.136	15.4

Rating of Alternatives on Operation Requirement (Additional Items/Components)

ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	Average
EIGHT 90° BENDS	1	7	7	1	EIGHT 90° BENDS	0.438	0.438	0.438	0.438	43.8
FOUR SCREW-SLOT ASSEMBLIES	1/7	1	1	1/7	FOUR SCREW-SLOT ASSEMBLIES	0.063	0.063	0.063	0.063	6.3
FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	1/7	1	1	1/7	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	0.063	0.063	0.063	0.063	6.3
FOUR LANCE-FIT ASSEMBLIES	1	7	7	1	FOUR LANCE-FIT ASSEMBLIES	0.438	0.438	0.438	0.438	43.8

Rating of Alternatives on Post Operation Requirement {Special Process (s) Required}

ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	Average
EIGHT 90° BENDS	1	1	1	1	EIGHT 90° BENDS	0.250	0.250	0.250	0.250	25.0
FOUR SCREW-SLOT ASSEMBLIES	1	1	1	1	FOUR SCREW-SLOT ASSEMBLIES	0.250	0.250	0.250	0.250	25.0
FOUR 90° BENDS &	1	1	1	1	FOUR 90° BENDS &	0.250	0.250	0.250	0.250	25.0
FOUR LANCE-FIT ASSEMBLIES	1	1	1	1	FOUR LANCE-FIT ASSEMBLIES	0.250	0.250	0.250	0.250	25.0

Rating of Alternatives on Production Equipment Requirement/Cost (Tooling/Machine Cost Required)

ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	Average
EIGHT 90° BENDS	1	5	9	3	EIGHT 90° BENDS	0.608	0.543	0.409	0.670	55.8
FOUR SCREW-SLOT ASSEMBLIES	1/5	1	5	1/3	FOUR SCREW-SLOT ASSEMBLIES	0.122	0.109	0.227	0.074	13.3
FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	1/9	1/5	1	1/7	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	0.068	0.022	0.045	0.032	4.2
FOUR LANCE-FIT ASSEMBLIES	1/3	3	7	1	FOUR LANCE-FIT ASSEMBLIES	0.203	0.326	0.318	0.223	26.8

Rating of Alternatives on Quantity of Product Required

ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	Average
EIGHT 90° BENDS	1	3	3	1	EIGHT 90° BENDS	0.375	0.375	0.375	0.375	37.5
FOUR SCREW-SLOT ASSEMBLIES	1/3	1	1	1/3	FOUR SCREW-SLOT ASSEMBLIES	0.125	0.125	0.125	0.125	12.5
FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	1/3	1	1	1/3	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	0.125	0.125	0.125	0.125	12.5
FOUR LANCE-FIT ASSEMBLIES	1	3	3	1	FOUR LANCE-FIT ASSEMBLIES	0.375	0.375	0.375	0.375	37.5

Rating of Alternatives on Achievable Operational Rate of Selected Means

ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	Average
EIGHT 90° BENDS	1	7	5	1	EIGHT 90° BENDS	0.427	0.389	0.441	0.427	42.1
FOUR SCREW-SLOT ASSEMBLIES	1/7	1	1/3	1/7	FOUR SCREW-SLOT ASSEMBLIES	0.061	0.056	0.029	0.061	5.2
FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	1/5	3	1	1/5	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	0.085	0.167	0.088	0.085	10.6
FOUR LANCE-FIT ASSEMBLIES	1	7	5	1	FOUR LANCE-FIT ASSEMBLIES	0.427	0.389	0.441	0.427	42.1

Rating of Alternatives on Degree of Available Quality Assurance Techniques

ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	ALTERNATIVES	EIGHT 90° BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES	Average
EIGHT 90° BENDS	1	1	1	1	EIGHT 90° BENDS	0.250	0.250	0.250	0.250	25.0
FOUR SCREW-SLOT ASSEMBLIES	1	1	1	1	FOUR SCREW-SLOT ASSEMBLIES	0.250	0.250	0.250	0.250	25.0
FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	1	1	1	1	FOUR 90° BENDS & TWO SCREW SLOT ASSEMBLIES	0.250	0.250	0.250	0.250	25.0
FOUR LANCE-FIT ASSEMBLIES	1	1	1	1	FOUR LANCE-FIT ASSEMBLIES	0.250	0.250	0.250	0.250	25.0

Selection of best PDE/design solution

The best design solution/alternative out of these four alternatives *(Eight 90^0 Bends, Four Screw Slot Assemblies, Four 90^0 Bends & Two Screw Slot Assemblies, Four Lance-Fit Assemblies)* is *Eight 90^0 Bends.* The highest added normalized value is *3427* for **Eight 90^0 Bends** as shown in the table on the next page.

CRITERIA	WEIGHTING (%)	RATING OF SUITABILITIY OF ALTERNATIVES			
		EIGHT 90^0 BENDS	FOUR SCREW-SLOT ASSEMBLIES	FOUR 90^0 BENDS & TWO SCREW SLOT ASSEMBLIES	FOUR LANCE-FIT ASSEMBLIES
User Requirement (Specific Age Group/Gender)	20	57.5	6.9	28.7	6.9
Component Material Properties	5	31.3	31.3	31.3	6.3
Quality of Means During Use (Degree of Fullfilling Intended Function in Different Conditions)	30	5.7	55.8	26.3	12.2
Pre-Operation Requirement {Preparation of Component(s)}	5	62.8	15.4	6.4	15.4
Operation Requirement (Additional Items/Components)	10	43.8	6.3	6.3	43.8
Post Operation Requirement {Special Process(s) Required}	5	25	25	25	25
Production Equipment Requirement/Cost (Tooling/Machine Cost Required)	15	55.8	13.3	4.2	26.8
Quantity of Product Required	2.5	37.5	12.5	12.5	37.5
Achievable Operation Rate of Selected Means	5	42.1	5.2	10.6	42.1
Degree of Available Quality Assurance Techniques	2.5	25	25	25	25
Consolidated Rating of Each Alternative	**100**	*3427*	**2421**	**1949**	**1944**

Case Study No. 4

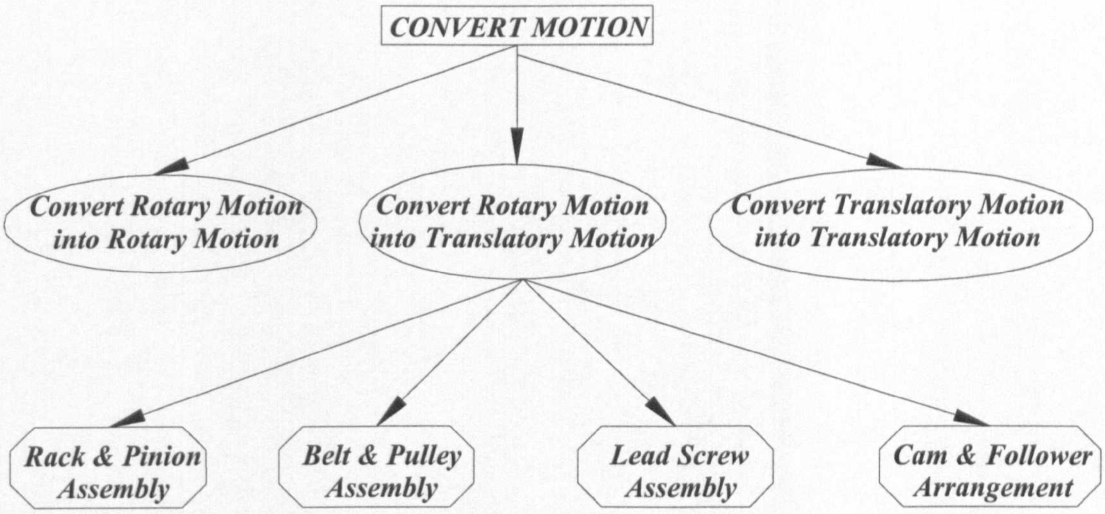
This case study is related to machined component engineering design domain. The conceptual design problem is related to *"Motion Conversion"*.

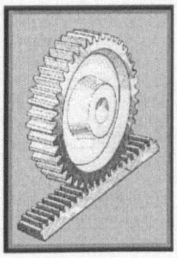
Functional Requirement

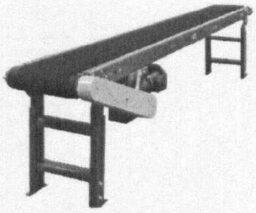
The functional requirement is to *"Convert Motion"*. This function is further decomposed to three more sub functions. These are *"Convert Rotary Motion into Rotary Motion"*, *"Convert Rotary Motion into Translatory Motion"* and *"Convert Translatory into Translatory Motion"*. The function taken for further consideration is *"Convert Rotary Motion into Translatory Motion"*.

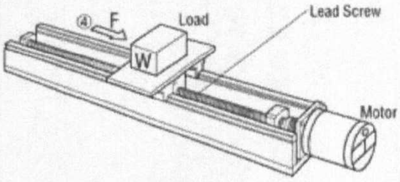
Conceptual Solutions

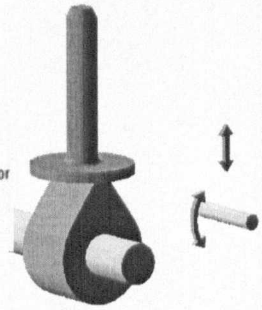
Based on the functional requirements following four conceptual solutions are generated/proposed.











[Gear 2004] **[Kramer 2004]** **[Motor 2004]** **[Cam 2004]**

A brief description of these solutions is

- *Rack & Pinion Assembly* consists of a rack and a pinion gear. The rack and pinion is used to convert between rotary and linear motion. The rack is the flat toothed part and the pinion is the gear.

- *Belt & Pulley Assembly* consists of a horizontal flat belt on a set of two pulleys. The pulleys revolve in a direction and due to friction the conveyor belt travels in a linear horizontal direction.

- *Lead Screw Assembly* consists of a screw and a nut mounted on it. It basically uses the principle of wedge to drive the nut linearly along the length of screw.

- *Cam & Follower Assembly* consists of a cam and follower system is system/mechanism that uses a cam and follower to create a specific motion. The cam is in most cases merely a flat piece of metal that has had an unusual shape or profile machined onto it. This cam is attached to a shaft, which enables it to be turned by applying a turning action to the shaft. As the cam rotates it is the profile or shape of the cam that causes the follower to move in a particular way.

Generated Context Knowledge and Reasoning

The context knowledge generated in seven categories along with corresponding consequences is shown on next page.

1- ***FUNCTION REQUIREMENTS***

- Capable of moving load at high speeds (1~ 15 inch/sec).
- Must be able to move heavy loads (1~10 kg).
- Must be able to give high accuracy.
- Must be able to give long travel (1~20 ft).

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rack & Pinion Assembly	***Good for heavy load, Capable to give medium travel Can be used for medium accuracy, Capable to move at high speed***	4
Belt & Pulley Assembly	***Good for heavy load, Capable to give long travel Can be used only for low accuracy, Capable to move at high speed***	5
Lead Screw Assembly	***Good for medium load, Capable to give medium travel Can be used for high accuracy, Capable to move only at low speeds***	3
Cam & Follower Arrangement	***Good for low load, Capable to give medium travel Can be used for high accuracy, Capable to move at high speed***	3

2- ***MOVING LOAD'S MATERIAL PROPERTIES***

-Capable of moving type of Load (Solid (packed), Liquid, Powdered solid)

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rack & Pinion Assembly	***Can be used for all type of Loads***	5
Belt & Pulley Assembly	***Can be used for all type of Loads***	5
Lead Screw Assembly	***Can be used for all type of Loads***	5
Cam & Follower Arrangement	***Can be used only for solid type of Loads***	3

3- ***QUALITY OF MEANS DURING USE (DEGREE OF FULLFILLING INTENDED FUNCTION IN DIFFERENT CONDITIONS)***

- Capable of working in high temperature environments
- Capable of withstanding abrupt loading and maintaining accuracy during working

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rack & Pinion Assembly	***High Temperature Resistant, Good Vibrational Resistant***	4
Belt & Pulley Assembly	***High Temperature Resistant, Poor Vibrational Resistant***	3
Lead Screw Assembly	***High Temperature Resistant, Very Good Vibrational Resistant***	5
Cam & Follower Arrangement	***High Temperature Resistant, Very Poor Vibrational Resistant***	2

4- ***PRE-OPERATION REQUIREMENT***

- Number of Components Required?
-Cost of Components?

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rack & Pinion Assembly	***One Rack & One Pinion required Medium Cost incurred in manufacturing components***	4
Belt & Pulley Assembly	***One Belt & Two Pulleys required Very High Cost of components***	1
Lead Screw Assembly	***One Mechanical Linkage & One Lead Screw required Low cost incurred in manufacturing components***	5
Cam & Follower Arrangement	***One Cam & One Followr required High Cost incurred in manufacturing components***	3

5- ***OPERATION REQUIREMENT (ADDITIONAL ITEMS/COMPONENTS)***

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rack & Pinion Assembly	***Load Holder Required***	4
Belt & Pulley Assembly	***Several Idlers requried***	2
Lead Screw Assembly	***No additional item requried***	5
Cam & Follower Arrangement	***Load Holder Required in some cases***	4

6- ***POST OPERATION REQUIREMENT {SPECIAL PROCESS (S) REQUIRED}***

- Type and cost comparison of maintenance required

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rack & Pinion Assembly	***Oiling and Alignment of Pinion is requried Low Cost***	4
Belt & Pulley Assembly	***Alignment of two pulleys and idlers, tightnening and replacement of belt required Very High Cost***	1
Lead Screw Assembly	***Oiling of Lead Screw required Very Low Cost***	5
Cam & Follower Arrangement	***Alignment of Cam and Follower, Oiling of Cam requried Low Cost***	4

7- ***ANGLE OF LOAD TRANSPORTATION***

FEATURE	CONTEXT/CONSEQUENCE KNOWLEDGE	DEGREE OF SUITABILITY
Rack & Pinion Assembly	***Can be used for Horizontal Load Transfer only***	3
Belt & Pulley Assembly	***Can be used for Horizontal and slightly inclined Load Transfer***	4
Lead Screw Assembly	***Can be used for Horizontal and Vertical Load Transfer***	5
Cam & Follower Arrangement	***Can be used for Vertical Load Transfer only***	3

Relative Weighting and Numerical Rating

The relative weighting among seven-design knowledge criterion (preference of one criteria over other) can be done by giving percentage weighting (out of 100) for each category. In this case study the relative weightings as designer's preference is shown below.

CRITERIA	WEIGHTING (%)
Function Requirements	40
Moving Load's Material Properties	10
Quality of Means During Use (Degree of Fullfilling Intended Function in Different Conditions)	5
Pre-Operation Requirement	20
Operation Requirement (Additional Items/Components)	5
Post Operation Requirement {Special Process(s) Required}	15
Angle of Load Transportation	5
Consolidated Rating of Each Alternative	**100**

Degrees of Suitability of each alternative to each context knowledge category is converted into relative numerical rating using AHP comparison scales and these are converted into percentage weighting as shown in the matrices below:

Rating of Alternatives on Function Requirements

ALTERNATIVES	RACK & PINION ASSEMBLY	BELT & PULLEY ASSEMBLY	LEAD SCREW ASSEMBLY	CAM & FOLLOWER ASSEMBLY	ALTERNATIVES	RACK & PINION ASSEMBLY	BELT & PULLEY ASSEMBLY	LEAD SCREW ASSEMBLY	CAM & FOLLOWER ASSEMBLY	Average
RACK & PINION ASSEMBLY	1	1/3	3	3	RACK & PINION ASSEMBLY	0.214	0.192	0.300	0.300	25.2
BELT & PULLEY ASSEMBLY	3	1	5	5	BELT & PULLEY ASSEMBLY	0.643	0.577	0.500	0.500	55.5
LEAD SCREW ASSEMBLY	1/3	1/5	1	1	LEAD SCREW ASSEMBLY	0.071	0.115	0.100	0.100	9.7
CAM & FOLLOWER ASSEMBLY	1/3	1/5	1	1	CAM & FOLLOWER ASSEMBLY	0.071	0.115	0.100	0.100	9.7

Rating of Alternatives on Moving Load's Material Properties

ALTERNATIVES	RACK & PINION ASSEMBLY	BELT & PULLEY ASSEMBLY	LEAD SCREW ASSEMBLY	CAM & FOLLOWER ASSEMBLY	ALTERNATIVES	RACK & PINION ASSEMBLY	BELT & PULLEY ASSEMBLY	LEAD SCREW ASSEMBLY	CAM & FOLLOWER ASSEMBLY	Average
RACK & PINION ASSEMBLY	1	1	1	5	RACK & PINION ASSEMBLY	0.313	0.313	0.313	0.313	31.3
BELT & PULLEY ASSEMBLY	1	1	1	5	BELT & PULLEY ASSEMBLY	0.313	0.313	0.313	0.313	31.3
LEAD SCREW ASSEMBLY	1	1	1	5	LEAD SCREW ASSEMBLY	0.313	0.313	0.313	0.313	31.3
CAM & FOLLOWER ASSEMBLY	1/5	1/5	1/5	1	CAM & FOLLOWER ASSEMBLY	0.063	0.063	0.063	0.063	6.3

Rating of Alternatives on Quality of Means During Use (Degree of Fullfilling Intended Function in Different Conditions)

ALTERNATIVES	RACK & PINION ASSEMBLY	BELT & PULLEY ASSEMBLY	LEAD SCREW ASSEMBLY	CAM & FOLLOWER ASSEMBLY	ALTERNATIVES	RACK & PINION ASSEMBLY	BELT & PULLEY ASSEMBLY	LEAD SCREW ASSEMBLY	CAM & FOLLOWER ASSEMBLY	Average
RACK & PINION ASSEMBLY	1	3	1/3	5	RACK & PINION ASSEMBLY	0.221	0.321	0.199	0.313	26.3
BELT & PULLEY ASSEMBLY	1/3	1	1/5	3	BELT & PULLEY ASSEMBLY	0.074	0.107	0.119	0.188	12.2
LEAD SCREW ASSEMBLY	3	5	1	7	LEAD SCREW ASSEMBLY	0.662	0.536	0.597	0.438	55.8
CAM & FOLLOWER ASSEMBLY	1/5	1/3	1/7	1	CAM & FOLLOWER ASSEMBLY	0.044	0.036	0.085	0.063	5.7

Rating of Alternatives on Pre-Operation Requirement

ALTERNATIVES	RACK & PINION ASSEMBLY	BELT & PULLEY ASSEMBLY	LEAD SCREW ASSEMBLY	CAM & FOLLOWER ASSEMBLY	ALTERNATIVES	RACK & PINION ASSEMBLY	BELT & PULLEY ASSEMBLY	LEAD SCREW ASSEMBLY	CAM & FOLLOWER ASSEMBLY	Average
RACK & PINION ASSEMBLY	1	7	1/3	3	RACK & PINION ASSEMBLY	0.223	0.318	0.203	0.326	26.8
BELT & PULLEY ASSEMBLY	1/7	1	1/9	1/5	BELT & PULLEY ASSEMBLY	0.032	0.045	0.068	0.022	4.2
LEAD SCREW ASSEMBLY	3	9	1	5	LEAD SCREW ASSEMBLY	0.670	0.409	0.608	0.543	55.8
CAM & FOLLOWER ASSEMBLY	1/3	5	1/5	1	CAM & FOLLOWER ASSEMBLY	0.074	0.227	0.122	0.109	13.3

Rating of Alternatives on Operation Requirement (Additional Items/Components)

ALTERNATIVES	RACK & PINION ASSEMBLY	BELT & PULLEY ASSEMBLY	LEAD SCREW ASSEMBLY	CAM & FOLLOWER ASSEMBLY	ALTERNATIVES	RACK & PINION ASSEMBLY	BELT & PULLEY ASSEMBLY	LEAD SCREW ASSEMBLY	CAM & FOLLOWER ASSEMBLY	Average
RACK & PINION ASSEMBLY	1	5	1/3	1	RACK & PINION ASSEMBLY	0.192	0.278	0.184	0.192	21.2
BELT & PULLEY ASSEMBLY	1/5	1	1/7	1/5	BELT & PULLEY ASSEMBLY	0.038	0.056	0.079	0.038	5.3
LEAD SCREW ASSEMBLY	3	7	1	3	LEAD SCREW ASSEMBLY	0.577	0.389	0.553	0.577	52.4
CAM & FOLLOWER ASSEMBLY	1	5	1/3	1	CAM & FOLLOWER ASSEMBLY	0.192	0.278	0.184	0.192	21.2

Rating of Alternatives on Post Operation Requirement {Special Process (s) Required}

ALTERNATIVES	RACK & PINION ASSEMBLY	BELT & PULLEY ASSEMBLY	LEAD SCREW ASSEMBLY	CAM & FOLLOWER ASSEMBLY	ALTERNATIVES	RACK & PINION ASSEMBLY	BELT & PULLEY ASSEMBLY	LEAD SCREW ASSEMBLY	CAM & FOLLOWER ASSEMBLY	Average
RACK & PINION ASSEMBLY	1	7	1/3	1	RACK & PINION ASSEMBLY	0.194	0.292	0.188	0.194	21.7
BELT & PULLEY ASSEMBLY	1/7	1	1/9	1/7	BELT & PULLEY ASSEMBLY	0.028	0.042	0.063	0.028	4.0
LEAD SCREW ASSEMBLY	3	9	1	3	LEAD SCREW ASSEMBLY	0.583	0.375	0.563	0.583	52.6
CAM & FOLLOWER ASSEMBLY	1	7	1/3	1	CAM & FOLLOWER ASSEMBLY	0.194	0.292	0.188	0.194	21.7

Rating of Alternatives on Angle of Load Transportation

ALTERNATIVES	RACK & PINION ASSEMBLY	BELT & PULLEY ASSEMBLY	LEAD SCREW ASSEMBLY	CAM & FOLLOWER ASSEMBLY	ALTERNATIVES	RACK & PINION ASSEMBLY	BELT & PULLEY ASSEMBLY	LEAD SCREW ASSEMBLY	CAM & FOLLOWER ASSEMBLY	Average
RACK & PINION ASSEMBLY	1	1/3	1/5	1	RACK & PINION ASSEMBLY	0.100	0.071	0.115	0.100	9.7
BELT & PULLEY ASSEMBLY	3	1	1/3	3	BELT & PULLEY ASSEMBLY	0.300	0.214	0.192	0.300	25.2
LEAD SCREW ASSEMBLY	5	3	1	5	LEAD SCREW ASSEMBLY	0.500	0.643	0.577	0.500	55.5
CAM & FOLLOWER ASSEMBLY	1	1/3	1/5	1	CAM & FOLLOWER ASSEMBLY	0.100	0.071	0.115	0.100	9.7

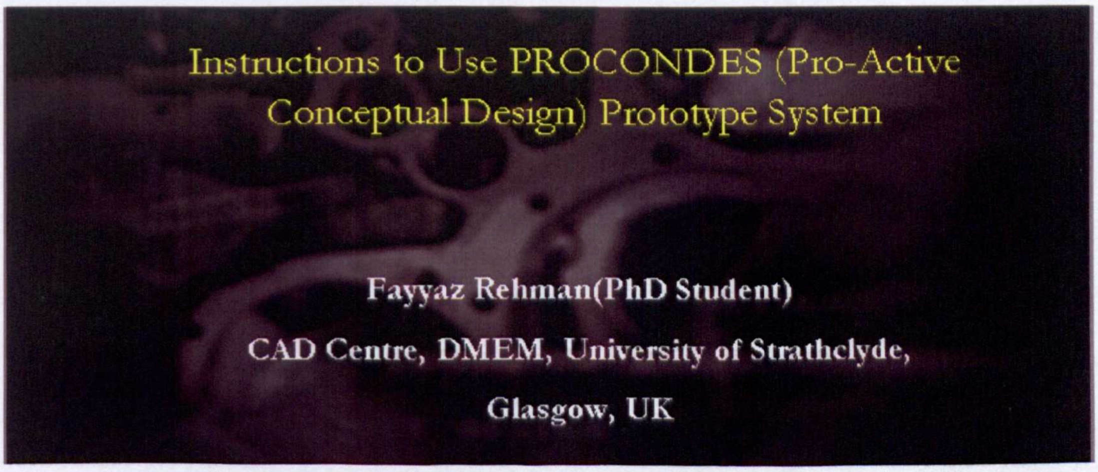
Selection of best PDE/design solution

The best design solution/alternative out of these four alternatives *(Rack & Pinion Assembly, Belt & Pulley Assembly, Lead Screw Assembly, Cam & Follower Assembly)* is *Lead Screw Assembly*. The highest added normalized value is *3425* for **Lead Screw Assembly** as shown in the table below:

CRITERIA	WEIGHTING (%)	RATING OF SUITABILITIY OF ALTERNATIVES			
		RACK & PINION ASSEMBLY	**BELT & PULLEY ASSEMBLY**	**LEAD SCREW ASSEMBLY**	**CAM & FOLLOWER ARRANGEMENT**
Function Requirements	40	25.2	55.5	9.7	9.7
Moving Load's Material Properties	10	31.3	31.3	31.3	6.3
Quality of Means During Use (Degree of Fullfilling Intended Function in Different Conditions)	5	26.3	12.2	55.8	5.7
Pre-Operation Requirement	20	26.8	4.2	55.8	13.3
Operation Requirement (Additional Items/Components)	5	21.2	5.3	52.4	21.2
Post Operation Requirement {Special Process(s) Required}	15	21.7	4	52.6	21.7
Angle of Load Transportation	5	9.7	25.2	55.5	9.7
Consolidated Rating of Each Alternative	**100**	**2469**	**2891**	***3425***	**1226**

Appendix-F: PROCONDES Working

This Appendix presents the instructions/procedure that should be followed to use PROCONDES prototype system. These instructions are shown in the form of power point presentation saved in the CD-ROM along with PROCONDES system. Screen dumps of this presentation are shown in this appendix.

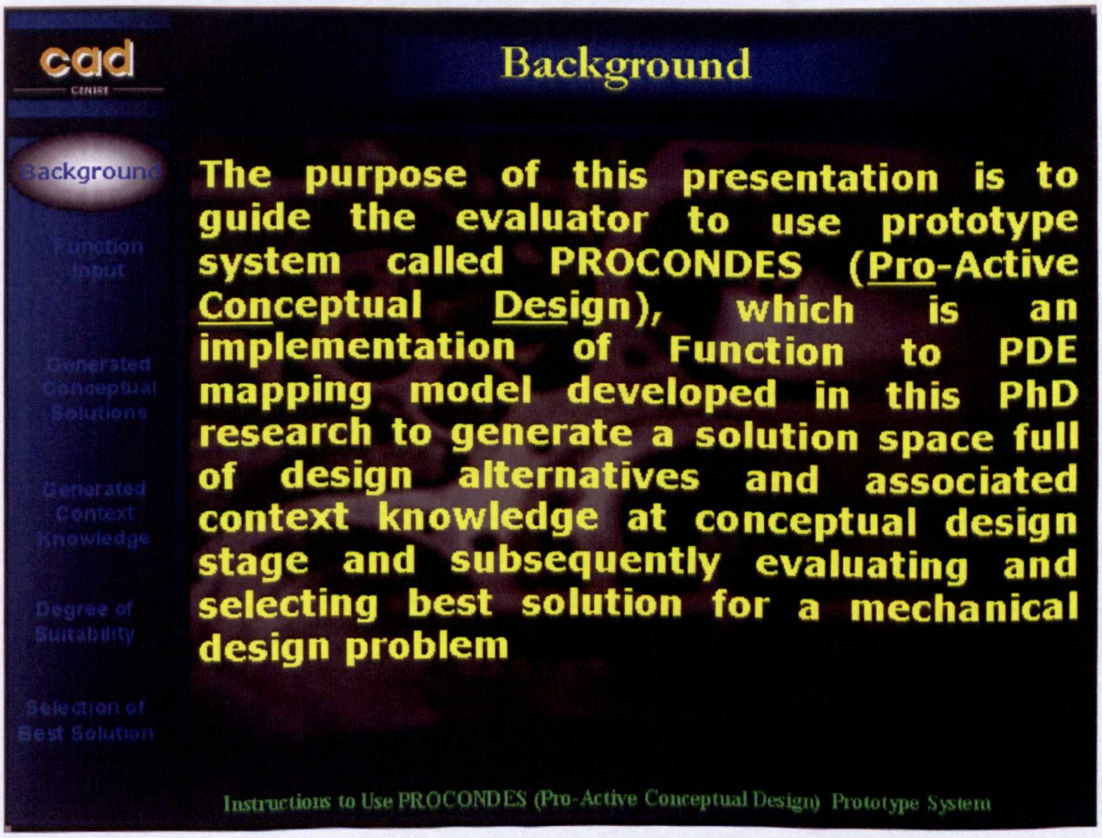


Instructions to Use PROCONDES (Pro-Active Conceptual Design) Prototype System

Fayyaz Rehman(PhD Student)

CAD Centre, DMEM, University of Strathclyde,

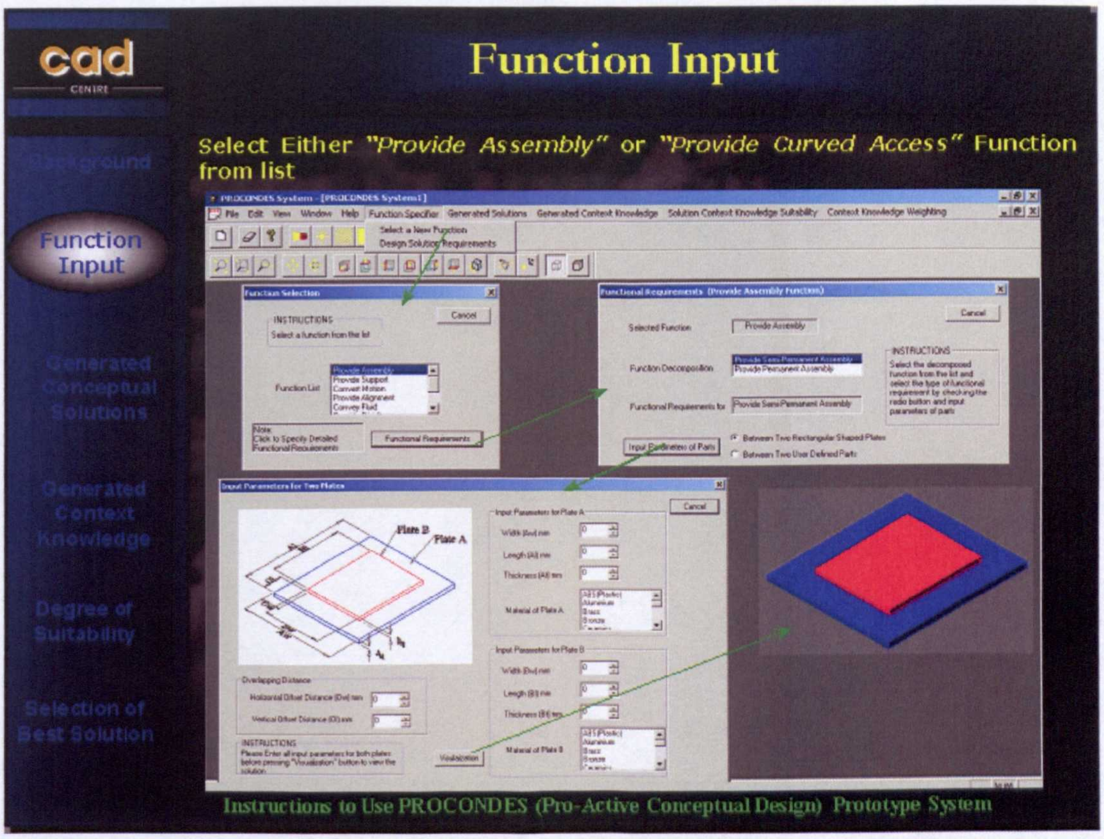
Glasgow, UK



Background

The purpose of this presentation is to guide the evaluator to use prototype system called PROCONDES (Pro-Active Conceptual Design), which is an implementation of Function to PDE mapping model developed in this PhD research to generate a solution space full of design alternatives and associated context knowledge at conceptual design stage and subsequently evaluating and selecting best solution for a mechanical design problem

Instructions to Use PROCONDES (Pro-Active Conceptual Design) Prototype System



Function Input

Select Either *"Provide Assembly"* or *"Provide Curved Access"* Function from list

INSTRUCTIONS
Select a function from the list

Note:
Click to Specify Detailed Functional Requirements

Selected Function: Provide Assembly

Functional Requirements for: Provide Semi Permanent Assembly

INSTRUCTIONS
Select the decomposed function from the list and select the type of functional requirement by checking the radio button and input parameters of parts

● Between Two Rectangular Shaped Plates
○ Between Two User Defined Parts

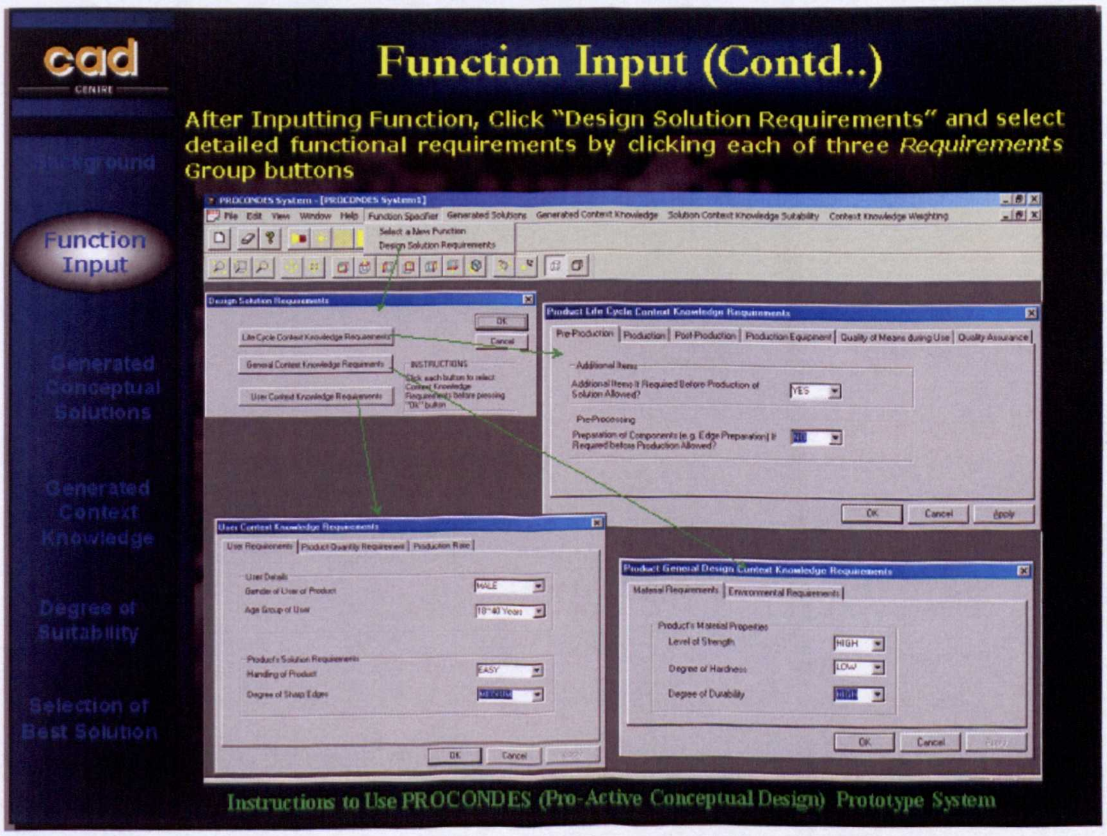
Width (Aw) mm: 0
Length (Al) mm: 0
Thickness (At) mm: 0

Width (Bw) mm: 0
Length (Bl) mm: 0
Thickness (Bt) mm: 0

Horizontal Offset Distance (Dw) mm: 0
Vertical Offset Distance (Dl) mm: 0

INSTRUCTIONS
Please Enter all input parameters for both plates before pressing "Visualization" button to view the solution.

Instructions to Use PROCONDES (Pro-Active Conceptual Design) Prototype System



Function Input (Contd..)

After Inputting Function, Click "Design Solution Requirements" and select detailed functional requirements by clicking each of three *Requirements* Group buttons

INSTRUCTIONS
Click each button to select Context Knowledge Requirements before pressing "OK" button

Additional Items
Additional Items If Required Before Production of Solution Allowed? YES

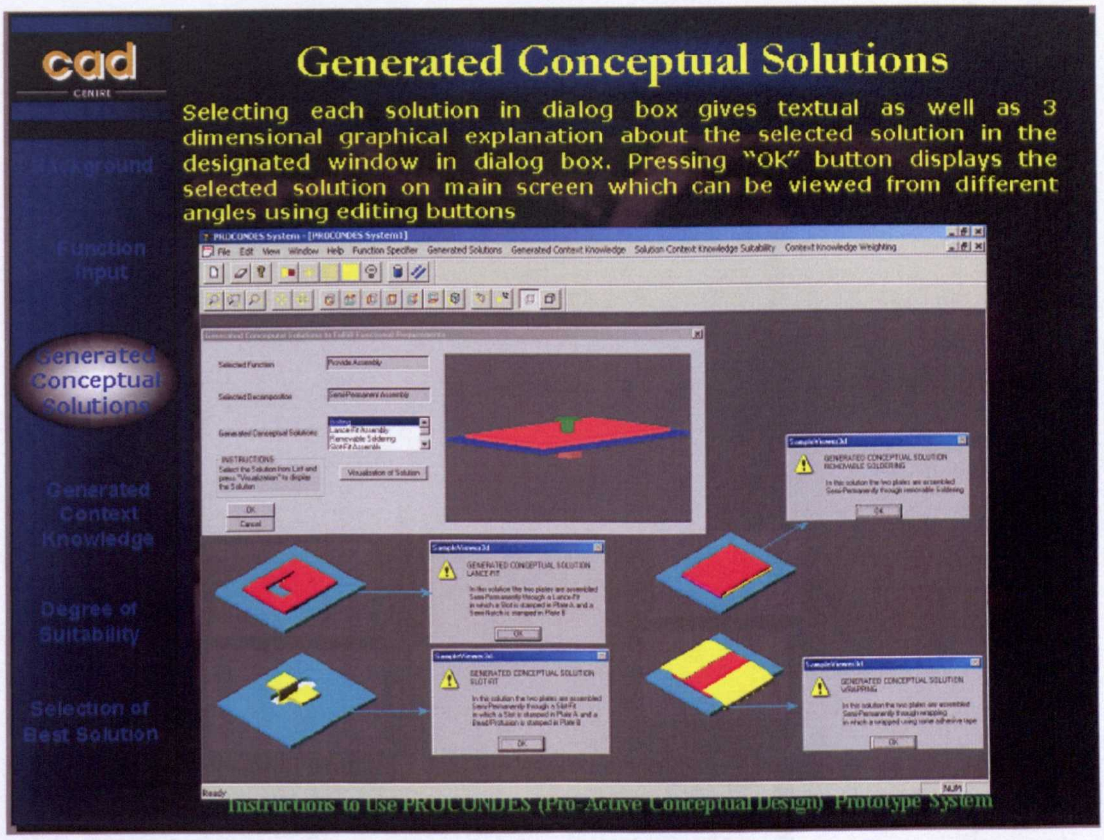
Pre-Processing
Preparation of Components (e.g. Edge Preparation) If Required before Production Allowed? NO

User Details
Gender of User of Product: MALE
Age Group of User: 18~40 Years

Product's Solution Requirements
Handling of Product: EASY
Degree of Sharp Edges: MEDIUM

Product's Material Properties
Level of Strength: HIGH
Degree of Hardness: LOW
Degree of Durability: HIGH

Instructions to Use PROCONDES (Pro-Active Conceptual Design) Prototype System



Generated Conceptual Solutions

Selecting each solution in dialog box gives textual as well as 3 dimensional graphical explanation about the selected solution in the designated window in dialog box. Pressing "Ok" button displays the selected solution on main screen which can be viewed from different angles using editing buttons

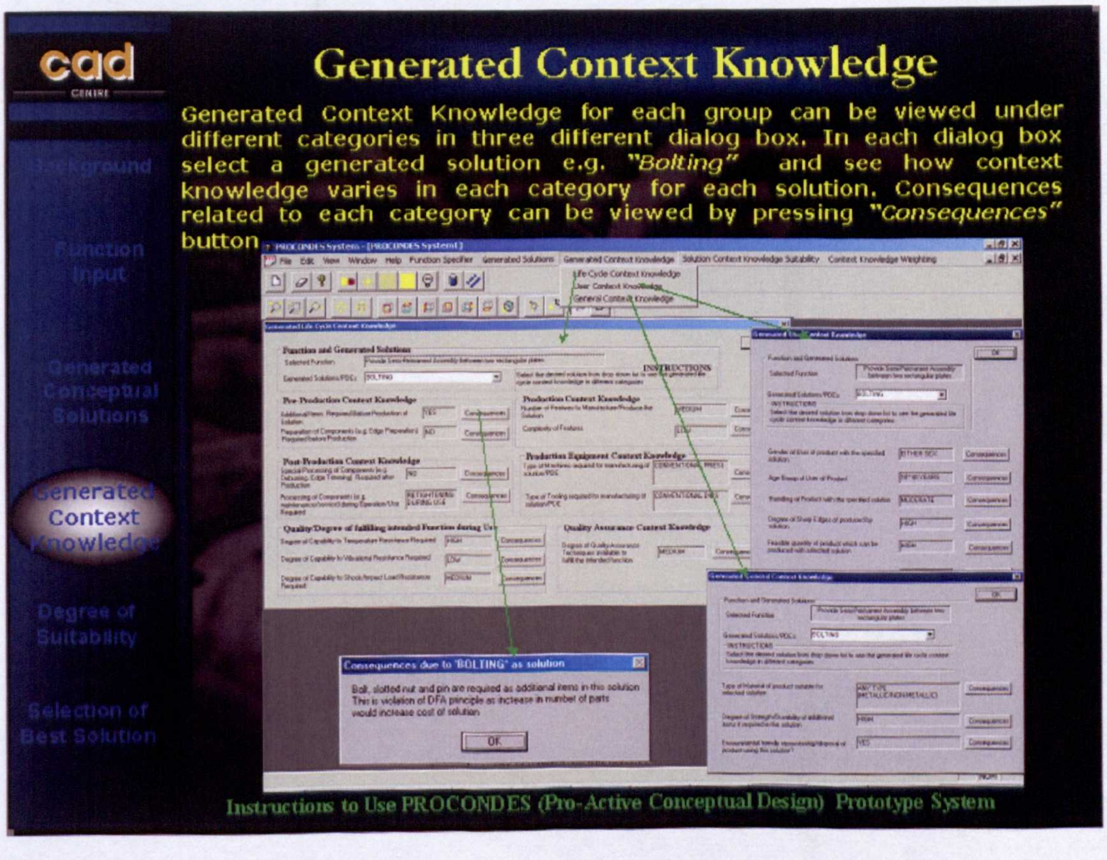
GENERATED CONCEPTUAL SOLUTION
REMOVABLE SOLDERING
In this solution the two plates are assembled Semi-Permanently through removable Soldering

GENERATED CONCEPTUAL SOLUTION
LANCE FIT
In this solution the two plates are assembled Semi-Permanently through a Lance-Fit in which a Slot is stamped in Plate A and a Semi-Notch is stamped in Plate B

GENERATED CONCEPTUAL SOLUTION
SLOT FIT
In this solution the two plates are assembled Semi-Permanently through a Slot-Fit in which a Slot is stamped in Plate A and a Bead/Protusion is stamped in Plate B

GENERATED CONCEPTUAL SOLUTION
WRAPPING
In this solution the two plates are assembled Semi-Permanently through wrapping in which a wrapped using some adhesive tape

Instructions to Use PROCONDES (Pro-Active Conceptual Design) Prototype System



Generated Context Knowledge

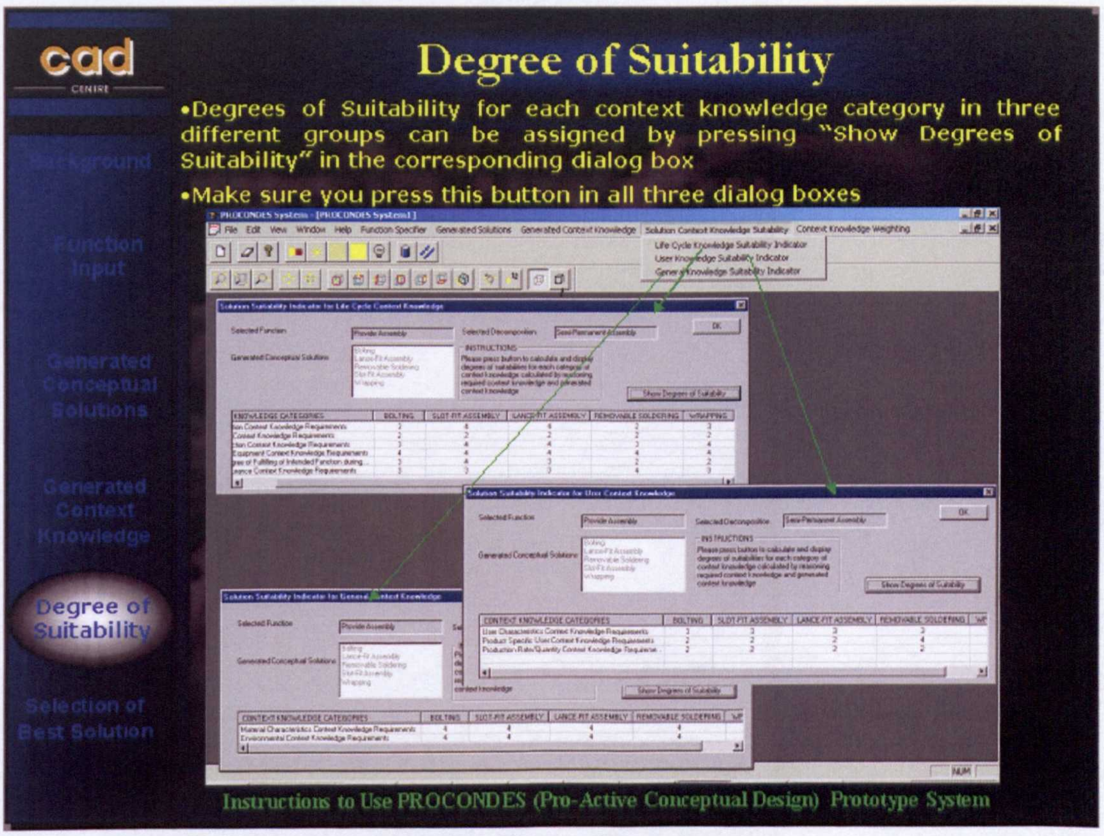
Generated Context Knowledge for each group can be viewed under different categories in three different dialog box. In each dialog box select a generated solution e.g. *"Bolting"* and see how context knowledge varies in each category for each solution. Consequences related to each category can be viewed by pressing *"Consequences"* button

Consequences due to 'BOLTING' as solution

Bolt, slotted nut and pin are required as additional items in this solution This is violation of DFA principle as increase in number of parts would increase cost of solution

OK

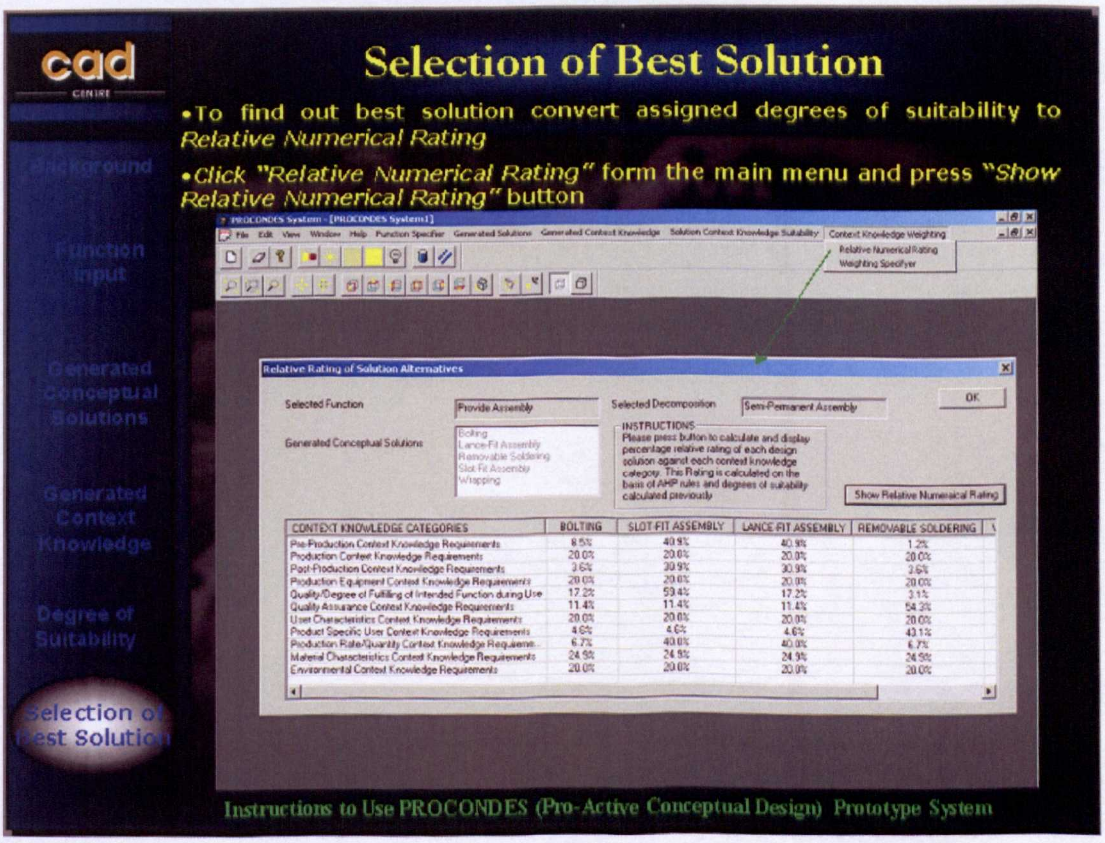
Instructions to Use PROCONDES (Pro-Active Conceptual Design) Prototype System



Degree of Suitability

- Degrees of Suitability for each context knowledge category in three different groups can be assigned by pressing "Show Degrees of Suitability" in the corresponding dialog box
- Make sure you press this button in all three dialog boxes

Instructions to Use PROCONDES (Pro-Active Conceptual Design) Prototype System



Selection of Best Solution

- To find out best solution convert assigned degrees of suitability to *Relative Numerical Rating*
- *Click "Relative Numerical Rating"* form the main menu and press *"Show Relative Numerical Rating"* button

Selected Function: Provide Assembly

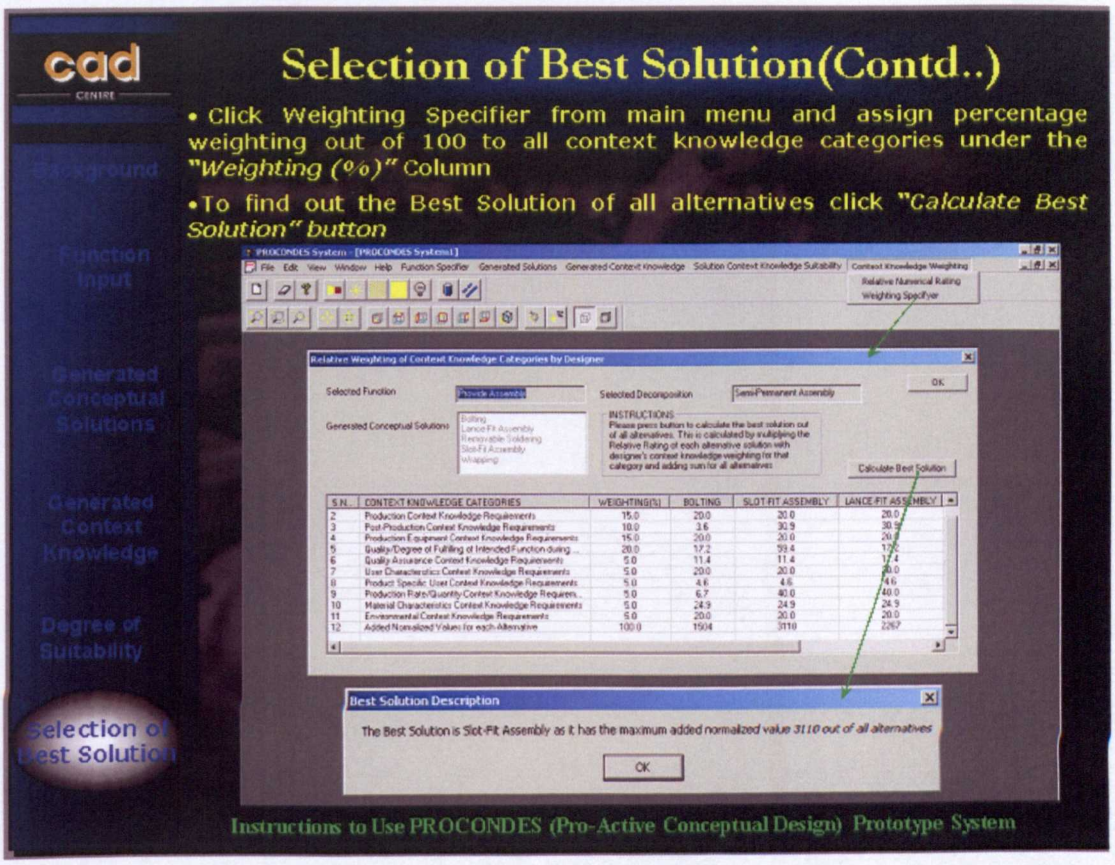
Selected Decomposition: Semi-Permanent Assembly

Generated Conceptual Solutions:
Bolting
Lance-Fit Assembly
Removable Soldering
Slot-Fit Assembly
Wrapping

INSTRUCTIONS
Please press button to calculate and display percentage relative rating of each design solution against each context knowledge category. This Rating is calculated on the basis of AHP rules and degrees of suitability calculated previously

CONTEXT KNOWLEDGE CATEGORIES	BOLTING	SLOT-FIT ASSEMBLY	LANCE-FIT ASSEMBLY	REMOVABLE SOLDERING
Pre-Production Context Knowledge Requirements	8.5%	40.9%	40.9%	1.2%
Production Context Knowledge Requirements	20.0%	20.0%	20.0%	20.0%
Post-Production Context Knowledge Requirements	3.6%	30.9%	30.9%	3.6%
Production Equipment Context Knowledge Requirements	20.0%	20.0%	20.0%	20.0%
Quality/Degree of Fulfilling of Intended Function during Use	17.2%	59.4%	17.2%	3.1%
Quality Assurance Context Knowledge Requirements	11.4%	11.4%	11.4%	54.3%
User Characteristics Context Knowledge Requirements	20.0%	20.0%	20.0%	20.0%
Product Specific User Context Knowledge Requirements	4.6%	4.6%	4.6%	43.1%
Production Rate/Quantity Context Knowledge Requireme...	6.7%	40.0%	40.0%	6.7%
Material Characteristics Context Knowledge Requirements	24.9%	24.9%	24.9%	24.9%
Environmental Context Knowledge Requirements	20.0%	20.0%	20.0%	20.0%

Instructions to Use PROCONDES (Pro-Active Conceptual Design) Prototype System



Selection of Best Solution(Contd..)

- Click Weighting Specifier from main menu and assign percentage weighting out of 100 to all context knowledge categories under the *"Weighting (%)"* Column
- To find out the Best Solution of all alternatives click *"Calculate Best Solution" button*

Selected Function: Provide Assembly

Selected Decomposition: Semi-Permanent Assembly

Generated Conceptual Solutions:
Bolting
Lance-Fit Assembly
Removable Soldering
Slot-Fit Assembly
Wrapping

INSTRUCTIONS
Please press button to calculate the best solution out of all alternatives. This is calculated by multiplying the Relative Rating of each alternative solution with designer's context knowledge weighting for that category and adding sum for all alternatives

S.N.	CONTEXT KNOWLEDGE CATEGORIES	WEIGHTING(%)	BOLTING	SLOT-FIT ASSEMBLY	LANCE-FIT ASSEMBLY
2	Production Context Knowledge Requirements	15.0	20.0	20.0	20.0
3	Post-Production Context Knowledge Requirements	10.0	3.6	30.9	30.9
4	Production Equipment Context Knowledge Requirements	15.0	20.0	20.0	20.0
5	Quality/Degree of Fulfiling of Intended Function during ...	20.0	17.2	59.4	17.2
6	Quality Assurance Context Knowledge Requirements	5.0	11.4	11.4	17.4
7	User Characteristics Context Knowledge Requirements	5.0	20.0	20.0	20.0
8	Product Specific User Context Knowledge Requirements	5.0	4.6	4.6	4.6
9	Production Rate/Quantity Context Knowledge Requirem...	5.0	6.7	40.0	40.0
10	Material Characteristics Context Knowledge Requirements	5.0	24.9	24.9	24.9
11	Environmental Context Knowledge Requirements	5.0	20.0	20.0	20.0
12	Added Normalized Values for each Alternative	100.0	1504	3110	2267

Best Solution Description

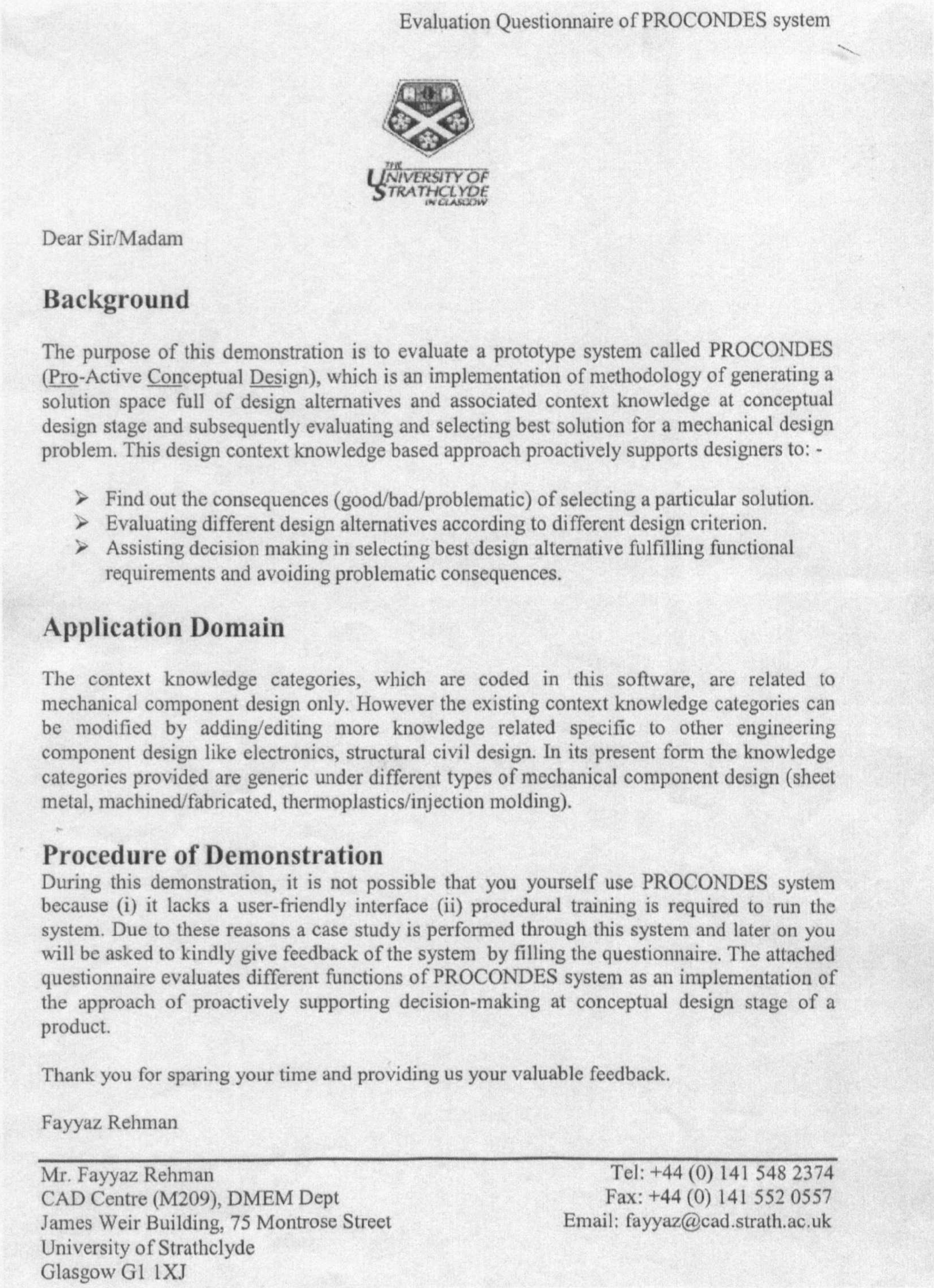
The Best Solution is Slot-Fit Assembly as it has the maximum added normalized value *3110 out of all alternatives*

OK

Instructions to Use PROCONDES (Pro-Active Conceptual Design) Prototype System

Appendix-G: Evaluation Questionnaire

This Appendix presents a sample questionnaire completed by an evaluator during the case study using PROCONDES prototype system.



Evaluation Questionnaire of PROCONDES system

Dear Sir/Madam

Background

The purpose of this demonstration is to evaluate a prototype system called PROCONDES (Pro-Active Conceptual Design), which is an implementation of methodology of generating a solution space full of design alternatives and associated context knowledge at conceptual design stage and subsequently evaluating and selecting best solution for a mechanical design problem. This design context knowledge based approach proactively supports designers to: -

- Find out the consequences (good/bad/problematic) of selecting a particular solution.
- Evaluating different design alternatives according to different design criterion.
- Assisting decision making in selecting best design alternative fulfilling functional requirements and avoiding problematic consequences.

Application Domain

The context knowledge categories, which are coded in this software, are related to mechanical component design only. However the existing context knowledge categories can be modified by adding/editing more knowledge related specific to other engineering component design like electronics, structural civil design. In its present form the knowledge categories provided are generic under different types of mechanical component design (sheet metal, machined/fabricated, thermoplastics/injection molding).

Procedure of Demonstration

During this demonstration, it is not possible that you yourself use PROCONDES system because (i) it lacks a user-friendly interface (ii) procedural training is required to run the system. Due to these reasons a case study is performed through this system and later on you will be asked to kindly give feedback of the system by filling the questionnaire. The attached questionnaire evaluates different functions of PROCONDES system as an implementation of the approach of proactively supporting decision-making at conceptual design stage of a product.

Thank you for sparing your time and providing us your valuable feedback.

Fayyaz Rehman

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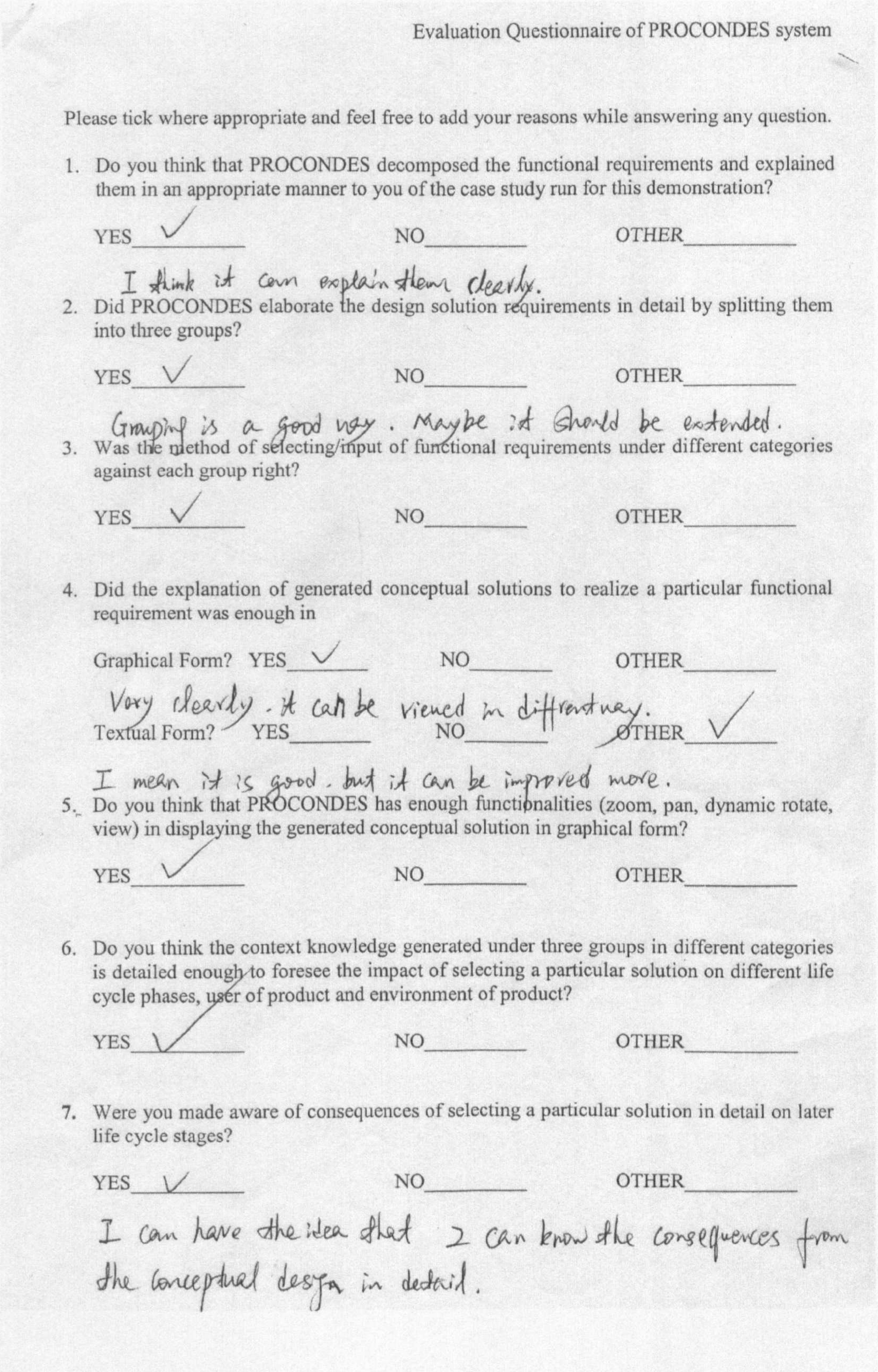
Email: fayyaz@cad.strath.ac.uk



Evaluation Questionnaire of PROCONDES system

Please tick where appropriate and feel free to add your reasons while answering any question.

1. Do you think that PROCONDES decomposed the functional requirements and explained them in an appropriate manner to you of the case study run for this demonstration?

YES ✓ NO OTHER

I think it can explain them clearly.

2. Did PROCONDES elaborate the design solution requirements in detail by splitting them into three groups?

YES ✓ NO OTHER

Grouping is a good way. Maybe it should be extended.

3. Was the method of selecting/input of functional requirements under different categories against each group right?

YES ✓ NO OTHER

4. Did the explanation of generated conceptual solutions to realize a particular functional requirement was enough in

Graphical Form? YES ✓ NO OTHER

Very clearly. it can be viewed in diffrent way.

Textual Form? YES NO OTHER ✓

I mean it is good. but it can be improved more.

5. Do you think that PROCONDES has enough functionalities (zoom, pan, dynamic rotate, view) in displaying the generated conceptual solution in graphical form?

YES ✓ NO OTHER

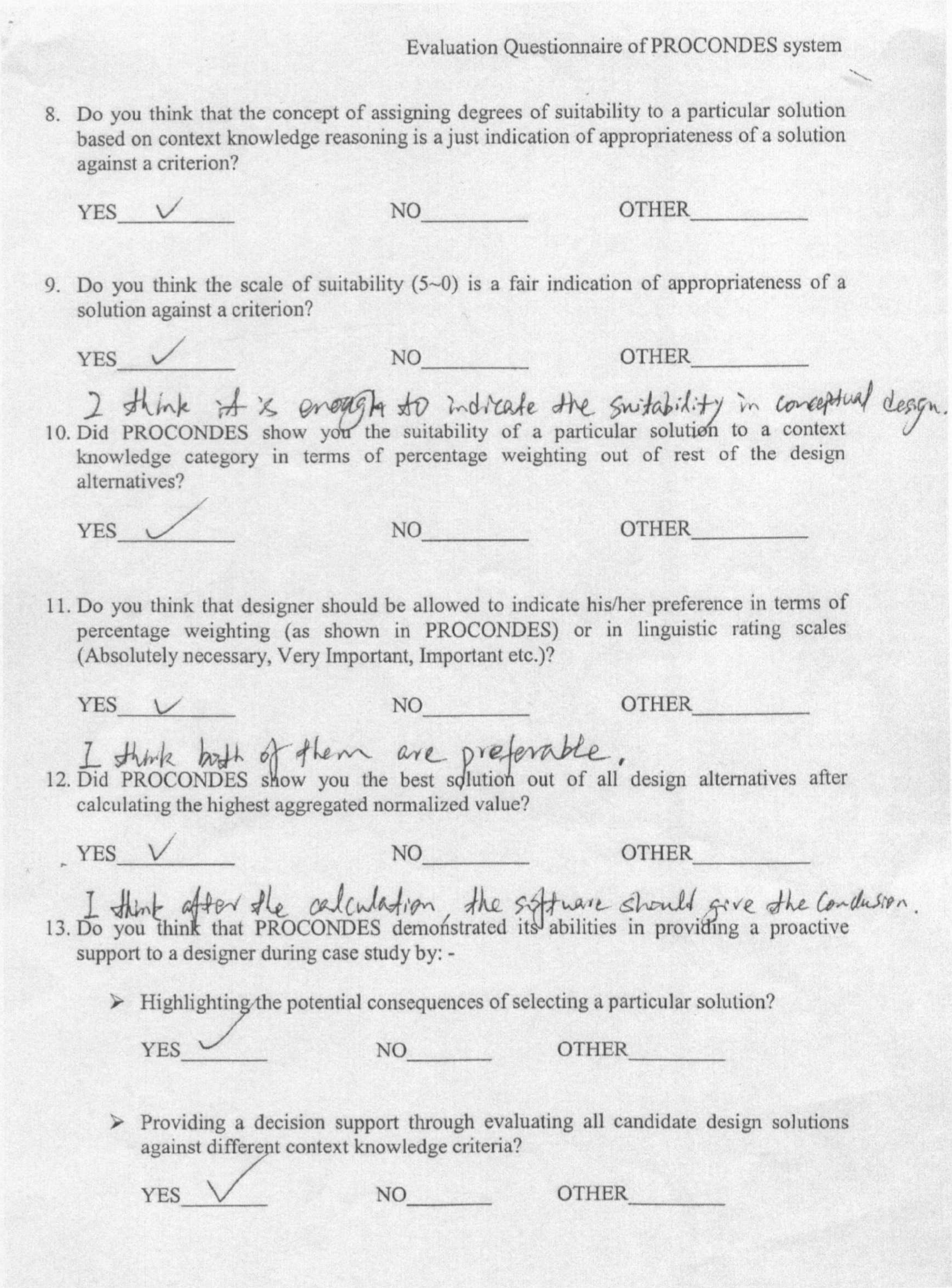
6. Do you think the context knowledge generated under three groups in different categories is detailed enough to foresee the impact of selecting a particular solution on different life cycle phases, user of product and environment of product?

YES ✓ NO OTHER

7. Were you made aware of consequences of selecting a particular solution in detail on later life cycle stages?

YES ✓ NO OTHER

I can have the idea that I can know the consequences from the conceptual design in detail.



Evaluation Questionnaire of PROCONDES system

8. Do you think that the concept of assigning degrees of suitability to a particular solution based on context knowledge reasoning is a just indication of appropriateness of a solution against a criterion?

YES ✓ NO________ OTHER________

9. Do you think the scale of suitability (5~0) is a fair indication of appropriateness of a solution against a criterion?

YES ✓ NO________ OTHER________

I think it is enough to indicate the suitability in conceptual design.

10. Did PROCONDES show you the suitability of a particular solution to a context knowledge category in terms of percentage weighting out of rest of the design alternatives?

YES ✓ NO________ OTHER________

11. Do you think that designer should be allowed to indicate his/her preference in terms of percentage weighting (as shown in PROCONDES) or in linguistic rating scales (Absolutely necessary, Very Important, Important etc.)?

YES ✓ NO________ OTHER________

I think both of them are preferable.

12. Did PROCONDES show you the best solution out of all design alternatives after calculating the highest aggregated normalized value?

YES ✓ NO________ OTHER________

I think after the calculation, the software should give the conclusion.

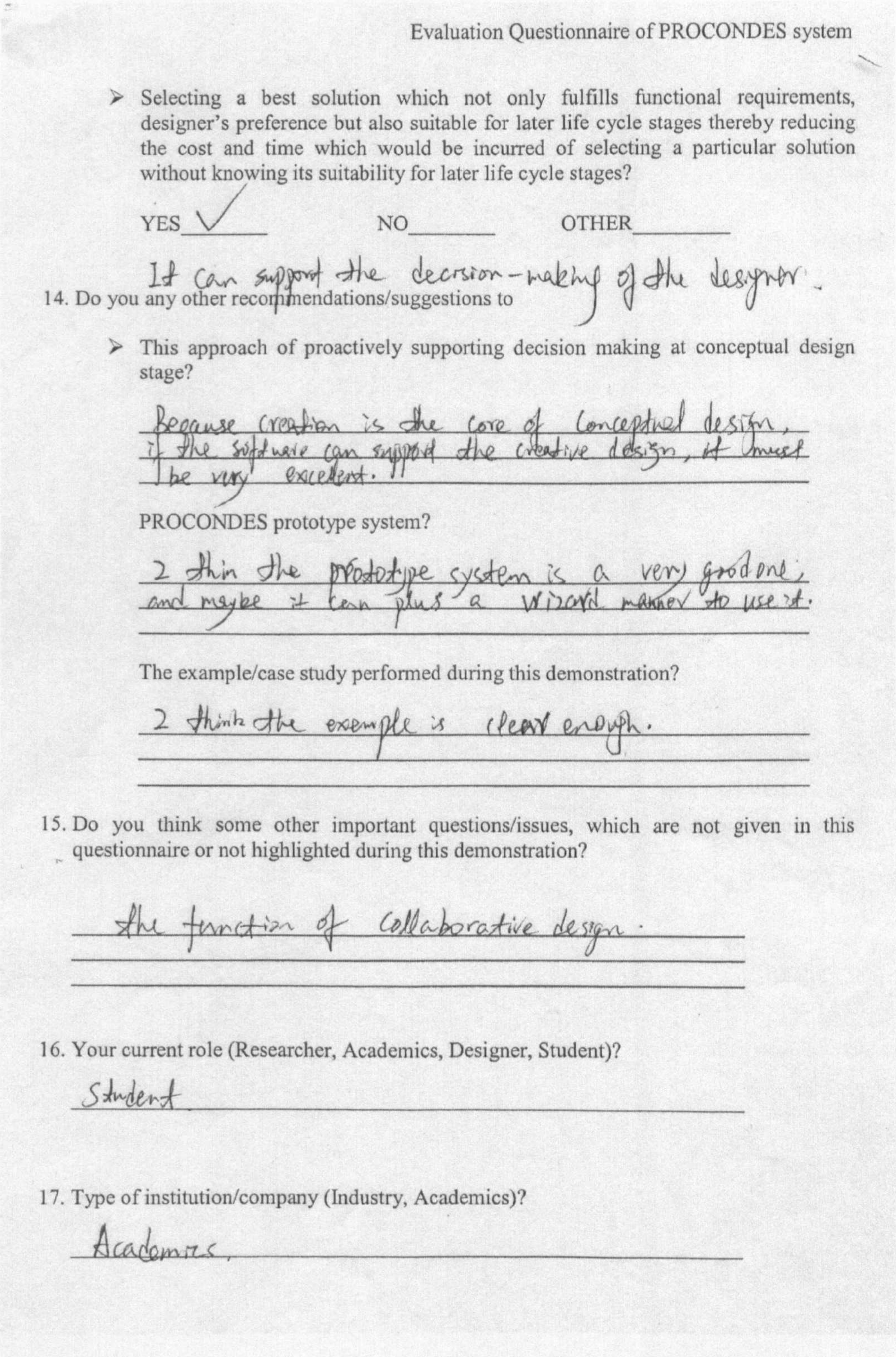
13. Do you think that PROCONDES demonstrated its abilities in providing a proactive support to a designer during case study by: -

   - Highlighting the potential consequences of selecting a particular solution?

     YES ✓ NO________ OTHER________

   - Providing a decision support through evaluating all candidate design solutions against different context knowledge criteria?

     YES ✓ NO________ OTHER________



Evaluation Questionnaire of PROCONDES system

- Selecting a best solution which not only fulfills functional requirements, designer's preference but also suitable for later life cycle stages thereby reducing the cost and time which would be incurred of selecting a particular solution without knowing its suitability for later life cycle stages?

YES ✓ NO_______ OTHER________

It can support the decision-making of the designer.

14. Do you any other recommendations/suggestions to

- This approach of proactively supporting decision making at conceptual design stage?

Because creation is the core of conceptual design, if the software can support the creative design, it must be very excelent.

PROCONDES prototype system?

I thin the prototype system is a very good one; and maybe it can plus a wizard manner to use it.

The example/case study performed during this demonstration?

I think the exemple is clear enough.

15. Do you think some other important questions/issues, which are not given in this questionnaire or not highlighted during this demonstration?

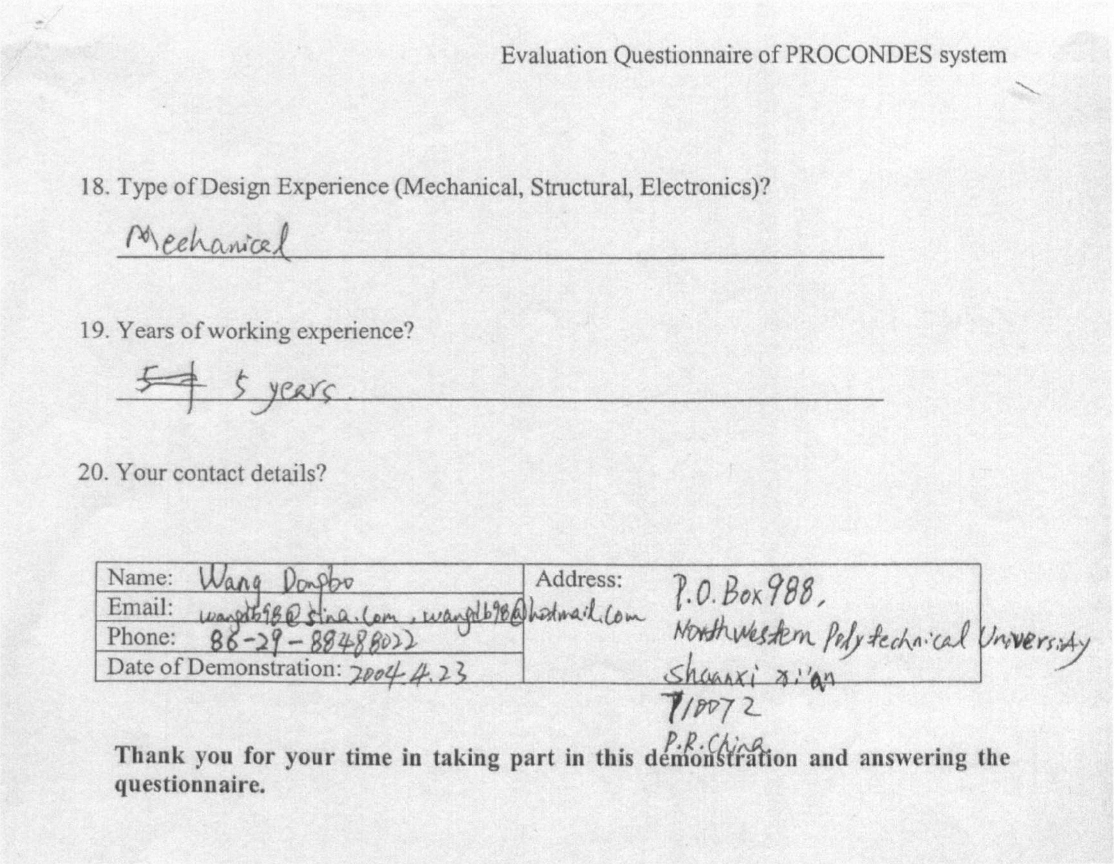
the function of collaborative design.

16. Your current role (Researcher, Academics, Designer, Student)?

Student

17. Type of institution/company (Industry, Academics)?

Academics,



Evaluation Questionnaire of PROCONDES system

18. Type of Design Experience (Mechanical, Structural, Electronics)?

Mechanical

19. Years of working experience?

~~5年~~ 5 years.

20. Your contact details?

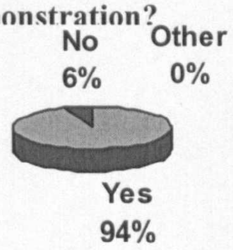
Name: Wang Dongbo	Address: P.O.Box988, Northwestern Polytechnical University shaanxi xi'an 710072 P.R.China
Email: wangdb98@sina.com, wangdb98@hotmail.com	
Phone: 86-29-88488022	
Date of Demonstration: 2004.4.23	

Thank you for your time in taking part in this demonstration and answering the questionnaire.

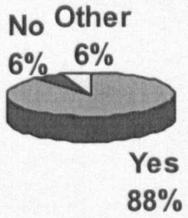
Appendix-H: Evaluation Results

This Appendix presents the evaluation results in graphical form of the demonstration carried out by performing case study in PROCONDES system. These results relate to questions, which are part of the questionnaire as shown in previous appendix.

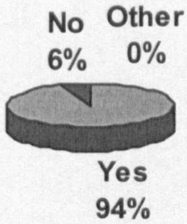
1. **Do you think that PROCONDES decomposed the functional requirements and explained them in an appropriate manner to you of the case study run for this demonstration?**



2. **Did PROCONDES elaborate the design solution requirements in detail by splitting them into three groups?**

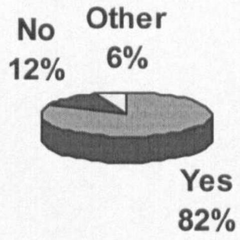


3. **Was the method of selecting/input of functional requirements under different categories against each group right?**

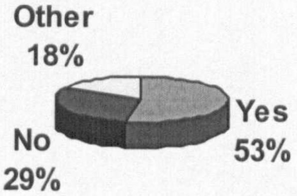


4. **Did the explanation of generated conceptual solutions to realize a particular functional requirement was enough in**

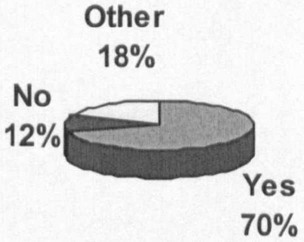
Graphical Form?



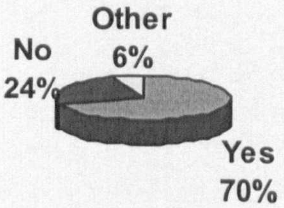
Textual Form?



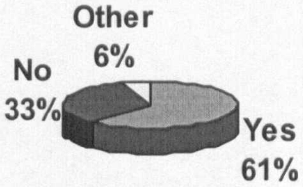
5. **Do you think that PROCONDES has enough functionalities (zoom, pan, dynamic rotate, view) in displaying the generated conceptual solution in graphical form?**



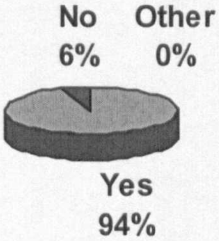
6. **Do you think the context knowledge generated under three groups in different categories is detailed enough to foresee the impact of selecting a particular solution on different life cycle phases, user of product and environment of product?**



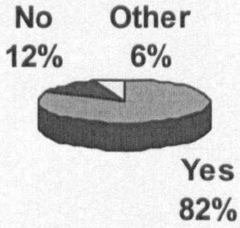
7. **Were you made aware of consequences of selecting a particular solution in detail on later life cycle stages?**



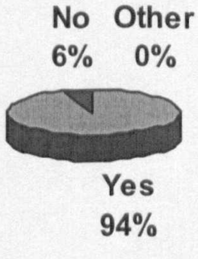
8. **Do you think that the concept of assigning degrees of suitability to a particular solution based on context knowledge reasoning is a just indication of appropriateness of a solution against a criterion?**



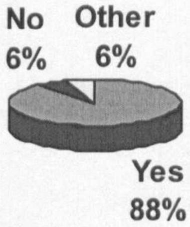
9. **Do you think the scale of suitability (5~0) is a fair indication of appropriateness of a solution against a criterion?**



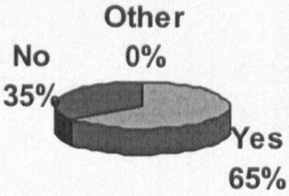
10. **Did PROCONDES show you the suitability of a particular solution to a context knowledge category in terms of percentage weighting out of rest of the design alternatives?**



11. **Do you think that designer should be allowed to indicate his/her preference in terms of percentage weighting (as shown in PROCONDES) or in linguistic rating scales (Absolutely necessary, Very Important, Important etc.)?**

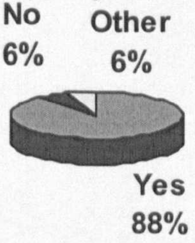


12. **Did PROCONDES show you the best solution out of all design alternatives after calculating the highest aggregated normalized value?**

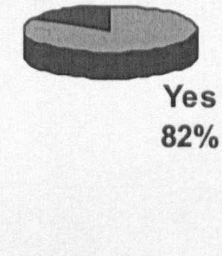


13. Do you think that PROCONDES demonstrated its abilities in providing a proactive support to a designer during case study by: -

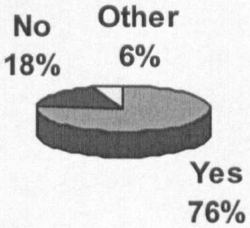
- **Highlighting the potential consequences of selecting a particular solution?**



- **Providing a decision support through evaluating all candidate design solutions against different context knowledge criteria?**



- **Selecting a best solution which not only fulfils functional requirements, designer's preference but also suitable for later life cycle stages thereby reducing the cost and time which would be incurred of selecting a particular solution without knowing its suitability for later life cycle stages?**



Appendix-I: Ph.D. Research Publications

This appendix details a list of publications related to original research work carried out during this Ph.D.

1. Rehman, F., Yan, X.T., "A Prototype System to Support Conceptual Design Synthesis for Multi-X", In *Proceedings of 15th International Conference on Engineering Design (ICED 05)*, held in Melbourne, Australia, AUGUST 15-18, 2005, Publishers Institute of Engineers, Australia, 11 National Circuit, Barton, ACT, pg. 479, ISBN 0-85825-788-2.

2. Rehman, F., Yan, X.T., "Using Context Knowledge Based Reasoning to Support Functional Design", In *Perspectives from Europe and Asia on Engineering Design and Manufacture: A Comparison of Engineering Design and Manufacture in Europe and Asia*, Edited by Xiu-Tian Yan, Cheng-Yu Jiang and Neal P. Juster, Kluwer Academic Publishers, Dordrecht, The Netherlands, 2004, pp. 69-78, ISBN 1-4020-2211-5.

3. Rehman, F., Yan, X.T., "PROCONDES: A tool for pro-active conceptual design synthesis of sheet metal components", In *Proceedings of 5th International Conference on Integrated Design and Manufacturing in Mechanical Engineering (IDMME 2004)* held in Bath, UK, April 5-7, 2004, Publishers University of Bath UK, pg. 16, ISBN 1-85790-1290.

4. Rehman, F., Yan, X.T., Borg, J. C., "Conceptual design decision making using design context knowledge", In *CD-ROM Proceedings of 5th International Conference on Integrated Design and Manufacturing in Mechanical Engineering (IDMME 2004)* held in Bath, UK, April 5-7, 2004, Publishers University of Bath UK, pg. 107, ISBN 1-85790-1290.

5. Rehman, F., Yan, X.T., "Product design elements as means to realize functions in mechanical conceptual design", In *Proceedings of 14th International Conference on Engineering Design ICED 03*, Stockholm, AUGUST 19-21, 2003, Publishers Design Society, University of Strathclyde, 75 Montrose Street, Glasgow, UK, G1 1XJ, pg. 213, ISBN 1-90467-0008.

6. Yan, X.T., Rehman, F., Borg, J.C., "Design context knowledge based proactive support for component design", In *Knowledge Intensive Design Tools*, Editors Philip J Farrugia and Jonathon C Borg, published by Kluwer Academic Publishers, 2004, pp. 169-184, ISBN 1-4020-7732-7.

7. Yan, X.T., Rehman, F., Borg, J.C. "FORESEEing design solution consequences using design context information", *In Preprints of the Fifth IFP Workshop in Knowledge-Intensive Computer Aided Design, Malta*, July 23-25, 2002, pp. 18-33, Publishers Impressions Ltd Malta.

8. Rehman, F., Yan, X.T., "Proactive support for conceptual design synthesis of sheet metal components", In *Recent Advances in Integrated Design and Manufacturing in Mechanical Engineering*, Editors Grigore Gogu, Daniel Coutellier, Parick Chedmail & P. Ray, Kluwer Academic Publishers, 2003, ISBN: 1-4020-1163-6.