A Fuzzy Approach to Support DFA Evaluation of Design Concepts

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Abstract

Design evaluation form one of the more important aspects in determining whether it has met the initial requirements. Post design evaluations however are less advantageous than those made in the earlier stage of design, since it provides for ample opportunity to make less costly changes to the design. During conceptual design stage, the knowledge and information about the design is often vague and incomplete and this makes evaluation even more difficult. At present there are not enough tools to support the designer to make evaluations on design concepts. This thesis presents an approach which will support designer doing evaluation on design concepts by incorporating DFA criteria into the evaluating tool. The criteria most useful at that stage would be the part count reduction analysis. The handling of the information and knowledge at this conceptual stage will be handled by a fuzzy logic expert system.

A demonstration on the usefulness of fuzzy logic together with the part count analysis was done on two case studies. The first use the approach to demonstrate the way it can support the designers at the concepts selection stage and the second examines the redesign of an existing product. The result of the case studies shows that it is possible to integrate the use of fuzzy logic with DFA in providing support to the designer in doing design concepts evaluation. This approach also highlights the ability of fuzzy logic in representing information and knowledge at this conceptual stage in the form of fuzzy sets.

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Chapter 1

Introduction

1.1 Background

The ever changing role and demand on the designer has led to product to be manufactured at a faster and faster rate. This combined with market demands give immense impetus on the part of the manufacturer, and hence designer, to come out with better and faster products. Apart from that, designers are also expected to incorporate within the constraints of environmental issues, manufacturing issues, recycling issues, in short, need to take into account not just the function of the product but also its entire life-cycle. This places considerable pressure on the part of the designers to meet these requirements. Studies done [1,2] has indicated that these designers need more and more sophisticated tools in order to support them to do their job thoroughly as demanded by these factors.

This heavy emphasis on faster and better product places demand on product development in constraining the design process in a tighter and compact schedule. Traditional sequential design breaks down the design task into sub-tasks that are serially executed in a predefined pattern. Researchers have found that sequential design is brittle and inflexible and often requires numerous iterations, which makes the design expensive and time-consuming, and also limits the number of design alternatives that can be carried out [2], Simultaneous activities in which many specialists perform duties at the same time is now prevalent in most manufacturing enterprises. This has been commonly termed concurrent or simultaneous engineering . The traditional way of compartmentalisation of design and manufacture has given way to more and more concurrent engineering methods which has helped this design process be more integrated.

More issues are taken into consideration in the design process than ever before and this makes the designer more and more liable to make errors if there is no support or tool to help them in this process. These errors, if not clearly identifed earlier, can contribute to unnecessary iterative cycles of adjustment/refinement and eventually to a high cost of product development. This can be avoided if readily available tools or support can weed out or flag problems early in the design process, thus eliminating design blunders and reducing design development time.

This thesis attempts to address this lack of tools, by providing for more support to the designers to help them in the product development process.

1.2 Engineering Design

Engineering design is a process of by which humans solve problems by the intelligent manipulation of knowledge [3]. Hence in understanding its process, its types and contents of knowledge involved is crucial. This is important in the sense that support for the designer can not only be provided but also provide for a structure for the automation of some the design activities.

There are numerous contributions by various authors [4, 5, 6, 7] on how engineering design comes about. Pahl and Beitz [4] had arguably been the most thorough in their investigation of the design process. In this thesis, the design process model by Pahl and Beitz was adapted as it provide for a systematic and detailed approach to design. This design process will, however, be compared to that of Suh [5], to highlight similar characteristic of design process model, as presented in Chapter 2.

1.2.1 Types of Design

Pahl and Beitz [4] had reported that engineering design activities can be classified in 3 manner:

- original design - original solution for a given system
- adaptive design - adaptation of known solution principles to a task
- variant design - variation of size or configuration of an existing system

The first type of design activity is rarely undertaken. The second type mostly reuse many existing components and subassemblies, while the third type mostly uses standard parts and subassemblies and hence new part development here is scarce. It has been reported that [8] upwards of 80% of design is adaptive or variant, which results in a process that is particularly reliant on information and knowledge.

1.2.2 Early Phase of Design

Most authors on engineering design process classify a phase during design where the ideation and concepts are formed from a set of initial requirements [4, 6, 9]. This phase has been identified with abstract, almost incomplete solutions that are expected to satisfy these requirements [10]. The intention of this phase is usually the exploration of the best compromise or alternatives, which stem from the desire of quality product and customer satisfaction. This phase of design is usually named the conceptual phase of design.

However, conceptual design is considered the least understood and the least formalised of all the design activities. Therefore most tools to guide and help designers has been largely concentrated in the latter end of design activities.

1.2.3 Limitation of Early Design Tools

With the advent of the computer and more recently the internet, the pertaining activities have largely been concentrated in the manufacturing area. Even though tools for the design stage have been around for many years, these tools have mainly been in the drafting or the detail design stages. Studies done by previous researchers estimate that up to 75% of life cycle design cost are committed at the early 10 to 20 % stage of the design phase, that is at the conceptual design [11]. This is in agreement with Lombeyda and Regli [12] who concur this view from their graph of cost and phases of product development. (Fig. 1.1)

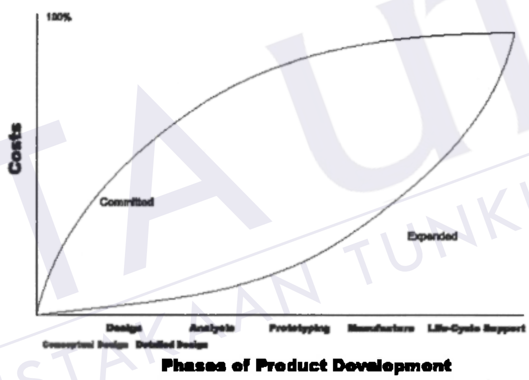

Fig. 1.1 Cost committed and expended during product development

However few computer tools exist to help designers at this early stage of design. Fig .1.2 shows the disparity that arises from impact of decision making at this stage with respect to the computer tools available. Great opportunity exists at this preliminary design stage. In the subsequent stages, it becomes increasingly difficult to change design decisions or concepts formulated at the conceptual design stage [2].

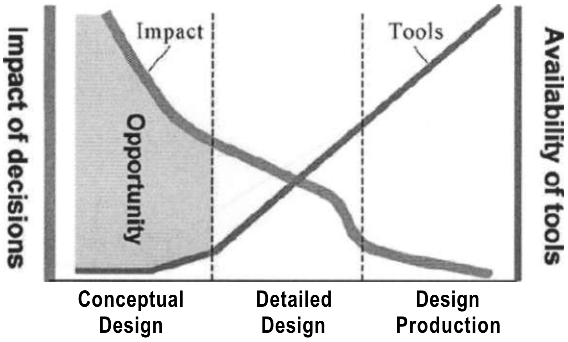

Fig. 1.2 Opportunity at early design stages

This shortcoming in the availability of computer tools is because knowledge of the design requirements and constraints during this early phase of a product's life cycle is usually imprecise and incomplete, making it difficult to utilise computer-based systems or prototypes [12], However the use of CAD/CAM technologies has been regarded by some as one of the greatest technologies of the 20^{th} century, for its engineering achievement over the preceding 25 years [14]. There is the potential therefore that as these technologies mature even further, their impact on product development will be even more.

1.2.4 Evaluation at Early Design Stage

Design concepts generated at the early stage go through a series of divergent and convergent process of ideation and evaluation [15] (Fig 1.3)

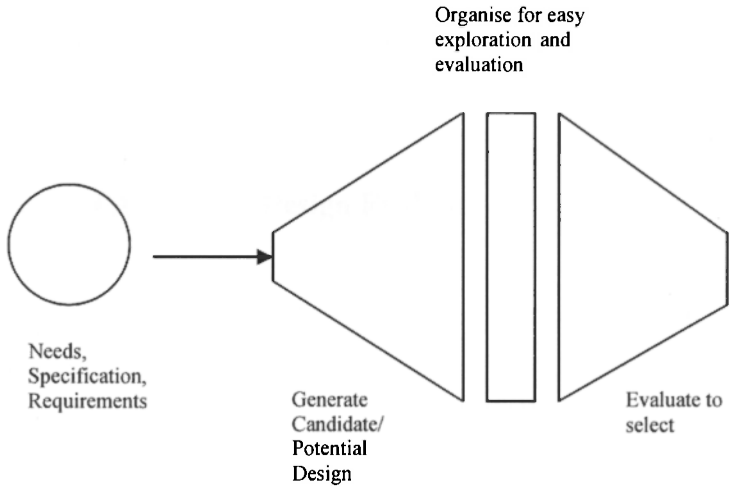

Fig 1.3 Divergent and Convergent Process in Conceptual Design [15]

This process of expanding and then limiting the design space derives from the principle of finding good design from several alternatives and then selecting the best design to meet the overall criteria. Hence, the evaluating process is one of the crucial procedures undertaken at this stage, in order for the design to be successful.

Numerous approaches [16] have been advocated for evaluating design. However, most of these evaluation techniques rely on knowledge and information that are only available when the design is complete. In the phase where design concepts are largely devoid of this information, there seems to be a lack of tools to support the evaluation process itself.

Dalgleish *et. al.* [17] reported that designers would rather have tools that can be used earlier in the design process in order to assess candidate design solutions. They do not always welcome tools that critically evaluate the completed design after much development effort and cost. In other words, designers would prefer to have such tools available at a point where evaluation would give them the opportunity to act on the results.

1.2.5 Bringing DFA to Early Design Evaluation

Design for Assembly (DFA) procedures have been around since the 1960's and have largely been used on completed design. Bringing DFA to the early stage of design has largely been identified as one key improvement to design concepts [18, 19]. While this idea is not new, it has proved elusive since the kind of information required to carry out DFA analysis requires much detailed information about the product geometric and manufacturing needs.

The needs of the DFA techniques coupled with concepts evaluation requires that approaches beyond quantitative methods be explored. Edwards [20] and Whitney [21] suggested that the solution lies in the development of knowledge representation at that phase and also utilising Artificial Intelligence (AI) techniques.

In this thesis, an attempt is made to link design concept evaluations using DFA techniques with that of an AI approach, namely Fuzzy Logic. The advantages of using Fuzzy Logic here is that it can both capture imprecise and vague knowledge about design concepts and it can also characterise the evaluating criteria into a set of fuzzy rules. Apart from that, fuzzy logic can also be adapted to suit the changing knowledge and information about the design along its development.

1.3 Research Objectives

From the discussion in Section 1.2.5, it is proposed that in developing evaluating techniques for design concepts, the use of DFA in conjunction with Fuzzy Logic appears the most promising path to explore. The aim of this thesis is then to contribute to research in conceptual design, in particular to concepts design evaluation, by meeting the following objectives:

Objective 1 To demonstrate the use of Fuzzy Logic as a basis for supporting DFA evaluation of design concepts.

Objective 2 To demonstrate the use of membership function and rule set to capture the information regarding design concepts evaluation by DFA.

In meeting these objectives, the research has created a framework and a computerised tool is used to demonstrate its usefulness.

1.3.1 Scope of Research

There is vast amount of research work applicable to DFA and Fuzzy Logic as well as areas related to both, so there is a need to explain the scope of this research work. This research focuses on:

- How to evaluate mechanical design concepts. The use of DFA also means that the mechanical design must have an assembly configuration.
- The kind of design that the tool will be used and demonstrated on are those in the adaptive and variant design categories.
- There are many guidelines in DFA for achieving the most benefits for assembly. The work in the research will look at one guideline which is identified as the

characteristic that can be addressed at the conceptual stage of design, namely on how to reduce the part count in the assembly.

- Fuzzy logic encompasses numerous sub-branches which typically include neural network fuzzy logic, fuzzy expert system, etc. This research proposes to use the fuzzy expert system as the guiding fuzzy approach to tackle the assemblability issues as provided in DFA.
- The knowledge representation derived in this research is only for the information required for the evaluation to complete. The information regarding the design itself is left to the domain expert or the designer.

1.3.2 Motivation

Green [16] has suggested two criteria that need to be addressed by a tool that support design concept evaluation as :

- It must be able to deal with a significant number of criteria and design options, and the dynamic nature of each
- It must employ multiple models to cope with varying types of data and representation format

The main motivation of this thesis is to assist the designer in evaluating concepts within the nature of the changing state of information at the conceptual stage of design.

Another motivation has been the need to explore further A.I. techniques [21] because current research and development in this area is still in its infancy [13]

1.4 Structure of Thesis

This thesis is structured into six chapters which discuss the following topics:

Chapter 2 - This chapter reviews the literature and provides for the motivation for providing tools to support designers at the conceptual stage of design. This chapter will look into the various design process models and characterise them into distinct stages. From these the chapter will focus on the early stage of design where support tools are most lacking. This chapter will emphasise the need for evaluating tools at the conceptual stage of design which will support the designer in making important decisions that will determine the successful outcome of the product development. This will allow the author to position his research relative to the work of others in the same domain and to introduce his approach to the research gap.

Chapter 3 - This chapter provides for a basic understanding of the two defining terms in the approach namely conceptual design and design-for-assembly (DFA). This will be placed in context into the larger body of conceptual design research. The chapter will be organised into 4 sections. The first section, section 3.2 will discuss the effect of evaluation on the design process. Section 3.3 will describe the various challenges in implementing an effective design evaluation. The third section, section 3.4 will describe the overall requirements of an effective design concept evaluating tool and relates the common traits of both conceptual design and DFA and how it can be used as an evaluation tool to aid designers. Lastly, section 3.5 briefly the DFA philosophy, its importance, its various characteristics and how DFA methodology can be applied to the conceptual stage of design.

Chapter 4 - This chapter defines the requirement for the framework of a conceptual DFA evaluating system. The use of fuzzy logic as the evaluating criteria is also introduced in this chapter and how it relates to the overall conceptual DFA system.

The common characteristics of fuzzy logic with conceptual design is also explained and used as a basis to justify the use of fuzzy logic in this research. This framework will also be flexible enough to accommodate changes and flexibility which is a common trait in the early stages of design. The outcome form the framework will provide the user with an informed scenario of the basic assembly issue of the design concept being considered. This provide the designers with enough early warnings or flags with which the designer can choose to make an informed decision.

Chapter 5 - This chapter shows how the proposed framework can be used to evaluate design concepts in the mechanical engineering domain. In case study one, a peristaltic pump design exercise is used whereby three design concepts already developed were evaluated and analysed by the approach. Case study two involved a reengineering case where a heavy duty stapler is used to demonstrate the capability of the approach in handling a reengineering exercise. Both these case studies were validated by comparing the results with established DFA methodology in industry and determining the possible explanation for any inconsistencies, if any.

Chapter 6 - This chapter summarises the research in this thesis by addressing the contribution to new knowledge as achieved by the conclusion of this research, the limitation and possibilities and also the recommendation for future research.

Chapter 2

Literature Review

This chapter reviews and examines the pertinent issues important to the availability and use of evaluation tools in engineering design. These issues are discussed in order for the research done in this thesis to link and place it in the overall domain of engineering design and justify its usefulness. The areas which are discussed are as follows:

- Design Process Models - an investigation of design process models with particular emphasis on the conceptual design phase
- Conceptual Design - a brief summary of conceptual design models, tools supporting this stage.
- Conceptual Design Evaluation - an examination of the current approaches of design evaluation and how design concepts are evaluated.
- Design for Assembly (DFA) - an survey of the current approaches use to achieve DFA at the early stages of design process.
- Fuzzy Logic in engineering design - an examination of the current uses of fuzzy logic in engineering design and in particular at the early stages of design.

2.1 Design Process Models

In this section, an examination of design process models will characterize what common stages or phases of the design process and how these are interrelated to each other. Leading from this, the conceptual design phase will be highlighted, where tools to support this stage are mostly lacking.

2.1.1 The Engineering Design Process

Design has always been regarded the cornerstone of engineering activities. The need for design arises due to human demand for tools or systems to simplify the burden of work. Engineering design is aimed at developing artefacts or systems which in turn has to satisfy the required functions. It is during the design stage that the form of the artefact is established which will meet not only the functionality required but also other factors such as manufacturing limits, safety guidelines, maintenance, product end disposal, etc.

Although design activities have been going on for centuries, it is only towards the middle of the 20th century, that effort began to give some formalism to the way design is done. In the survey done by Evbuomwam, *et. al.* [22] and Finger and Dixon [23, 24], these authors classify design methodologies into 3 main categories:

- Prescriptive design method
- Descriptive design method
- Computational design method

Prescriptive models can be further divided into two categories : those that prescribe how the design process ought to proceed and those that prescribe the attribute that the design artefact ought to have. The former prescriptive design method suggests how the design process ought to be carried out, and encourages designers to follow a more rigid and systematic procedure. Model of these kind includes those of Pahl and Beitz [4] , French [9] and Pugh [7], The latter category is based on product attributes, where the focus is on distinguishing between good and poor design. This relates to the product performance, cost and quality with respect to the user requirement. Prominent among these are the model by Suh [5] and Taguchi [25].

Descriptive design models originate from both the experience of designers and from studies done on how design are created, that is, what process, strategy, problem solving method designers use. Models done by Cross [6] and Hybs [26] falls into this category.

Computational design method place emphasis on the use of numerical and qualitative computational techniques which will aid designers. Among models that can be categorised in this group are Gero [27] and Cagan and Agogino [27].

There are many arguments about whether design model are actually used and practised by designers or whether it will produce better design [24]. Most practitioners argue that a systematic approaches to design tends to stifle creativity and the difficulty in adopting these approaches are due to their own 'in-house' approach. However the prescriptive method of systematic approaches can result in the increased likelihood of obtaining a 'best' solution for the design. The reason for this is given by Evbuomwan, *et. al.* [22] who argue that the overall purpose of a systematic approach is to make the design process more visible and comprehensible so that all those providing input to the process will appreciate where their contributions fit in. Moreover, the need to equip and train engineers as well as support collaborative design teams will necessitate the adoption of a structured and systematic approach to design. This makes engineering design fully learnable, and provides a context to design, including industrial, societal, economic and other factors.

The following section will describe briefly two design processes by Pahl and Beitz [4] and also by Suh [5], which will provide the background for which the proposed research will be structured. These two models were chosen because they are representative of two schools of thought that arise with design model. The Pahl and Beitz model is also recognised as the most accepted representative of the European school of thought, having influenced also American authors on the subject [11, 28]. Furthermore, it is comparable to work done along the same tradition, such as that of Hubka and Eder [29].

2.1.2 Phases of Design according to Pahl and Beitz

Pahl and Beitz [4] present a detailed description of design, built from previous efforts in the German design literature. They propose their own method of systematic design by breaking it into various stages and expanding on these sub-phases, as shown in Fig.2.3. According to Pahl and Beitz the phases of design consist of:

- Clarification of task

  This task involves the identification and clarification of information/data about the requirement and constraints to be fulfilled in the final design. A detailed specification is written here.
- Conceptual design

  This phase requires the establishment of the function structures, searching for solution principles and combining them into concept variants. These concept variants are then evaluated against technical and economic criteria. This phase begins with investigating the information in the specification and refining it into essential problems. This should focus the designers mind towards the design problem. This is important as Pahl and Beitz states that subsequent detail and embodiment phases are unlikely to correct fundamental shortcomings in the concept.

- Embodiment design

  Within this phase, the layout and form of the product is developed, in accordance with the technical and economic requirement. Parts lists and production document are thus prepared. Several iterations of analysis and synthesis is carried out so that the definitive layout prepared can be checked.

- Detail design

  This final stage determines the configuration, form, dimensions, material and properties of all individual components. The technical drawings and production documents are produced and is rechecked with the technical and economic viability.

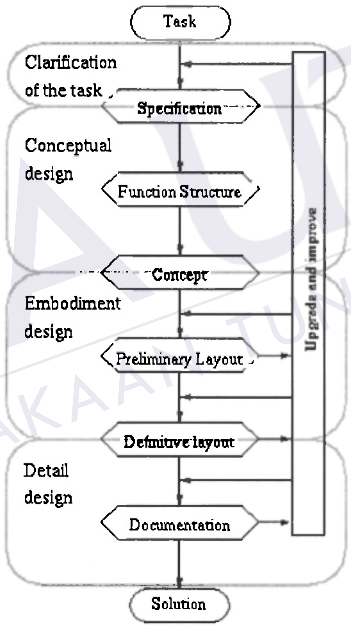

Fig.2.1 Phases of Design by Pahl and Beitz

2.1.3 Design according to Suh

The basic premise of Suh [5] axiomatic approach to design is that there are basic principles that govern decisions made during design, just as the law of physics and chemistry govern the laws of nature. He propose that the design process as a mapping between the functional requirement (FRs) in the functional domain and the design parameters (DPs) in the physical domain as in Fig. 2.2

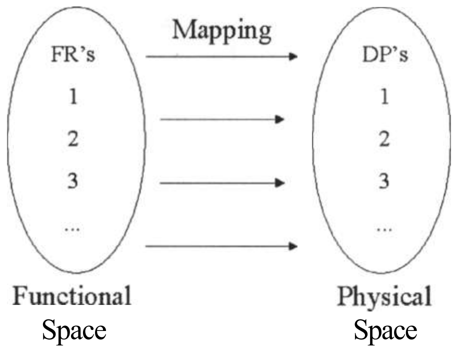

Fig. 2.2 Mapping from FR's to DP's in Suh's Axiomatic Design

This can be expressed mathematically in matrix form as : {FR} = [A] {DP}
Where the matrix [A] represents the design relationship. Suh also proposes two axiom for design : 1) Maintain independence of functional requirements, and 2) Minimise the information content necessary to meet the functional requirements. To put it simply: a good design meets its various requirements independently and simply. Suh classifies design into 3 categories namely, uncoupled, coupled and decoupled design. An uncoupled design is a design that obeys the independence axiom and any specific DP can be adjusted to satisfy a corresponding FR. A coupled design have some of the FRs dependent on other function. When the coupling is due to an insufficient number of DPs when compared to the number of FRs, they may be decoupled by adding more DPs. A decoupled design may have more information content.

Suh also deduce that the design process will follow an iterative loop (Fig. 2.3). Once the functional requirements and constraints has been identified and defined, the process passes through an iterative loop of ideation/creation, analysis and comparison, until an acceptable solution is achieved.

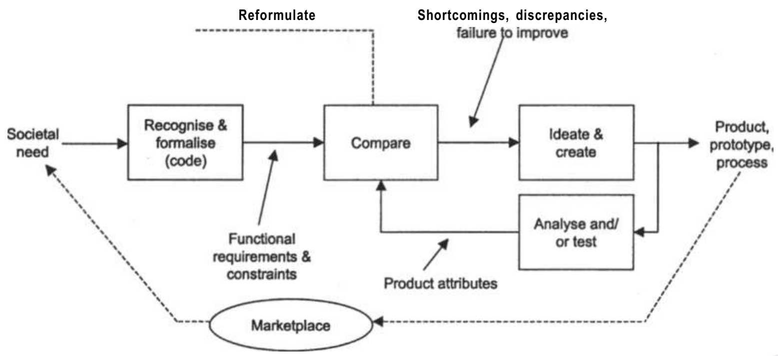

Fig. 2.3 Suh's iterative design process

2.1.4 Common Characteristics of Design Models

The design models of Pahl and Beitz and that of Suh share some similar characteristics, which are also common among other prescriptive model. These models take the design process in an iterative manner. The tasks that are common among these models are the identification of needs, develop functional requirement, develop concept, compare with earlier requirement by some sort of analysis and coming up with a solution.

While Suh's axiomatic approach makes the distinction that there are attributes that distinguish between a good and unacceptable design, Pahl and Beitz only list out the task that should be followed in order to come to an acceptable design. In a sense, Pahl and Beitz provide for a systematic, detailed account of the engineering design process, whereas Suh is more concerned with the functionality of the final product developed. The former is process-based and the latter is product-based.

One of the common theme among these two models is the stage where the ideation and creation of solution takes place, namely the conceptual design phase.

In subsequent section, the conceptual design phase which is a important characteristic of these design models, will be used as a basis for the development of the research.

2.2 Conceptual Design

There is no single accepted definition of conceptual design. However, limiting to the scope of engineering design, conceptual design is defined as the stage in the design process where ideas are formalised within the limits of the initial specification. Conceptual design provides abstract, sometimes incomplete solutions that are expected to satisfy the requirement of customers, from all functional, economic, technology, servicing and other points of view. The output from the conceptual design stage is the desired design concept that can be used as a basis for embodiment and detail design. Since it more or less determines the technical merit of the finished product, and its overall cost, this early stage of design is considered the most important part in the whole design process [30],

2.2.4 Conceptual Design Models

Various authors identifies conceptual design as a phase in engineering design where the ideation and characteristic of the design is being generated and developed. Cross [2000] describes it as the phase that takes the statement of the problem and generates broad solutions to it in the form of schemes. It is the phase that makes the greatest demand on the designer and where there is the most scope for striking improvements.

With Pahl and Beitz [4] model, detailed description of this phase as the phase which determines the principle solution by abstracting the essential problems, establishing the function structures, searching for a suitable working principles and then combining these principles into a working structure (Fig 2.4).

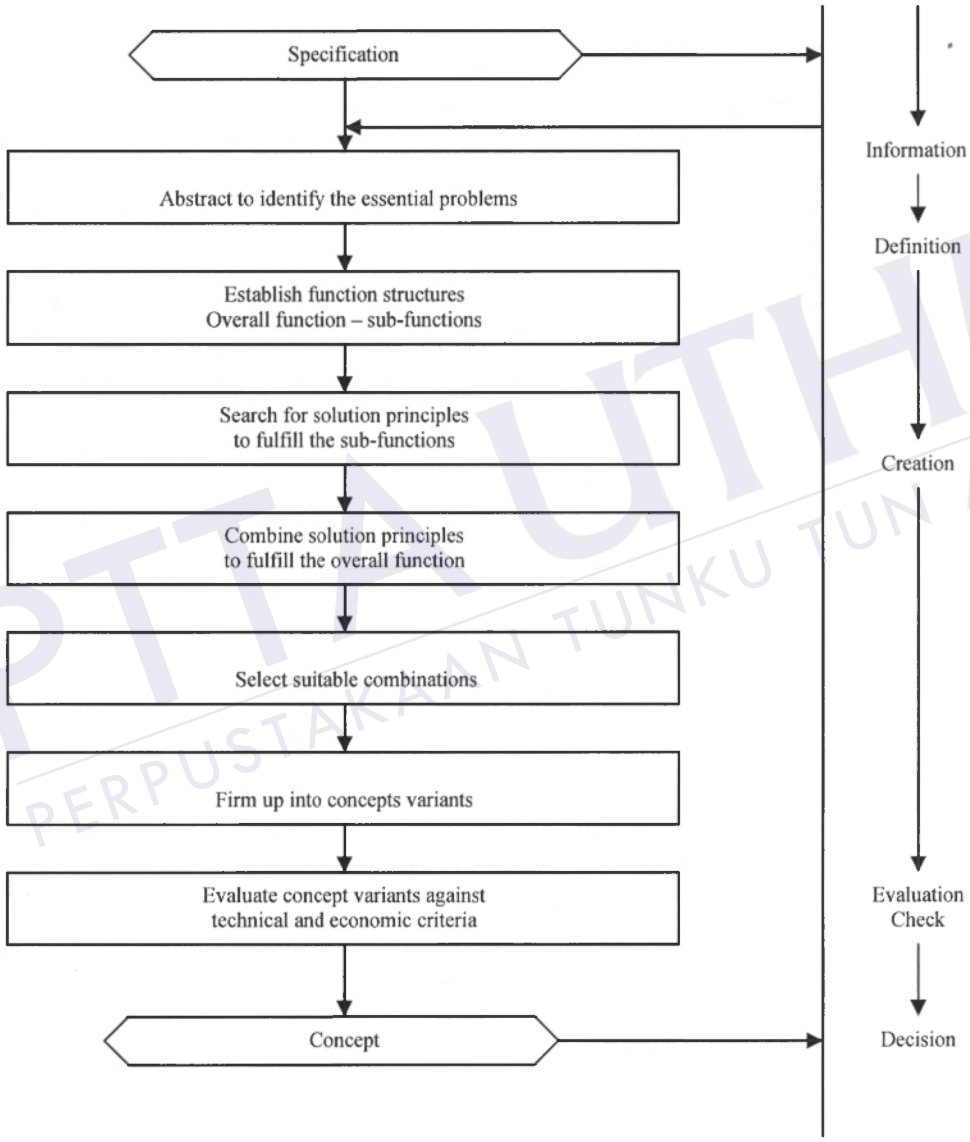

Fig. 2.4: Pahl and Beitz model of conceptual design

2.2.5 Tools to Support Conceptual Design

The primary aim of the conceptual design stage in an engineering design process is the generation of physical solutions to meet the design specifications. However, most of the decisions made at the conceptual design stage have significant influence on the cost, performance, reliability, safety and environmental impact of a product. Yet few CAx tools exist to support conceptual design activities [1,2]. This is mainly due to the knowledge of the design requirements and constraints during the early stage of a product's life cycle is usually uncertain, imprecise and incomplete, making it difficult to utilise computer-based system and prototypes. Stacey *et. al.* [31] even argue that any tools to support conceptual design should provide the ability to work with any mixture of decisions and constraints with uncertainty and imprecision. Moreover, a design tool at this stage should also provide the ability to work with concepts at different level of abstractions; to switch between abstraction levels and also include elements at very different abstraction levels in the same product model.
Hsu and Woon [32] in their survey paper identified two main areas of difficulties in conceptual design, namely the modelling and reasoning problems which needs to be resolved. The modelling problem involves the complexity in supporting the many facets of a mechanical product. The modelling representations ranges from the formal specification method such as languages to the highly visual representation such as images.

Computer-oriented modelling refers to techniques whose main goal is to ensure that computational reasoning be carried out efficiently. On the other hand, human-oriented modelling techniques focus on providing conducive modelling environment that aid the human designer.

The second area in supporting conceptual design is the difficulty of generating and selecting appropriate means of mapping the user's requirement to some physical structure that can realise the initial requirements, i.e. the reasoning problem. The three pairs of mappings concerned here are : function <-» form, behaviour <-» form, and function <-> behaviour. While researchers argue the distinctions between function and behaviour [33,34,35], most have adopted function as the perceived use of the product, and behaviour as the sequence of states in which the product goes through to achieve the function.

Hsu and Woon [32] also divide the reasoning problem into whether the particular reasoning techniques requires large amount of data (data driven) or whether it requires prior knowledge about the domain (knowledge driven). Table 2.1 summarises the reasoning approaches identified by these researchers.

	Data driven	Knowledge driven
Function -» Form	Neural Networks, Case-Based Reasoning	Knowledge-Based, Value Engineering
Form —> Function	Machine Learning	Knowledge-Based
Behaviour —> Form	Case-Base Reasoning	
Form —» Behaviour	Qualitative Reasoning	

Table 2.1 Reasoning techniques classification [32]

They propose four areas of research areas that would contribute to an overall support of the conceptual design activity, namely (1) use of multimedia techniques to help designers visualise design process, (2) efficient information retrieval techniques so as to take advantage of the huge amount of data over the internet, (3) collaborative techniques that would permit different parties to contribute to the conceptual design process, and (4) feedback approaches in reasoning techniques.

More recently, Brunetti and Golob [36] have taken the feature-based approach to handle the information flow within the conceptual design stage. Features are the information carriers that allow modelling the relationships between requirements, functional descriptions and physical solutions of a product. Al-Hakim *et. al.* [37] proposed the incorporation of reliability with functional perspective, using graph theory to represent a product and the relationships between its components.

Wang [2] expanded the idea of collaborative conceptual design by looking at the state of the art and future trends in this area. They found that most techniques in this domain rely on internet technologies, to enable information flow among various parties working on the conceptual design. However, web technology only supports limited co-ordination through provision of shared information space. To enable a more collaborative environment, the information needs not only to be data-oriented but also provide a task-oriented view of the design project. Existing tools such as XML, VRML, Java are capable of supporting task-oriented views, which can be implemented on top of a data-oriented web structure.

While all these approaches are enabling much better support for conceptual design, one key issue at the end of conceptual design is the question of evaluation of the design concepts generated. The next section will examine how design concepts are evaluated with current approaches.

2.3 Conceptual Design Evaluation

During the design process, a number of design concepts are usually generated, in which each of these concepts need to satisfy the original requirements. From these, a concept is selected for further development and refinement. The activity of selection is confined within the design concept evaluation. Among the question raised from these activity include the following [28]:

- How can the best concept be selected, given that all the concepts are still very abstract ?
- How can a decision be made that is acceptable to all concerned ?
- How can the desirable attributes of rejected concepts be used in the selected one ?
- How can this process of selection be documented ?

Although the research presented in this thesis is not to answer the question above, but the issues here are supported in the proposed methodology, in that design concept evaluation is given prime importance. This will in turn support decision making strategies, which however, is outside the scope of this thesis.

Ullrich and Eppinger [28] best illustrates the various methods used in determining a concept to choose, which vary in effectiveness, namely:

- External decision, where the customer or outsiders makes the decision
- Product champion, where an influential member of the design team chooses a concept
- Intuition, where the concept is chosen by its "feel"

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