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.

Contents

Figures

Tables

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To

my late Mum and Dad,

who had always supported and believed in me.

Nomenclature

This section is intended to explain and clarify the use of various technical terms and acronyms used throughout this thesis. It should not be seen as a complete dictionary of all the words used in this field, but merely as a guide for clarification.

DFA : Design for Assembly

CAD : Computer Aided Design

CAM : Computer Aided Manufacturing

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)

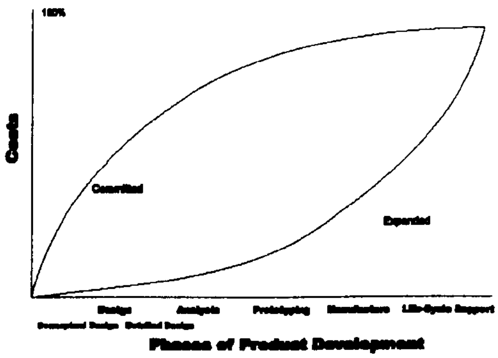


Fig. 1.1 Cost committed and expended during product development

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].

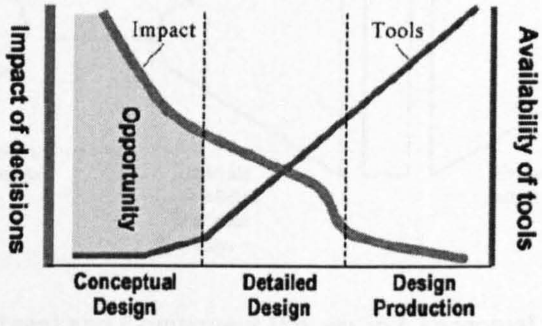


Fig.1.2 Opportunity at early design stages

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)

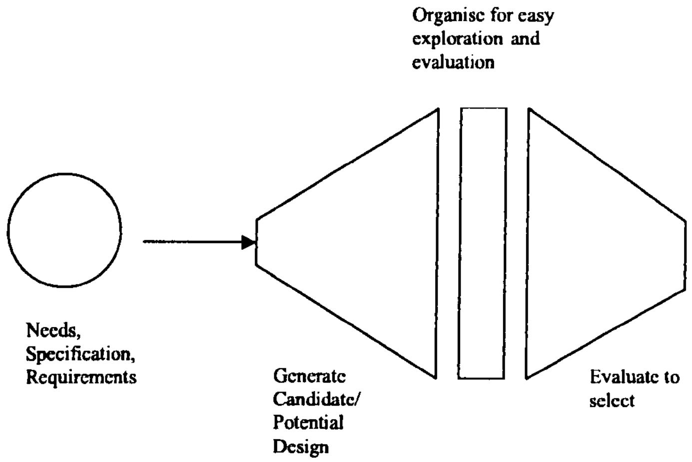


Fig 1.3 Divergent and Convergent Process in Conceptual Design [15]

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.

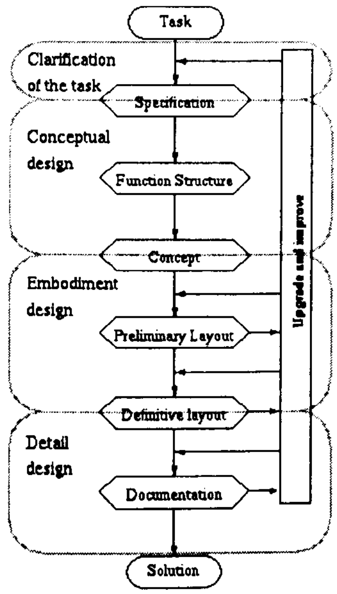


Fig.2.1 Phases of Design by Pahl and Beitz

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

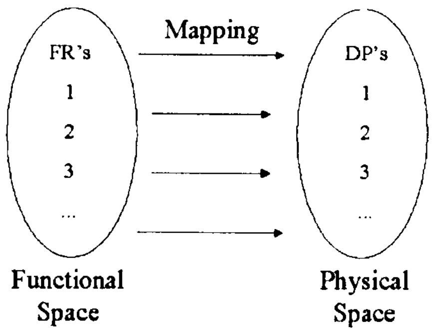


Fig. 2.2 Mapping from FR's to DP's in Suh's Axiomatic Design

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.

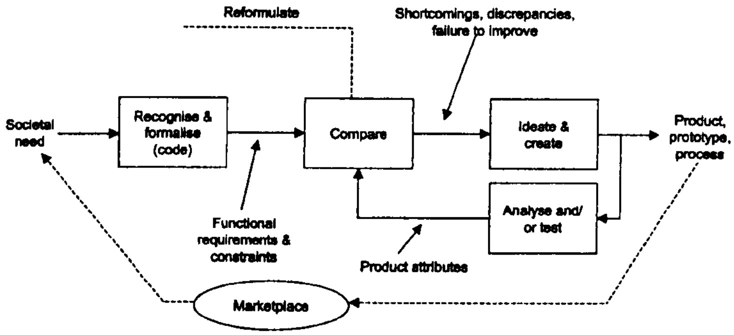


Fig. 2.3 Suh's iterative design process

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).

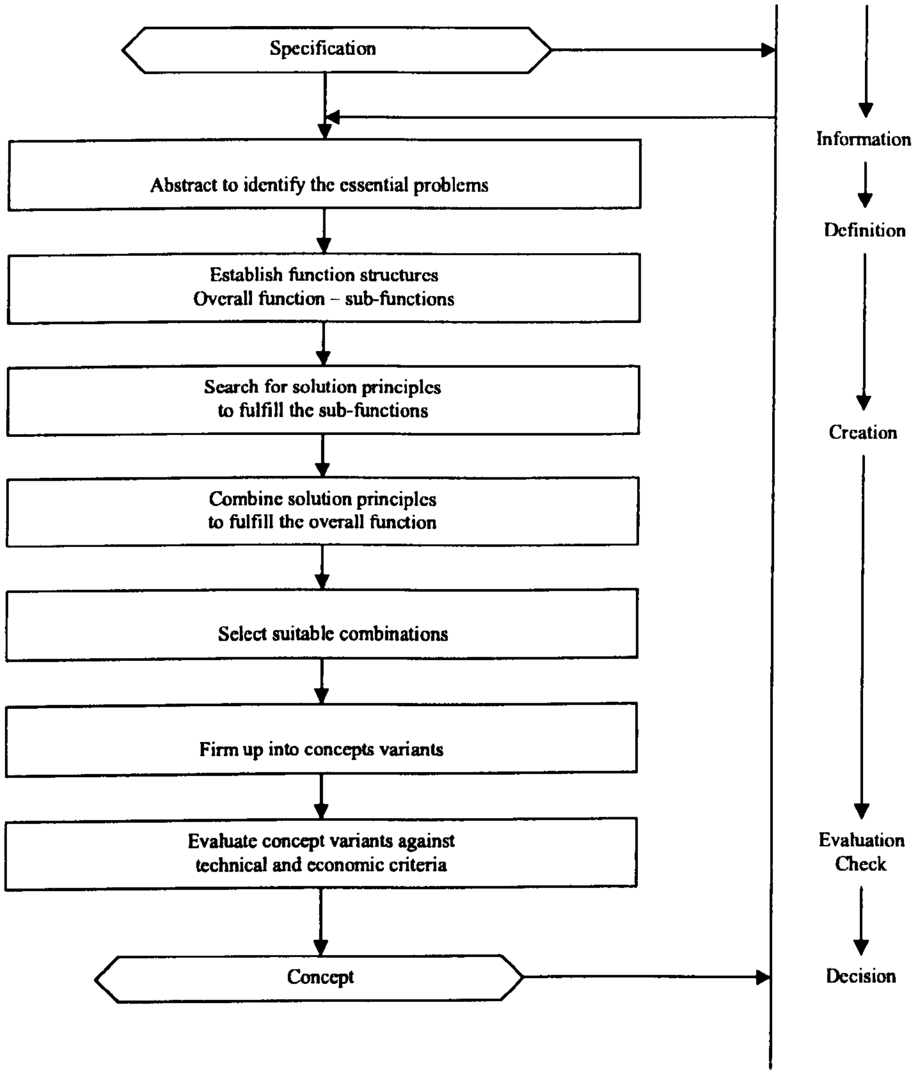


Fig. 2.4: Pahl and Beitz model of conceptual design

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"

- Pros and Cons, where the team weigh the strength and weakness of each concept and one is chosen by group opinion
- Prototype and test, where the development team build or simulate and test each concept and select based on data obtained
- Decision matrices, where the design team evaluate each concept based on predetermined criteria.

While each of these methods has its own merit, the very subjective nature of the first four methods makes them very unreliable. The method of making prototypes or computer models to simulate and test can also be very demanding on resources and time constraints. Decision matrices form the most common form of evaluation since the concepts are directly rated to the original requirements. It is also because of its structured nature that these metrics and its variants are proving very popular in industry. [38]

The benefits from these matrices [28] has prompted more and more life-cycle considerations to be incorporated into the evaluation. All the more so now that the emphasis had tended towards terms like concurrent engineering, design for X (where X can be any life-cycle interest like manufacturing, assembly, recyclability, etc.). The increasing concern to have a full life-cycle interest from conception to final disposal of product means that more and more factors have to be considered and evaluated during conceptual design.

Among the many challenges facing designers include the ability to sift through all these factors and give them priorities when taking these factors into consideration in the design. Prioritising however has never been easy when dealing with all these factors. The domain of the design, the designer's experience, the working environment, the managerial strategies will all influence the way these factors are prioritised. These issues are more prominent when environmental concern are given top priority. Environmental issues affect almost all aspects of the design process from early conception to final product disposal. Hence the consideration of environmental issues from the early design process is an important step towards realising total product design.

In the next section, a examination of current approaches to evaluate design concepts is discussed which will also highlight some issues arising from the investigation of these approaches within the scope of this thesis.

2.3.1 Definition of Terms

The two significant terms here is 'evaluation' and 'design concepts'. These two terms will be defined within this thesis context so as to scope the work properly.
To evaluate is to assess or appraise. Evaluation is the process of examining an artifact and rating it based on its important features. We determine how much or how little we *value* something, arriving at our judgment on the basis of criteria that we can define. The Cambridge Advanced Learner's On-Line Dictionary (2002) describes evaluation as "to judge or calculate the quality, importance, amount or value of something".

Concept is describes as "a principle or idea". Thus design concepts can be defined as "the basic principle or idea of a design". Hence, Green [16] succinctly defines "evaluating design concepts" as the activity of judging between and selecting from a range of design concepts. This is similar to the definition given by Taylor and Ben [38] which defines evaluation as a "comparative activity and therefore have factors against which to evaluate, be they design specifications, alternative solutions, user requirements or acknowledged standards of safety and performance."

For the purpose of this thesis "design concepts evaluation" may be defined as:
The activity of trying to determine the acceptable idea or principle from which to proceed, in terms of the design constraints and to provide knowledge and information to enable future decisions.

2.3.2 Design Concepts Evaluation Approaches

Table 2.2 summarises the main research into design concepts evaluation specifically for the mechanical design domain.

#	Author	System	Methodology
1	Pugh (1991)	Controlled Covergence Method	A systematic and controlled evaluation and selection of concepts
2	Hurst (1991)	Pugh's Method	Spreadsheet implementation of Pugh's approach
3	Jansson et.al. (1990)	GMI	Evaluation of design concepts through the use of a set of Generalised Manufacturability Indices (GMI)
4	Maher (1989)	EDESYN	Evaluation of concepts using multicriteria analysis from decision theory, during the synthesis and evaluation of design within an expert system
5	Hyde & Stauffer (1990)		Reliability of measures used to evaluate quantitative attributes such as quality
6	Thurston (1990)	MEDA	Deterministic multiattribute utility analysis to compare the overall utility of an alternative design as a function of selected performance characteristics.
7	Chen & Lee (1993)	QPM	Qualitative Programming Method which seeks to allow qualitative information to be incorporated within the numerical design process.
8	Ishii et.al. (1989)	DCA	Design Compatibility Analysis which focus on the compatibility between the design specification and the proposed design. Uses fuzzy measures to quantify the compatibility evaluation (called match index MI)

9	Esterline & Kota (1992)	IDS	Descretization of design space to make an initial design selection (IDS) of prior design using specification matching to direct redesign with evaluation and iteration.
10	Pahl & Beitz (1984)	UVA	Most useful method proposed is the Use-Value Analysis which is basically the Cost-Benefit Analysis (from guideline VDI 2225)
11	Green (1997)	DM	Design Margin where the evaluation is based on a number of statistically based methods and approaches taken from the probability, reliability and quality domains.
12	Wang (1997)	FOM	Fuzzy Outranking Method – somewhat like DCA, it employs a fuzzy set theory to address the imprecise preference structure inherent in conceptual design.
13	McGowan et.al. (1998)	DR	Design Representation – concepts retrieved from knowledge-based development process of concepts via sketch, or drawing information and/or an evaluation of the information content of concepts design sketches.
14	Sun et.al. (2000)	Design candidate identification	Method for design candidate evaluation and identification using neural network-based fuzzy reasoning.
15	Chen & Lin (2002)		A mathematical decision model based on AHP that selects concepts with maximal performance and minimal coupling with respect to both functions and constraints.
16	Wu et. al. (1996)	Inexact reasoning model	Based on the integration of D-S theory and fuzzy theory, which is applied to evaluate mechanical design
17	Takai et .al. (2001)	Cost-Specification Analysis	This method seeks to satisfy both target cost and required functionality simultaneously. Evaluates design concept candidates based on target cost calculated from its worth and the target spec.
18	Bradley & Maropoulus (1998)	Relation-based product model	An aggregate product model scheme which can support product design assessment throughout the design life-cycle of a product.
19	Shehab & Abdalla (2001)	Manufacturing Cost Modelling	A knowledge base system that help user estimate the manufacturing cost of a product at the conceptual stage.

20	Verma & Knezevic (1996)	Fuzzy Weighted Wedge Mechanism	Feasability assessment of system reliability during the conceptual design analysis involving compliance analysis between the required and predicted value.
21	Swift et. al. (1998)	Pro Active DFA	This system consists of the part count advisor expert module; starting part expert module; and next part expert module. Modules use an expert system to incorporate the DFA analysis required.
22	Stone et. al. (2002)	Conceptual DFA	This method uses the functional basis and the method of module heuristics; used to derive a functional model to identify a modular product architecture.
23	Hsu et. al. (1998)	DFA synthesis of concepts	This system takes as input a description of the functional requirement in the form of a state transition diagram and a library of past design cases used to incorporate DFA into these design concepts.

Table 2.2: Current Approaches to Evaluating Design Concepts

The work done in these literature can be classified into 4 main categories according to Green [16]. This can be illustrated in the Fig. 2.5, whereby the 4 categories are based upon the assertion that three primary areas characterise the evaluation at the conceptual stage i.e. the product design specification, a set of design concepts and a knowledge base of past design cases. Therefore the 4 categories are made up of comparison between these 3 areas, thus as follows:

a) Specification – Knowledge Base Comparison
b) Concept – Specification Comparison
c) Concept – Concept Comparison
d) Concept – Knowledge Base Comparison

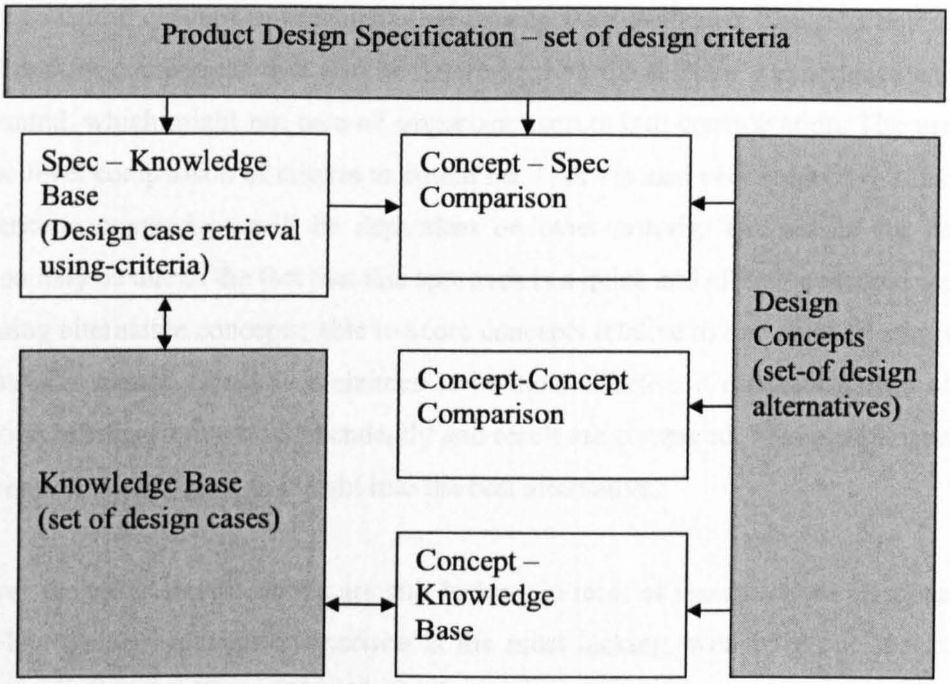


Fig 2.5 – Classification of Design Concepts Evaluation Approach (Green [16])

Most of the approaches in Table 2.2 fall under the category of Concept-Specification Comparison. This typically include 1, 2, 8, 9, 10, 11, 14, 15, 17. This is not surprising since the most obvious evaluation to be done on design concepts is to find out whether it satisfies the initial requirement or specification. This indicates that most of the techniques here are align with the prescriptive design process models where the evaluation is iteratively done with increasing resolution, compared to the design specification.

One interesting point that surfaces when looking into design evaluation at the early stages of design is that the most prominent approach which is adopted/advocated by industry is the Pugh's selection matrix or variation of it [38]. This approach however assumes a datum concept from which other concepts are evaluated. The selection of the criteria for comparison will also be determined by the selector's experience and background, which might not take all important aspects into consideration. The use of three level comparison of criteria to datum i.e. +, 0, - is also very subjective since most criteria comparison will be dependent on other criteria. The reason for its adoption may be due to the fact that this approach is a quick and effective method for comparing alternative concepts; able to score concepts relative to one another; and it is iterative in nature. Hence it is claimed to be most effective if different parties of the design team performs it independently and result are compared. This comparison of scores will usually give an insight into the best alternative.

However the other classifications are still lacking in term of research done in those areas. The concept-concept comparison is the most lacking, with only one recent notable work done by Wang [39, 40] which compare pairwise concepts. Most of the other approaches falls into the remaining two categories. Work done in relation to DFA evaluation of design concepts will arguably be categorised under the concept-knowledge base classification, since DFA techniques and evaluation done, stem from a body of knowledge specific to it. Likewise most other DFX (Design for Life Cycle Consideration) evaluation done in this early stage will invariably be in this classification too. Section 2.4 will look further into the use of DFA as an evaluating technique of design.

One development in this area has been the use of fuzzy logic as a tool to support design concepts evaluation [39, 41, 42]. The use of fuzzy logic has been advocated here to deal with imprecise or vague requirements, where other approaches are not flexible enough to deal with these vague information [43]. Vanegas and Labib [43] argues that fuzzy sets or fuzzy numbers can appropriately represent imprecise parameters, and can be manipulated through different operations on fuzzy sets or fuzzy numbers. The use of fuzzy logic in design is explored further in section 2.5.

The evaluation in the end, only make suggestions about the most promising design candidate , at that stage, for further development. None of these systems actually make the decision of which design to use. This is left to the human designer to decide as he also needs to consider other internal and external factors involved in the design. Thus tools in this evaluation area assist the designer in making more informed judgement based upon available indications.

2.4 Design for Assembly (DFA)

Design-for-Assembly (DFA) form one of the more important aspect of life-cycle concern that is being taken into account into the design process. Most of the existing DFA methods employs approaches that requires that the design be complete, i.e. in the final stages of design. This is due to the nature of the analysis that needs information detailed enough for the analysis to be carried out. This includes information about handling and fitting analysis apart form the issues of assembly as in the Boothroyd and Dewhurst [44] method.

DFA techniques aim to reduce the cost and time of assembly by simplifying the product and process through such means as reducing the number of parts, combining two or more parts together, reducing or eliminating adjustments, simplifying assembly operations, designing for parts handling and presentation, selecting fasteners for ease of assembly, minimising parts tangling, and ensuring that parts are easy to test.

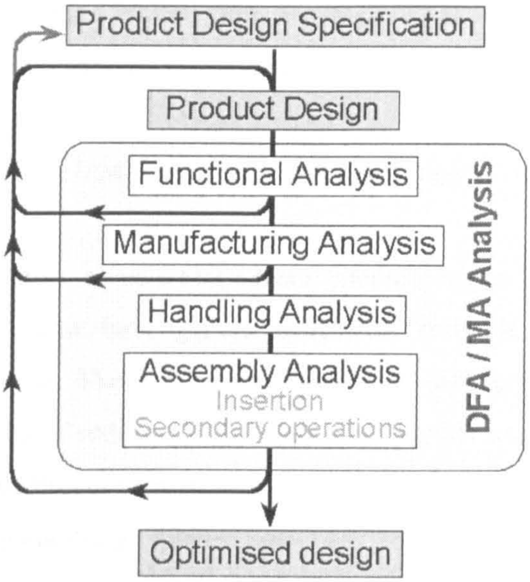


Fig. 2.6 DFA Analysis

2.4.1 Design for Assembly Procedures

Design for Assembly (DFA) is a product design evaluation tool which through simple structured analysis gives the information required by designers to achieve the following benefits.

- Parts count reduction
- Easier parts handling
- Simplified assembly

The evaluation is carried out by the following method as shown in Fig. 2.6

Boothroyd *et.al.* [44] reported improvement of up to 72% reduction in parts, assembly time and product cost when DFA procedures were applied to 43 case applications. There are however, possible drawbacks in implementing DFA procedures, which includes:

- Slowing down the concept-generation phase in design;

- Giving the designer a limited view, looking only at assembly issues;
- Requiring significant training or management effort to establish the discipline of use;
- Requiring design effort before the benefits are seen.

A survey of the literature reveals that several methodologies have been developed since the mid-70's. Some have gained worldwide recognition while others are limited to in-house use. These DFA methods uses different approaches but all achieve the same aims of reduced parts count, easier parts handling and simplified assembly. Reported methodologies include :

- Approaches using design rules :
  Andreasen [45]
- Approaches using quantitative evaluation strategy :
  Hitachi-Assemblability Evaluation Method (AEM)[47]
  Boothroyd & Dewhurst (BDI's DFMA) [44]
- Approaches using knowledge-based method :
  Swift Lucas/Hull DFA [46]

The first category while having the advantage of being fully documented and available to all, is however not popular, thus raising questions about its effectiveness. The last three methods, Hitachi, BDI and Lucas/Hull, while being proprietary have been proven to be successful . These three method will be briefly outlined below.

- Hitachi Assemblability Evaluation Method (AEM) [47]

This method was developed in the late 1970's as part of Hitachi's plan for new products, which could be efficiently assembled by automation. The essential principle of the method is "one part-one motion"; for each part of the assembly there should be only one straight forward, simple motion required to fit and secure it. An assembly scoring system is used, where simple straight motions score no losses, and more complex motions score progressively greater losses. Two performance indicators are used, the "Design Quality" E and the "Assembly Cost Ratio" K. The aim here is to minimise K.

- Boothroyd and Dewhurst DFMA [44]

This method is a very comprehensive guide which includes analysis for manual assembly, automated assembly, analysis of manufacturing requirement of components, support for key decision-making (manual vs automated, flexible vs dedicated). For the purpose of this thesis, only the DFA part of this method is discussed. This is focussed further still to the design for manual assembly where the key element is the identification of essential parts. These assessment identifies the initial agenda for redesign, that is the number of non-essential parts must be minimised.

- Lucas/Hull DFA [46]

This methodology is similar in some ways to Boothroyd and Dewhurst method, and also uses a structured, cyclic approach where analysis, evaluation and synthesis are carried out iteratively. The key differences are in scope where no suggested recommendation for manual or automatic assembly is given and also in its implementation where an expert system is used to prompt, infer, classify and quantify. On each iteration, the performance of the design is compared with criteria. When the design meets the criteria, the method is complete and an optimal design has been achieved. There are three essential stages to the process, each with its own pass criterion: functional analysis, handling analysis and fitting analysis.

2.4.2 Comparison of DFA Methodologies

Comparing these three methodologies reveals similarity with its overall objectives and the key differences lies with their scope, structure and implementation. Further investigation reveals similar evaluation criterion used in the BDI analysis for manual assembly and the Functional Analysis in Lucas/Hull method, i.e. minimising part count. This is not surprising as these two method share the same guiding principles, i.e. those developed by Boothroyd and Dewhurst. As such, these three criterion form the basis for part reduction in an assembly, which is the first step towards the achieving the full objectives of DFA. However all these system work on the detail-level design rather than on the conceptual-level design. So with these systems, much time and effort would have been expanded by the time the product is analysed as it is performed only after the detail design is complete.

As a design is being developed from the conceptual level to the detailed level, a physical and functional requirement envelope is defined in which a part must fit and perform. Within the constraints of this envelope, a designer must design or select a part or assembly for use. A designer may have many alternative ways to design a part to meet requirements within this envelope.

While the design of a custom part or selection of a new part may be the most optimal approach to meet product requirements from the designer's point of view, it may not be the best overall approach for the company. Product cost and quality may be negatively affected by the proliferation of specialised items that require specialised capabilities or prevent efficient manufacture and procurement. Minimising the number of active or approved parts through standardisation not only simplifies product design, but can also result in operational efficiencies and lower inventories. A formal policy of parts standardisation and emphasis on use of parts from an approved parts list for certain commodities provides management direction to the designer.

The Boothroyd-Dewhurst DFA [44] evaluation centres on establishing the cost of handling and inserting component parts. The process can be applied to manual or automated assembly, which is further subdivided into high speed dedicated or robotic. Regardless of the assembly system, parts of the assembly are evaluated in terms of, ease of handling, ease of insertion and an investigation for parts reduction. The opportunity for this reduction is found by examining each part in turn and identifying whether each exists as a separate part for fundamental reasons.
The fundamental reasons are:
1. During operation of the product, does the part move relative to all other parts already assembled? Only gross motion should be considered – small motions that can be accommodated by elastic hinges, for example, are not sufficient for a positive answer.
2. Must the part be of a different material that or be isolated from all other parts already assembled? Only fundamental reasons concerned with material properties are acceptable.
3. Must the part be separate from all those already assembled because otherwise necessary assembly or disassembly of other separate parts would be impossible?

The process of challenging the existence of each component in a product is key to efficient assembly. Products that consist of the minimum number of parts are not only enhanced for assembly but also provide knock on benefits through reduced stock holding and inventory, reduced manufacturing or sourcing costs, and increased reliability.

The number of parts in an assembly has a significant impact on the total assembly cost. Generally, the goal is to generate a design with the minimum number of parts, while achieving the necessary functionality at the same time. Less parts results in reduced assembly operations and less materials (fasteners, adhesives, etc). Less assembly materials also contributes to weight savings. However, a more integrated structure tends to create a more "complex" design, which makes the accessibility more difficult. A more complex design requires also complicated and expensive tooling.

Hence a balance has to be made in reducing part count in an assembly. There has to be an optimum number where the cost of assembly far outweigh the cost-savings in part count. However this issue of complexity is outside the scope of this thesis. Development of work being done in this research area is currently undertaken as part of the Designers Sandpit project at Hull [17, 48, 49].

2.4.3 DFA Use in Conceptual Design

Assembly issues have traditionally been a factor largely in the latter stage of design. More often than not after a design is completed, will it then go through the rigorous assembly analysis. This is not always welcomed by the design development team as this would mean changes in design need to be made after finalising on the details of the original design.

Introducing design for assembly evaluation into the conceptual design stage poses several issues. Hsu *et.al.* [50] identified three main obstacles that will hinder the integration of the two domains. The first and foremost is the seemingly different information requirement of the two activities. During conceptual design, information is often vague, incomplete and imprecise. Such information contents is too abstract to support a computer based DFA analysis to be carried out. Secondly, the difficult issue of functional requirement specification and function-form mapping techniques will crop up, and thirdly, using DFA analysis to guide for a good initial design solution is in Hsu et. al. opinion a NP-complete problem. (a class of problem that has no known polynomial-time solution).

Hsu *et. al.* [50] suggested the use of a heuristic algorithm to search for an approximate solution rather than an optimal one, where the use of state-transition diagram is proposed as the input of functionality. A search algorithm is then invoked which accesses a library of stored design concept to find possible mapping that can meet the stated requirement. Each of these design concept is then associated with a DFA index to indicate the ease of assembly. The selected design concept is then passed to a synthesis procedure which perform a Global DFA index to give an indication of ease of assembly of the product.

Zha *et. al.* [51] used an expert system approach for concurrent product design and assembly planning which includes among others the design for assembly analysis. This system is implemented through an agent-based framework with concurrent integration of multiple knowledge sources and software. This approach is wider in scope as it views the product not only from the assembly viewpoint, but also from the planning, manufacturing, detail design, among others.

Barnes [52] uses assembly sequences as a basis for the approach to a proactive DFA system. The SPADE system uses a two-tier method in which an assembly design is concurrently generated together with its assembly sequence. This work is relevant since assembly sequence form the initial point from which DFA evaluation is made.

Ongoing work at Hull and Cranfield has been to develop an assembly oriented design environment which leads to the Designers Sandpit project [17, 48, 49]. This project incorporates many DFA rules into its system in such a way that help the designer at all levels of product development. Modules developed as part of the ProActive DFA system act as an advisor for the user of the system. The system while being comprehensive in nature, incorporating almost every aspect of the DFA rules, still relies heavily on detailed information to be garnered from the design or from the user of the system. The author would argue that these tools are more suited towards the latter part of design when this kind of information is readily available.

The kind of analysis which is performed on completed designs in order to optimise it for assembly include the following:

- part count reduction strategy
- handling operations
- assembly and disassembly sequence procedure
- insertion operations
- manufacturing operations

However for uncompleted design, i.e. design that are still the conceptual stage, this list will likely reduce to part count reduction analysis only, since this analysis only requires information that are much readily available at that stage. Section 3.4 looks at common DFA criteria against design phase level at which these analysis could be done.

2.5 Fuzzy Logic in Engineering Design

In section 2.3.2, one of the approach used to provide support to evaluate design concepts has been fuzzy logic. This section will examines in more detail how engineering design had benefited from the use of fuzzy logic, in various stages of the design process.

2.5.1 Fuzzy Logic Overview

Fuzzy Logic was introduced by Zadeh [53] as a means to model the uncertainty of natural language and it resembles human reasoning in its use of approximate information and uncertainty to generate decisions. It was specifically designed to mathematically represent uncertainty and vagueness and provide formalised tools for dealing with the imprecision intrinsic to many problems and had since gained interest and is found in a variety of control applications including chemical process control, manufacturing, and in such consumer products as washing machines, video cameras, and automobiles. More recent work , as discussed in the next section, however suggests that the use of fuzzy logic in engineering design, especially at the conceptual stage of design is on the increase.

2.5.2 Fuzzy Logic Approaches in Engineering Design

The fuzzy logic approach was used by Verma and Knezevic [42] where they employ fuzzy set together with Quality Function Deployment (QFD) as a mechanism to assess system feasibility and reliability. The same approach was taken by Yang *et.al.* [54] when developing their FuzzyQFD for buildability evaluation by integrating fuzzy set with the House of Quality adaptation. Wu *et.al.* [55] uses fuzzy theory and extended D-S theory to come up with the inexact reasoning model to evaluate mechanical design. His work however did not include any case studies to support or test his approach.

Comparing between two competing design candidates using fuzzy outranking preference model is the approach taken by Wang [39, 40] to evaluate pairs of design concepts. The use of this approach necessitates that there is more than one design concept available, as the approach ranks them in pair to determine which fits certain criteria.

Sun *et.al.* [41] used neural-network based fuzzy reasoning of design candidate evaluation to suggest the optimum design candidate. The evaluation is done based on the design specification from the customer initial requirements. Thirty-two rules were developed to represent the fuzzy relations for design candidate evaluations in the form of If-Then rules.

Other approaches that uses fuzzy logic includes Jensen [56] where the optimisation of structural systems is done by fuzzy sets and work done Shehab and Abdalla [57] by estimating manufacturing cost of product at conceptual design stage where fuzzy set is used to handle uncertain cost representation. Knowledge base of engineering information using fuzzy logic was used by Jones and Hua [58] and also by Deneux and Wang [59] to model design constraints, used to support routine engineering design.

Wang [60] integrate the fuzzy set approach into the Pugh's concept selection matrix [7] in order to measure the quality of a chosen concept. The Pugh's selection matrix has its merit but it still lack the confidence of the user in adopting the highest scoring result as it does not contain enough information to allow the designers to put faith in the obtained results.

Hsiao [61] evaluated product design by a two-prong approach. First the evaluation objectives are arranged in a hierarchical structure with several levels. The weighting functions of each are then calculated and quantified with the membership functions of a fuzzy set. A decision can then be made quantitatively on selecting the optimum design alternative. The results are then compared to an industry standard DFA analysis (Boothroyd and Dewhurst [44]) which confirms the selection. However this approach uses fuzzy set and DFA in total separation, i.e. not an integrated tool that utilise both method in one strategy.

More recently, Coma *et. al.* [62, 63], used fuzzy logic as a tool to identify geometric and form features, essential to carry out handling and insertion analysis in DFA. This approach was intended for automated DFA analysis on completed design, since the information required regarding parts feature, symmetry and orientation are available at the latter stages of design. This work together with that of Hsiao [61] are attempts to integrate fuzzy logic into DFA analysis. However, there is still area in DFA where fuzzy logic can provide support, especially in the early stages of design.

2.6 Summary

There are still gaps on attempt to integrate both DFA and Fuzzy Logic as an approach to analyse design concepts candidate, especially with that of the part count reduction analysis. The work in this thesis can be viewed from a perspective of the related work done in this area and this is shown in Fig. 2.7.

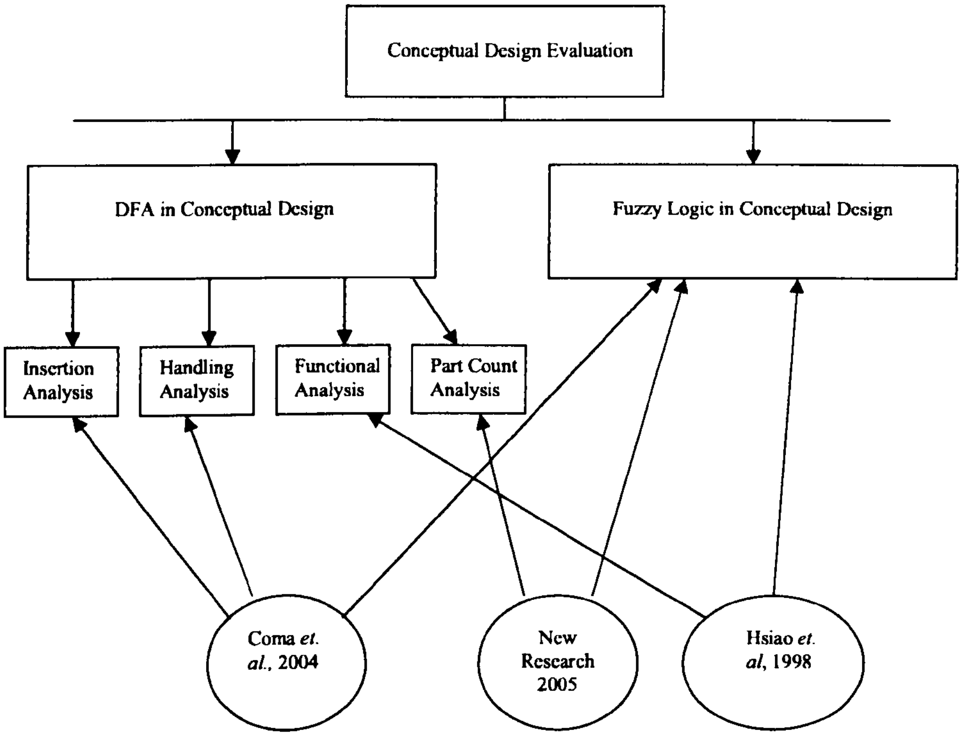


Fig 2.7 Research area in relation to others

In Chapter 3, this gap in research area is explored further to identify the needs and requirements of establishing the link between part count analysis and fuzzy logic, to be used as a tool for design concept evaluation.

Chapter 3

Conceptual DFA Evaluation

3.1 Introduction

In Chapter 2, a research gap was identified in the evaluation of design concepts. In this chapter this gap is explored deeper, in order to extract the set of requirements needed for conceptual design evaluation.

At this early design stages, design concepts are always modified and refined and subject to change [64]. This design iteration however should be kept at a minimum to allow for the need of companies to produce more and more innovative products in an increasingly competitive market place, at a faster pace. Therefore any concepts evaluation should not be a hindrance to the design process flow and being done at the early conceptual stage will benefit the designer, the design process and the product itself.

However, design concepts evaluation has not received the same amount of attention and research as most activities in the latter stages of design, for example analysis, and detailed CAD. Most activities in evaluating design concepts rely on the judgement, skills and experience of individual designers [38]. This poses several problems as the number of inherent design candidates increases and the limited amount of time available at this early stage.

3.2 Effect of Evaluation on the Design Process

Concept generation and evaluation are generally expressed as a series of divergent and convergent process steps (see Fig. 1.3). Divergent to open the scope of possible considerations or solutions as wide as possible to generate design concepts. The divergent process is followed by a convergent process were the field of possible considerations is reduced to one or a select few by an evaluation process.

Most designers, whether they realise it or not, make some sort of evaluation on their design continually. Most of it is done subconsciously, when they compare their concepts to similar design cases that they have come across, i.e. from past experiences. The designer also has to make judgement or decisions based on available data and resources available at that time. Most design concepts also has to be bounded within the constraints put to the designer by standards, regulation, rules, etc. Therefore these design concepts have already been evaluated against past experience and constraints. However, the evaluation done is highly subjective, i.e. will vary from condition to condition and from designer to designer.

The actual quantifiable evaluation that follows usually come in the form of comparing design concepts to the initial requirement or specification. This form the basis of most evaluation approaches that was highlighted in Chapter 2. Thus the information content of this requirement or specification must be detailed enough to provide some criteria or support for this kind of evaluation. However, most customers rarely know their exact requirement until a iterative process of identification and negotiation has been made between them and the designer. Thus a design specification has to be well defined first, before design concepts can evaluated against its need.

Since time to market is of utmost importance in any product development, it is essential that the duration of time spend in any stage be minimised. Thus, any tool that purports evaluating design concepts must be able to provide some guidance and indication, in the minimum of time. This is also true of any evaluation strategy done at any design stage, be it conceptual, embodiment or detailed design.

As the number of design concepts increases and the time available for any evaluation decreases, designers will require tools to help them make objective evaluation throughout the design process [16]. This is even more so during the conceptual design stage where critical decision must be made for the most appropriate design concept to be selected for further development. Ultimately, this decision will determine the success or failure of the product.

3.3 Challenges of Effective Early Evaluation

In the early stages of design, information available to designers is often seen as vague, incomplete and uncertain. This accentuates the underlying nature of this conceptual stage of design, where most data and information are very dynamic in nature. The process of data gathering at this stage is also iterative, whereby data available at one stage may be superseded by new data acquired at some later stage. This means that any evaluation of design concepts at this early stage, will need to incorporate this characteristic in its system.

Any evaluation done within the design process will have to measured against certain criteria. Identifying and giving weighting to these criteria is the usual strategy used by designer to provide for a quantitative value of the design worth [4]. However, there are no clear and objective method in determining these criteria or weighting, relying more on judgement and experience of those doing it. Moreover, some of these criteria are also interrelated to another, which makes this process even more complex and subjective.

Green [16] summarises the basic characteristics that a tool supporting design concept evaluation should ideally have :

- It must be able to deal with a significant number of criteria and design options, and the dynamic nature of each.
- It must have an effective design case and data retrieval system.
- It must employ multiple models to cope with varying types of data and representation formats
- It must use complementary, valid and robust models that have the respect of human evaluators.

While these characteristics are challenging in nature, most of the past work done on design concepts evaluation have explored some of these characteristics, if not all. More recent work have begun to incorporate most of the features required but the last characteristic which has proven to be elusive, given the current evaluation approaches.

Most designers sees evaluation as an extra burden to be done during the design process, where it might hinder or even delay the product development. However, designers would rather have tools that assess design concepts earlier in the design process, which will more likely lead to competitive product. They do not always welcome tools that critically evaluate completed design after much time and effort spend in development. Thus designers would prefer to have such evaluation tools carried out at point where they have the most opportunity to act on the result, where the results in terms of lead-time and improved product are clear [17]. In short, development of concepts are cheap while development of final product are very expensive.

3.4 Overall Requirements of Design Concepts Evaluation

The identified research done in this area, as reported in Chapter 2, covers most stages in the latter part of the design process, which leaves the important early stages still in its infancy. Most of the work done here is either domain-dependant or rigidly entrenched in mathematical model which will exclude the dynamic nature of information in the conceptual design stage. These approaches can be further classified into product-based and process-based approach. The former is where the approach concentrate on the getting an acceptable concept while the latter look at the process required for that concepts to be realised.

The diagram in Fig 3.1 illustrates the gap in research for evaluating design concepts, whereby current approaches mainly address issues related to the product but still lacking in method to address process-based approaches. There arise a need to close this gap between the process-based and product-based approaches. As concurrent engineering has broken down the barrier between different departments and stages of engineering design, so too must evaluation procedures so as to take into account the many complex factors involved in design. This is the challenge of this research area, that is to find a generic evaluation tool applicable to any stage in the design process. To realise this, more work must be done first in the process-based approach for example to take into account assembly issues when evaluating competing design concepts.

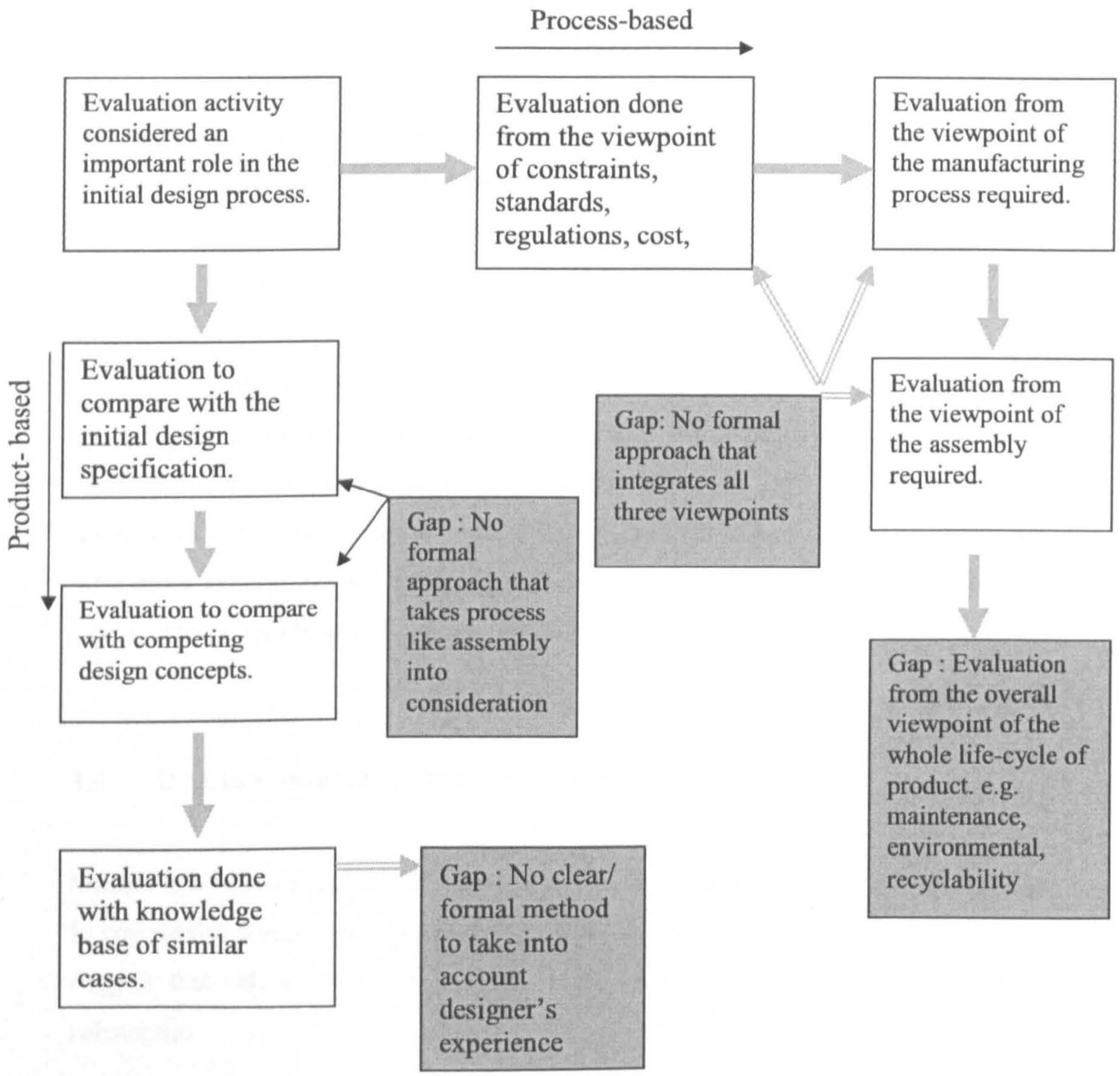


Fig 3.1 – Research gap in design concepts evaluation

3.4.1 Common Traits of Concept Evaluation

While most approaches to evaluating design concepts presented here give some indication of some optimum fit , it still lack a comprehensive evaluation technique that tackles important question such as:

- is the design good enough to proceed to the next level;
- does the evaluation have bias towards certain criteria;
- is the human designer confident enough to accept the suggested concepts;
- are there any tool to assess these evaluation techniques.

To some of these questions, Green [16] has suggested the use of an integrated design evaluation tool where several techniques are used concurrently, to verify each others' results. The approach triangulates the output from a number of models to achieve robust evaluation of competing design concepts. This could be the basis of a more generic tool for evaluating design concepts, as it underscore the fact that no one tool would be able to give a reliable and robust evaluation.

3.5 DFA in Conceptual Design Evaluation

Section 2.4.3 discusses how DFA is being used as an approach in conceptual design. In conceptual design evaluation however, there are even fewer tools available, which suggest that this area is still in its infancy, whereas the benefit to be gained is substantial .

3.5.1 DFA Principles in Design Evaluation

As pointed out in Section 2.4, most DFA tools are only provided at the latter stages of design and limited tools available to use DFA at the conceptual stage of design. The most widely used DFA methodology is the Boothroyd and Dewhurst method [44] which suggest that the best way to achieve assembly cost reduction is to first ensure that the number of components that must be assembled must be minimised and then to ensure that the remaining components are easy to assemble. These two guiding principle are used for the work done in this thesis to incorporate element of DFA into the conceptual design evaluation process. However, the next section explores the kind of DFA analysis which can possibly be done at this early stage of design to highlight possible areas for consideration.

3.5.2 Conceptual DFA Evaluation

As discussed in section 3.2.2, there exist gaps in this the area where assembly issues can be incorporated into the evaluation. This requires that an identification of the sort of analysis that can be done at the conceptual level for the type of DFA criteria or guidelines. This is done in Table 3.1 where the sort of DFA criteria that can be done at that phase is highlighted. The phase of design described here are those that are identified with Pahl and Beitz [4], while the DFA guidelines are summaries from the three DFA methodologies discussed in section 2.4

Design for Assembly Criteria/Guidelines	Consideration at What Stage
Standardised component should be incorporated	Detail
Materials and method of fabrication must be the cheapest acceptable	Detail, Manufacturing
Manual processes should be reduced to a minimum	Manufacturing
Interchange ability of components should be arranged	Detail, Manufacturing
The design must be planned for production	Embodiment, Detail

Make components symmetrical	**Conceptual**, Embodiment, Detail
Design a base component to reduce the need for jigs and fixtures	**Conceptual**, Embodiment, Detail
Design a stacked product in order to achieve simpler assembly	Detail
Products for automatic assembly are easy to assemble manually	Detail, Manufacturing
Minimise tolerance and surface finish demands on components so that production costs are reduced	Detail, Manufacturing
Keep the number of components and assemblies to a minimum	**Conceptual**, Embodiment, Detail
Simplify handling of components	Detail, Manufacturing
Do not specify tolerances tighter than essential necessary for functioning	Detail
Do not specify materials that is available only on special order purchase unless there is no alternative	Detail
Do consider the use of economical order quantities	Embodiment, Detail
Do consider using stock items when you need only a small quantity of components	Detail
Aim at simplicity and economy of construction including interchangeable components	**Conceptual**, Embodiment
Design for the most suitable production process with economic assembly as goal	Detail
Redesign to simply assembly	Detail
Design components to serve more than one function	**Conceptual**, Embodiment, Detail
Eliminate high precision fits where possible	Detail
A reduction in the number of components in a product or assembly should be the first objective of a designer wishing to reduce assembly cost	**Conceptual**, Embodiment, Detail
The most obvious way in which the assembly process can be facilitated at the design stage is by reducing the number of different components to a minimum.	**Conceptual**, Embodiment
The introduction of automation may result in a cheaper product but one that is quite uneconomical to repair	Detail, Manufacturing
Sharp corners must be removed from components so that they are guided into their correct position during assembly	Embodiment, Detail
Apart from product simplification, great improvement can often be made by the introduction of guides and tapers which directly facilitates assembly	Embodiment, Detail
It is always necessary in automatic assembly to have a base component on which the assembly can be built.	**Conceptual**, Embodiment, Detail
Make the components symmetrical	Embodiment, Detail
Avoid component features that induce tangling or nesting	Detail
It should be pointed out that components that are easy to handle automatically will also be easy to handle manually	Detail, Manufacturing
Attempts to make the components symmetrical to avoid the need for extra orienting	Embodiment, Detail
If symmetry cannot be achieved, exaggerate asymmetry features to facilitate orienting	Detail
Avoid expensive and time consuming fastening operations	Detail
Minimise number of components	**Conceptual**
Minimise production steps	Manufacturing
To achieve a high level of reliability, the designer must	Embodiment, Detail

consider the use of well tried and tested components and materials, rather than new and uncertain ones.	
Standardise and reduce the number of materials and components	**Conceptual**, Embodiment, Detail
Avoid unnecessary requirements for accuracy of manufacture	Detail
Standard sizes and components should be used wherever possible	Embodiment, Detail
Introduce datum systems whenever a high degree of accuracy is necessary in the location of interchangeable components	Detail
Will one spanner fit all clamp bolts and nuts	Detail
Follow symmetrical layout	**Conceptual**, Embodiment, Detail
Design should be made for ease of packing	Detail
Use standard components, processes and procedures whenever possible	Embodiment, Detail
Use bought-out components whenever possible	Detail, Manufacturing
Avoid sharp edges and angles	Detail
Make sure disassembly is equally practicable as assembly	Detail

Table 3.1 Stage in design where DFA is possible

Hence the type of analysis for this phase will include:

- Minimising the parts in the assemblies.
- Making part symmetrical and geometrically simple.
- Standardise and reduce the number of materials.

Thus, one of the main important guideline that can be incorporated into a conceptual DFA evaluation is to reduce the number of parts (and hence materials) in an assembly. This criteria is used in this thesis to form the evaluating analysis of the framework as discussed in Chapter 4.

3.6 Summary

This chapter has discussed the possibility of using DFA at the conceptual stage of design and in particular how it can be used in evaluating design concepts.
Section 3.3 highlights the type of characteristics a tool should have in supporting design concepts evaluation.

By looking at characteristics of DFA and that of conceptual design, the common traits of each was highlighted in section 3.4.2. Section 3.5.2 looks at possible ways in which DFA guideline can be incorporated into a conceptual DFA tool.

Chapter 4

Framework of Conceptual Fuzzy DFA

4.1 Introduction

In Chapter 3, it was shown that only a limited DFA analysis can be carried out at the conceptual stage, the main one being the part count reduction analysis. This analysis will be used in conjunction with a fuzzy logic expert system to provide for a framework for a conceptual fuzzy DFA evaluation system. In this Chapter, these two applications will be developed to test how it can evaluate design concepts. These two applications are:

- Part Count Reduction Analysis, which will provide for the evaluation criteria for which the concepts will be scrutinised.
- The Fuzzy Logic Expert System shell, which will provide for the management of data and information within the analysis.

The objective of this chapter is to integrate these two applications into one system which will allow for the support of DFA evaluation of design concepts.

4.2 The Part Count Analysis in DFA

In Section 2.3.2, the three fundamental questions for the examining the value of each part in an assembly is highlighted. The process of challenging the existence of each component in a product is key to efficient assembly. These three underlying question will provide for the core analysis here. The flowchart for the use of these analysis can be described in Fig 4.1

Here apart from these 3 question, there also arises a need to question whether the part in question is a base part and also whether it is a functional part. The base component will be defined by the component (usually the larger ones) onto which others are assembled [45] and the functional component being the component for which its feature is vital for the operation of the assembly. The base component must be established for the assembly in question in order to avoid it being considered for elimination or combination. The functional part examination of is to provide the opportunity to question the need of non-functional part, so that it could be combined with other parts in the assembly.

The evaluating procedure here relies on the knowledge and experience of the designer or user. While the three basic evaluating criteria are used in this thesis, the other reasoning criteria in DFA such as the handling analysis and insertion analysis, requires information much more than can be provided by the expert system as discussed in the next section. Thus the main body of work here will look into details at how the three evaluating criteria can be supported by the fuzzy expert system.

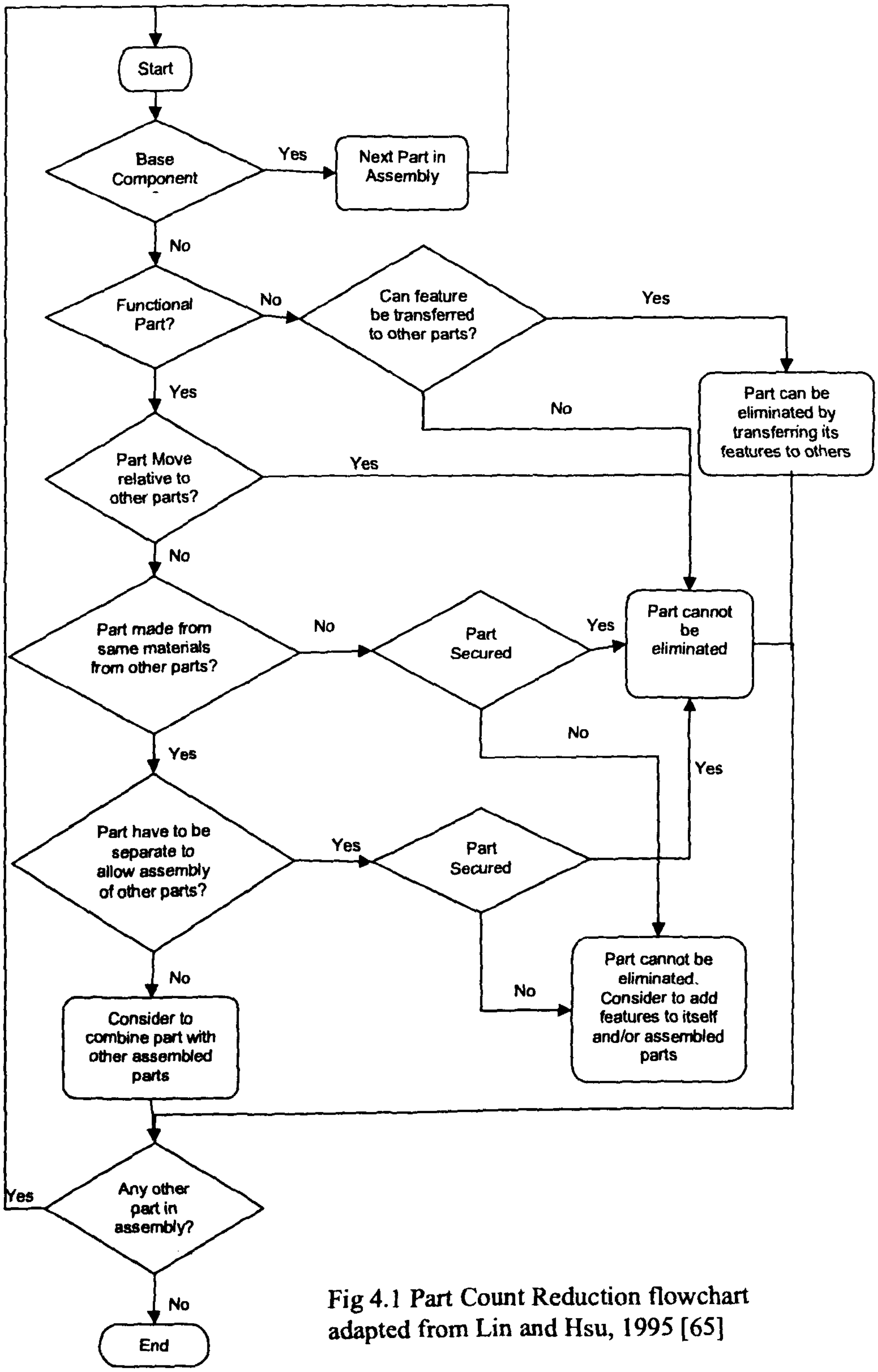


Fig 4.1 Part Count Reduction flowchart adapted from Lin and Hsu, 1995 [65]

4.3 Fuzzy Expert System

A fuzzy expert system is an expert system that uses a collection of fuzzy membership functions and rules, instead of Boolean logic, to reason about data. The rules in a fuzzy expert system are usually of a form similar to the following:

if x is low and y is high then z = medium

where x and y are input variables (names for known data values), z is an output variable (a name for a data value to be computed), low is a membership function (fuzzy subset) defined on x, high is a membership function defined on y, and medium is a membership function defined on z. The antecedent (the rule's premise) describes to what degree the rule applies, while the conclusion (the rule's consequent) assigns a membership function to each of one or more output variables. Most tools for working with fuzzy expert systems allow more than one conclusion per rule. The set of rules in a fuzzy expert system is known as the rulebase or knowledge base.

The general inference process proceeds in three (or four) steps.

1. Under Fuzzification, the membership functions defined on the input variables are applied to their actual values, to determine the degree of truth for each rule premise.
2. Under Inference, the truth value for the premise of each rule is computed, and applied to the conclusion part of each rule. This results in one fuzzy subset to be assigned to each output variable for each rule. Usually only Min or Product are used as inference rules. In Min inferencing, the output membership function is clipped off at a height corresponding to the rule premise's computed degree of truth (fuzzy logic AND). In Product inferencing, the output membership function is scaled by the rule premise's computed degree of truth.

3. Under Composition, all of the fuzzy subsets assigned to each output variable are combined together to form a single fuzzy subset for each output variable. Again, usually Max or Sum are used. In Max composition, the combined output fuzzy subset is constructed by taking the pointwise maximum over all of the fuzzy subsets assigned to variable by the inference rule (fuzzy logic OR). In Sum composition, the combined output fuzzy subset is constructed by taking the pointwise sum over all of the fuzzy subsets assigned to the output variable by the inference rule.
4. Finally is the (optional) Defuzzification, which is used when it is useful to convert the fuzzy output set to a crisp number. There are a number of defuzzification methods available but two of the more common techniques are the Centroid and Maximum methods. In the Centroid method, the crisp value of the output variable is computed by finding the variable value of the centre of gravity of the membership function for the fuzzy value. In the Maximum method, one of the variable values at which the fuzzy subset has its maximum truth value is chosen as the crisp value for the output variable.

This can be illustrated further in Fig. 4.2, where the mechanism of the fuzzy inference takes the measurement of x of the outside world in the form of crisp data and is transformed by fuzzification into fuzzy values. Then these fuzzy values are processed by the fuzzy rules in the rulebase in the form of 'If-Then' through fuzzy implications. The output expressed in fuzzy set after fuzzy implication is finally transformed by defuzzification into a non-fuzzy (crisp) output, as output of the system to the outside world.

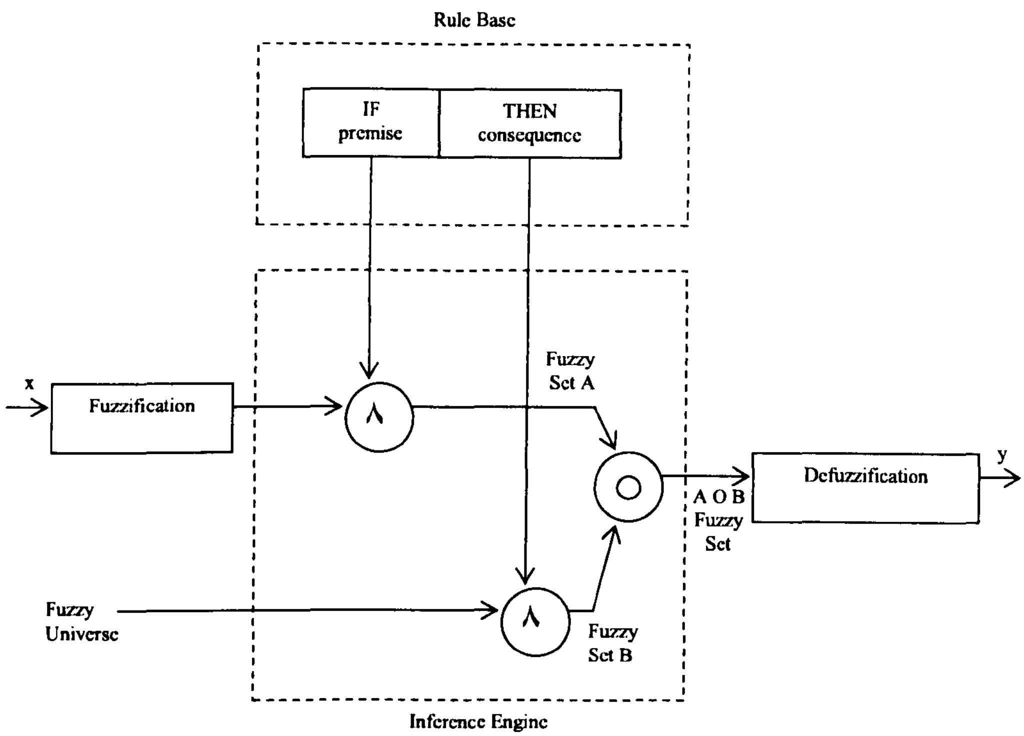


Fig. 4.2 Mechanism of Fuzzy Inference and Rule Base

4.3.1 The Reasoning Process in Fuzzy Expert System

The reasoning process in Fuzzy Expert System takes the form of

IF *(certain specified patterns occur in the data)*
THEN *(take the appropriate actions, including modifying old data or asserting new data)*
The results of which could also be the input to other rules.

4.3.2 Relating Fuzzy Expert System to Part Count Reduction

The three criteria outlined in Section 4.2 in the Part Count Reduction analysis can be used as the reasoning process in the approach. These rule set were developed from a heuristics approach by examining the required information at each reasoning level. These level of reasoning can be further decomposed if so required. The first level of reasoning process would consider the relative movement of part in the concept assembly in turn.

- IF (part move relative to others) THEN (move to next part in analysis)
- IF (Movement of part is Large) THEN (Part cannot be eliminated)
- IF (Movement of part is Small or Nil) THEN (move to next analysis)

When the part examined does move relative to other parts in the assembly, the part has next to scrutinised about the movement itself. The issue here is how Large or Small movement is defined. What is to be considered here whether the small movement is part of the function needed or is it an elastic movement of part due to thermal or loading conditions. If these operating conditions are vital to the function of the design, then these part cannot be eliminated. Nevertheless elastic movement which are not required for function of the part and is the side effect of the part in operation, may indicate that the part may be considered for the next analysis. The gradation between Large and Small movement will be defined using membership function of the fuzzy logic analysis.

The next step in the reasoning process is the determination whether that part has to be made from a different materials from other parts in the assembly. This suggest that the IF..THEN rules considers mechanical properties of the said part. What is the one common mechanical property that ties every materials in the mechanical engineering domain. Boothroyd and Dewhurst states that only fundamental reasons concerning material properties are acceptable to this analysis but does not state which particular properties. This implies that the properties concerned are reflective of the kind of design and function that is required for the function to be fulfilled. These fundamental reasons have to be that if the mechanical property selected will have grave consequences if that particular property is ignored.

- IF (Material is different from other parts) THEN (identify important material property)
- IF (material property is important) THEN (move to next analysis)
- IF (material property is unimportant) THEN (part is a candidate for elimination/combination)

The relative importance of the material properties here will define whether the part in question is a candidate for elimination or combination. How these relative importance be identified is supported by the membership function of the fuzzy logic analysis.

The next step in the analysis is whether the part has to be separate to allow assembly or disassembly of the product. This requires much more information about the product assembly as opposed to the two previous analysis. The kind of information required here will encompasses the assembly sequence, the disassembly sequence, the product BOM structure, how one part relates to other parts in the assembly, i.e. spatial and kinematic relationships.

The main contention here is whether that part really has to be there in the first place and whether it can be combined with other parts in the assembly. Thus the evaluation can be stated as such:

- IF (part can be combined with other part in the assembly) THEN (eliminate part)
- IF (part will hinder the assembly process if it is not separate) THEN (look at other parts)
- IF (part allows other parts to be assembled easily) THEN (candidate for elimination/combination)

Since the assembly sequence information here is still incomplete until the design has been finalised, only knowledge about the relative spatial position of each part in the assembly is inherent here from the sketches of the concepts.

4.3.3 The Membership Function

The membership definition will determine how the Fuzzy Expert System will perform the inferencing process. From the identification of the reasoning rules above, three important membership functions have been distinguished. These are :

1) The distinction between the relative movement from Small to Large. One membership function to allow for this is of the linear type. This obviously depends on the function of the part, whether to allow movement at all (zero movement) to complete movement or rotation of part to allow for the function to be performed.

   An example of a fuzzy set for part movement can be defined as follows:

Movement (mm)	Confidence in:	
	SMALL	LARGE
0	1000	0
3	900	0
6	500	100
9	100	500
12	0	1000
15	0	1000
18	0	1000

Here, these values were selected based, on the distinction between elastic movement and actual movement. Elastic movement can vary in range from very small displacement (degree of 10^{-6} m) up to substantial movement (degree of 10^{1} m), depending on the materials used.

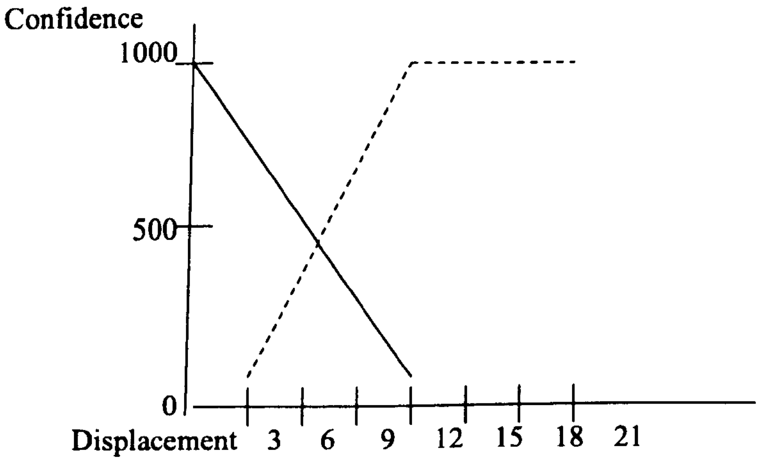


Fig 4.3 Membership Function for Part Movement

However the true shape of the membership function will depend on the nature of the movement in the parts involved. Apart from linear movement, angular and rotational movement are also possible. The process above is called fuzzification.

2) The materials differentiation refers to the material property in question. The material property here needs to be the determining property that will suffice to ensure that the material is really necessary for the function of the part. This property can either be in the form of surface hardness, Young's Modulus, density, coefficient of thermal expansion, etc. However, if several material properties are taken into consideration, then the relative importance of these material properties need to be considered. This is usually the case in most consideration, where no one property determines its importance for the part to function. Deciding on which properties and to what extend their relative importance to the function of the part will be left for the domain expert to input into the system.

The membership function can thus be laid out as :

Material Property	Confidence in:	
	Contribute to function	Non-contribution
Property A	1000	0
Property B	900	0
Property C	500	100
Property D	100	500
Property E	0	1000

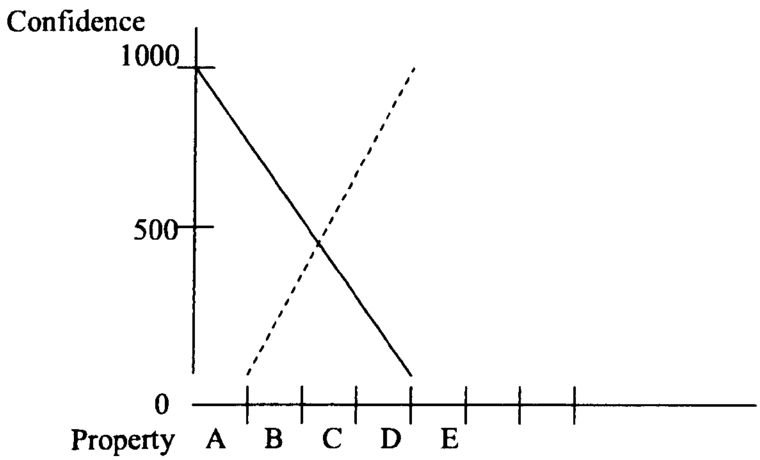


Fig 4.4 Membership Function for Material Property

3) The analysis regarding the part in question being regarded in terms of its relative position with other parts in regards to the overall assemblability of the product. If the part shows the inclination that it can be separated out to allow other parts to be assembled. Hence the gradation of truth here refers to the hindrance to and free movement of other parts to be assembled.

Part	Confidence in:	
	Hindrance	Free Movement
A	1000	0
B	900	0
C	500	100
D	100	500
E	0	1000
F	0	1000
G	0	1000

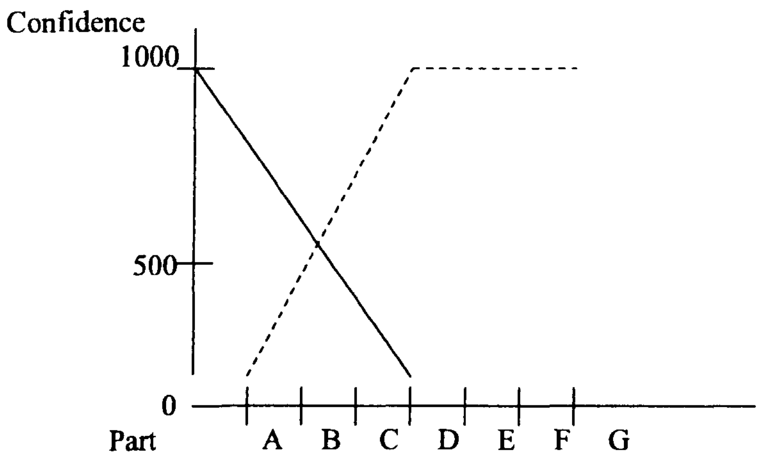


Fig. 4.5 Membership Function for Part Position

Here the system will require input from the domain expert each of the part in questions and the expert relative merit on the part being a hindrance or not to other part to be assembled.

Thus the premise is built upon the degree of truth of each of these analysis. Once these are in place, only then can the analysis of the assembly be carried out in order to determine which part is a candidate for combination or elimination.

4.4 Implementation

In this section, the implementation and architecture issues are addressed. This involves defining an application which integrate the structure of Part Count Reduction and the Fuzzy Exper System into one system known as the Fuzzy Part Count Expert System. The overall structure is given in Fig 4.6

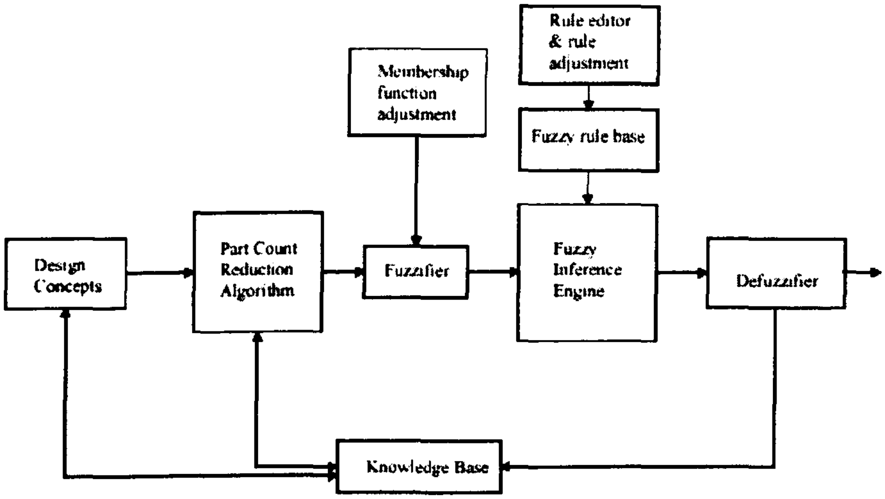


Fig 4.6 Fuzzy Part Count Expert System

The kind of task that Fuzzy Part Count Expert System are capable of performing are :

- Allow designers to change membership function according to the changes in information about the assembly as the product development progresses.
- Allow designers to manipulate and tweak the rule editor using the rule editor and rule adjustment to suit the assembly needs
- Take design concepts input in the form readily available (usually sketches) at the conceptual stage

- Result from the system will inform the designer of the need for the part in question.

4.4.1 Implementation Structure

Each element in Fig 4.6 perform an important task in providing the requirement of Fuzzy Part Count Expert System. The role of each of these element is describe below:

1. **Part Count Reduction Algorithm** – this element of the system takes in as input from the user, information about the design concept being analysed. Each part will be scrutinised separately in turn.
2. **Fuzzifier** – the input into this element will be determined from the setup of the membership function. Here, the user either need to input the structure of membership function or have it read from other supporting files. The membership function adjustment that is available here ensures that the user can change or vary the structure of membership function as the design develops.
3. **Fuzzy Inference Engine** – the rule for the reasoning process in determined in this element. The set of these rules are contained in the rule base, which also can be changed or varied according to the requirement of the concept design.
4. **Defuzzifier** – this element is essential in the system as it converts back the output from the engine into a form that is readily understandable to the user and output to the screen as the possible suggestion for the part or component of the assembly in question.
5. **Knowledge Base** – this element is assumed to be with the domain expert or the designer themselves when using the system. The body of knowledge

regarding the design concepts is best left to the human expert himself as any library or taxonomy of knowledge used here would be taxing on the system.

4.4.2 Implementation Method

The implementation of Fuzzy Part Count Expert System was carried out using the FLOPS software available online as a demo version, on the Windows environment. FLOPS (Fuzzy Logic Production System), originally developed at Kemp-Carraway Heart Institute by D. Tucker and W. Siler [66] for medical image analysis. It is a set of tools for building and running fuzzy expert systems to solve reasoning problems, especially those involving uncertainties, ambiguities and contradictions. It has been used in in areas of trouble shooting, pattern recognition, medical diagnosis, alarm system.

The choice of using FLOPS was due to its easy availability, a significant number of example code library and its potential of representing the uncertain knowledge available at the conceptual stage of the design process.

FLOPS is a rule-base language, as distinct from statement-based language such as C or FORTRAN. It is also data-driven and the order in which FLOPS rules are fired has nothing to do with the order in which they are written. The FLOPS code for the implementation of Fuzzy Part Count Expert System is given in Appendix A.

4.5 Summary

The objective of this chapter was to describe the development of an application which takes the part count reduction analysis of the DFA procedures to the conceptual stage, as described in Chapter 3. The application developed using FLOPS was the Fuzzy Part Count Expert System which provides for the designers to vary the membership function and the fuzzy rule base to suit the uncertain body of knowledge at the conceptual stage of design. This allows the designer to evaluate parts in the design concepts to challenge its need in the assembly or product. In the next chapter, Fuzzy Part Count Expert System was used in case studies involving the redesign of two products.

Chapter 5

Application to Case Studies

5.1 Introduction

In Chapter 4 the Fuzzy Part Count Expert System approach has been proposed and developed to support some of the DFA procedures which has been identified in Chapter 3 to evaluate design concepts. Hence the objective of this chapter is to evaluate the usefulness of the Fuzzy Part Count Expert System application by using it to support the design process of two case studies. The first case study involve the redesign of an industrial product. The second case study pertains to a design of a household product, which has been under study in another research. These case study were selected based on the following merit:

- The first case study looks at a real industrial product which is undergoing a redesign exercise and will provide for an ideal platform from which to test and demonstrate its usefulness. The results from the case study can be compared to the actual selection criteria used to select the most appropriate concept for further development.
- The second case study was selected due to its concepts being evaluated using another approach to evaluate them for assembly matters. This can be used to compare the method with the approach in Chapter 4 to triangulate whether they will come to the same conclusions.

5.2 Case Study 1 - Selection of Peristaltic Pump Design Concepts

This example considers the redesign issue which will relate to the design process involved when doing a real industrial redesign exercise. The Verder industrial peristaltic pump design (originally invented by Bredel) has been in the market for a number of years. An example of the current design is shown in Fig. 5.1

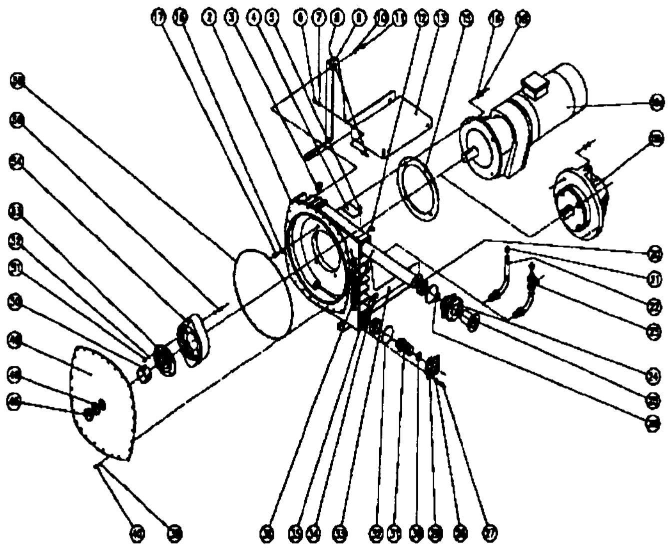


Fig. 5.1 Original Design of Peristaltic Pump (courtesy of Verderflex)

The peristaltic pump operational characteristic is often likened to the action of the intestine wall when delivering moving food. It uses the contraction and expansion of the wall of the tube to traverse the fluid along the wall. The action on the wall of the tube is provided by the action of an external mechanism that acts on the wall intermittently. The use of the peristaltic pump has been to deliver fluid and semi-fluid that are prone to deterioration by means of normal pump action. Its uses in the food industry and also in the medical profession has proven its worth, with its unique characteristic.

The pump design usually comes in 4 separate main parts. The outer casing, the pipe itself, the delivery mechanism and the motor to provide the traction. The mode of delivery of the mechanism will depend on the pump delivery speed and load. The challenge of the redesign exercise is to reduce the cost of the pump by 50%. Verder has been losing its market stake in the industry due to competition and this has led to the this redesign exercise. The project was undertaken by an engineer working on the TCS scheme in the University of Leeds over a period of 2 years. This case study will look at the three design concepts developed and make suggestion on how to improve the assemblability of each and later make recommendation for the most appropriate concept for further development, in terms of its assembly.

5.2.1 Peristaltic Pump Characteristic

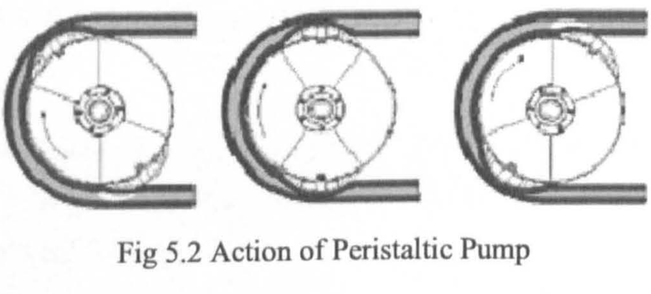


Fig 5.2 Action of Peristaltic Pump

The principle of the peristaltic hose pump is based on alternating contraction and relaxation of the hose forcing the contents through, operating in a similar way to the throat and intestines.

A smooth wall, flexible hose is fitted in the pump casing which is completely squeezed by the shoes on the rotor, inside the pump casing. The rotation action moves the product through the hose at a constant rate of displacement without slip, making the pump suitable for high dosing applications and pressure ratings up to 16 bar/230 psi.

The hose restitution after the squeeze produces an almost full vacuum that draws the product in the hose, so very viscous liquids are pumped without problems using the hose pump. The pump casing is half-filled with a specially designed lubricant, to lubricate and cool the pump to lengthen service life of the hose. Since the product only comes in contact with the hose and not with any rotating parts, the hose pump is very suitable for shear sensitive fluids even when the liquid contains particles.

Verder which has a market share of about 5%, produces peristaltic pump of a similar configuration and market and user demand has lead Verder to completely redesign the pump in such a way so as to reduce cost by 50 %.

Three design concept were developed using basic principles from past patents and user requirements. The main priority has been to have a minimum 'down-time' during use, i.e. increased reliability.

5.2.2 Peristaltic Pump Redesign Requirement

There are 3 concepts to be analysed in this case study i.e. Lobe , Helical Linear and Eccentric as shown in Fig 5.3

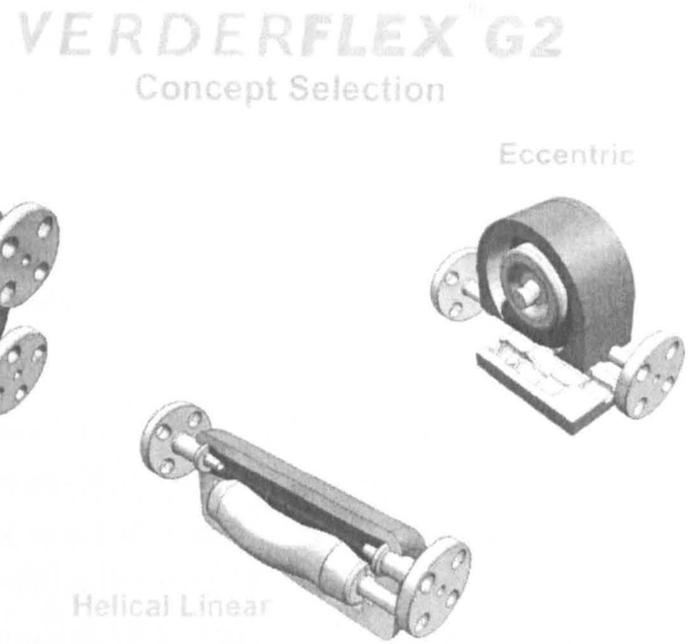


Fig 5.3 Design Concepts for the Peristaltic Pump (courtesy of Verderflex)

The first concept uses a lobe cam to produce the peristalsis action on the tube. This mechanism and the tube is encased in the housing and lubricated by the oil in the housing itself. This concept is very similar to the original design but with lesser parts.

The second concept uses helical linear shape of the second shaft to produce the required movement. This is a completely novel concept and the idea is similar to the action in a direct injection principle of a plastic moulding machine.

The third concept uses the principle of an eccentric configuration of a wheel on a shaft, which produces the required motion when the wheel move against the tube eccentrically. This is another novel idea that came out of this project and the idea comes from the eccentric configuration of the 4-stroke engine.

5.2.3 Criteria for Pump Selection

The pump selection was based on a number of criteria selected by the designer. These criteria were based on past experiences of the original pump in the market. These criteria were laid out in a matrix table as in Figure 5.4 where the three concepts are considered for further development. The matrix provide for a broad based evaluation tool, reminiscent of the Pugh's selection matrix, as described in section 2.4

Concept Selection

Category	Selection Criteria	Verderflex (Datum)		Helical Linear		Lobe		Eccentric	
Physical and Operational Characteristics – Performance	Discharge pressure	Medium	0	High	+	High	+	High	+
	Self priming ability	Good	0	Good	0	Good	0	Good	0
	Continuous max flow	Low	0	Medium	+	Medium	+	High	++
	Discharge / inlet pulsation	High	0	Low	++	Low	++	Low	++
	Pump head withstanding of media temperature	Good	0	Good	0	Good	0	Good	0
	Hose withstanding of media temperature	Good	0	Good	0	Good	0	Good	0
	Will reliably pump highly viscous media	Average	0	Good	+	Good	+	Very Good	++
	Will reliably pump highly abrasive media	Average	0	Good	+	Good	+	Very Good	++
	Will reliably pump highly aggressive (corrosive) media	Good	0	Good	0	Good	0	Good	0
	Will not degrade shear sensitive media	Average	0	Good	+	Good	+	Very Good	++
	Will not contaminate valuable or pure media	Good	0	Good	0	Good	0	Good	0
	Flow accuracy	Average	0	Good	+	Good	+	Very Good	++
	Flow repeatability	Average	0	Good	+	Good	+	Very Good	++
	Zero cross contamination	Good	0	Good	0	Good	0	Very Good	+
	May be cleaned / sterilised by CIP / SIP	Yes with bypass	0	Yes	+	Yes with bypass	+	Yes	+
	Is reversible	Yes	0	Yes	0	Yes	0	Yes	0
	May be run dry	Short Periods	0	Medium Periods	+	Short Periods	0	Long Periods	++
	Rotor / hose friction	High	0	Medium	+	Medium	+	Zero	++
	Occlusions per rev	2	0	1	+	2	0	1	++
	Inlet / discharge	One side	0	Linear	+	One side	0	Linear	+
	Fluid path	180 degrees	0	Linear	++	180 degrees	0	360 degrees	-
	Load dynamics	Oscillating	0	Static	+	Oscillating	0	Oscillating	0
	Load support	Overhung GMU	0	Direct independent	++	Direct independent	++	Direct independent	++
	Hose support	Poor	0	Fully	++	Almost Fully	+	Fully	++
	Pulsation	High	0	Low	++	Low	++	Low	++
	Efficiency	Low	0	High	++	High	++	High	++
	Needs Verderlube	Yes	0	Yes	0	Yes	0	No	+
Reliability	Pump head reliability	Average	0	Very Good	++	Very Good	++	Good	+
	GMU reliability	Average	0	Good	+	Good	+	Good	+
	Hose life	Average	0	Good	+	Good	+	Good	+
Maintenance	Hose replacement time	Medium	0	Very Low	++	Low	+	Low	+
	Bearing replacement time	Medium	0	High	-	Medium	0	Low	+
	Hose burst bearing protection	Average	0	Good	+	Good	+	Average	0
	GMU replacement time	High	0	Low	++	Low	++	Low	++
Size	Pump envelope (inc GMU)	Medium	0	Small	+	Small	+	Small	+
Mass	Pump mass (inc GMU)	Medium	0	Low	+	Low	+	Low	+
Drive Requirements	GMU purchase cost	High	0	Low	+	Low	+	Low	+
Aesthetics	Conveys elements of Verder & Verderflex branding	High	0	Medium	-	Enhanced	+	Enhanced	+
	Conveys recommendations made from affective design study	N/a	0	None	0	Most	+	Most	+
Materials	Chemical resistance to all current pumped media	Yes	0	Yes	0	Yes	0	Yes	0
	Material Costs	Medium	0	Medium	0	Low	+	Low	+
Ergonomics	Assembly time	Medium	0	Medium	0	Low	+	Medium	0
	Assembly ease	Medium	0	High	+	High	+	Medium	0
	Accessible fastenings	Average	0	Good	++	Good	++	Good	++
Quality	Surface tolerance requirements	Medium	0	High	-	Low	+	Low	+
Safety	Likelihood of hose spallation	Medium	0	Low	+	Low	+	Very Low	++
	Operator-proof design	Average	0	Average	0	Average	0	Good	+
Manufacturing Processes	Manufacturing process costs	Average	0	Average	0	Low	+	Very Low	++
	Processes technically scaleable	Average	0	Good	+	Good	+	Good	+
Packaging	Easily packable design (either assembled or otherwise)	Average	0	Average	0	Average	0	Average	0
Standards & Guidelines	Is compatible with standard GMU mountings and shafts	Some	0	Most	+	Most	+	Most	+
	Port flanges compatible with standard PN16 (DIN), ANSI and JIS flanges	Yes	0	Universal	+	Universal	+	Universal	+
Customers	Applicable to key functions: Dosing/Metering, Filtering and General Fluid Transfer	Yes	0	Yes	0	Yes	0	Yes	0
	Potential customers: Pharmaceutical and food manufacturers	Average	0	Very Good	++	Very Good	++	Very Good	++
Market Constraints	Is easily comparable against other makes of industrial peristaltic pump	Yes	0	No	-	Yes	0	Yes	0
	Market acceptance due to aesthetics	Good	0	Poor	-	Very Good	+	Very Good	+
	Possesses traditional 'hallmarks' of high quality	Average	0	Good	+	Good	+	Good	+
Competition	Performance against direct competition such as Bredel, Abaque and Dasseco	Average	0	Very Good	++	Very Good	++	Very Good	++
	Performance against indirect competition such as AOD and PC pumps	Poor	0	Good	+	Good	+	Good	+
Target Product Cost	Estimated list purchase cost	High	0	Average	+	Low	++	Low	++
	Sum +'s	+0		+51		+51		+60	
	Sum 0's	60		16		19		14	
	Sum -'s	-0		-6		-0		-1	
	Net Score	0		45		51		55	
	Rank	4		3		2		1	
	Action	N/A		To file		Prototype		Prototype	

Fig 5.4 Concept Selection Matrix for Peristaltic Pump

The concept selection matrix done here indicate the eccentric and lobe concepts are to be suggested for the next phase of development.

5.2.4 Peristaltic Pump Analysis by Manual DFA

The Part Count Reduction evaluation of the DFA analysis of the concepts done manually is referred to the flowchart in Fig 4.1 Each of the concept part is scrutinised along the line of the flowchart, with the design knowledge of each part assumed to be with the designer.

Identification of the criteria that are important for the consideration of assembly here will make easier with comparison with the DFA analysis. Referring to Fig.5.4, these are lumped under the subheading ergonomics, i.e. the consideration of assembly time, assembly ease and accessible fastening. Apart from that, other consideration that might involve assembly include hose replacement time, bearing replacement time and GMU replacement time. However, the evaluation is only restricted to Low, Medium and High and give no clear indication of the scrutiny used in its evaluation. A more quantifiable measure here would be helpful.

The analysis for Design-for-Assembly requires the parts for each to be identified first. This is relatively simple as these concepts can identified with its corresponding part in the original peristaltic pump. These main parts are the hose, the peristaltic mechanism, the housing and the connectors. The results of the analysis by the Boothroyd & Dewhurst DFA method is outlined in table 5.1a, b and c

Concept						
Part	Flange	Connector	Hose	Body	Shaft	Cam
Part Movement	N	N	Y	-	Y	Y
Material Differentiation	Y	N	Y	-	N	N
Spatial positioning in Assembly	Y	N	Y	-	N	N
Candidate for elimination/combination	N	Y	N	-	N	N

Table 5.1a Boothroyd Part Count Reduction analysis on Lobe concept

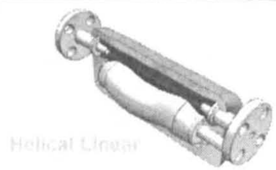
Concept						
Part	Flange	Connector	Hose	Body	Shaft	Cam
Part Movement	N	N	Y	-	Y	Y
Material Differentiation	Y	N	Y	-	N	N
Spatial positioning in Assembly	Y	N	Y	-	N	Y
Candidate for elimination/combination	N	Y	N	-	N	N

Table 5.1b Boothroyd Part Count Reduction analysis on Helical Linear concept

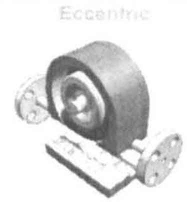
Concept						
Part	Flange	End Flange	Hose	Body	Eccentric Shaft	Cam
Part Movement	N	N	Y	-	Y	Y
Material Differentiation	Y	N	Y	-	N	N
Spatial positioning in Assembly	Y	N	Y	-	Y	Y
Candidate for elimination/combination	N	Y	N	-	N	N

Table 5.1c Boothroyd Part Count Reduction analysis on Eccentric concept

The above table shows that there are two parts that are likely to be considered superfluous in terms of assembly and can be justified as a candidate for elimination or for combination with other parts. Most of the other parts are functional i.e. required for the operation of the design.

5.2.5 Peristaltic Pump Analysis by Fuzzy Part Count Expert System

The peristaltic pump analysis by Fuzzy Part Count Expert System requires that the membership function and rule based be established. These are discussed in Chapter 4 and this case was tested against linear function of the membership function and up to 15 rules in the analysis.

Initially, the confidence value (rconf) was taken arbitrarily and after several iterations was set to match value from the membership functions.

Fuzzy Part Count Expert System only suggest that some extraneous part be considered for elimination or combination for all three concepts as follows:

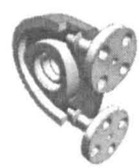
Concept	Lobe 					
Part	Flange	Connector	Hose	Body	Shaft	Cam
Part Movement	N	N	Y	-	Y	Y
Material Differentiation	Y	N	Y	-	N	N
Spatial positioning in Assembly	Y	N	Y	-	N	N
Candidate for elimination/combination	N	Y	N	-	N	N

Table 5.2a Fuzzy Part Count Expert System analysis on Lobe concept

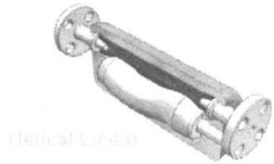
Concept						
Part	Flange	Connector	Hose	Body	Shaft	Cam
Part Movement	N	N	Y	-	Y	Y
Material Differentiation	Y	N	Y	-	N	N
Spatial positioning in Assembly	Y	N	Y	-	N	Y
Candidate for elimination/combination	N	Y	N	-	N	N

Table 5.2b Fuzzy Part Count Expert System analysis on Helical Linear concept

Concept						
Part	Flange	End Flange	Hose	Body	Eccentric Shaft	Cam
Part Movement	N	N	Y	-	Y	Y
Material Differentiation	Y	N	Y	-	N	N
Spatial positioning in Assembly	Y	N	Y	-	Y	Y
Candidate for elimination/combination	N	Y	N	-	N	N

Table 5.2c Fuzzy Part Count Expert System analysis on Eccentric concept

Results show similar identification of the part that can be considered for elimination or combination to other parts. However, there are some indication from this analysis that other parts can also be considered if the membership function of the fuzzifier is altered to a more relaxed range. These include the connectors and the cam. In section 5.3, these results will be discussed along with the result from the second case study in the next section.

5.3 Case Study 2 - Heavy Duty Stapler Analysis

This case study was taken from the work done by Stone *et. al.* [63] in analysing the heavy duty stapler in a post design DFA analysis, involving the use of a product-architecture based technique. While the work done here also involves other strategies in DFA, this case study will only consider the Part Count reduction analysis done in this work.

5.3.1 Heavy Duty Stapler Assembly

The heavy duty stapler used in this case study is as shown in Fig. 5.5. It consists of 29 parts in the assembly as shown in Fig 5.6. This design of the heavy duty stapler has been on the market for a number of years and its design hasn't changed much over the ensuing years.

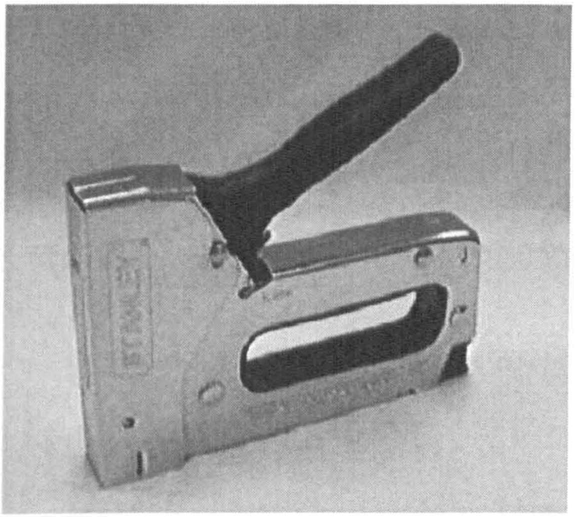


Fig 5.5 The Heavy Duty Stapler used in the case study

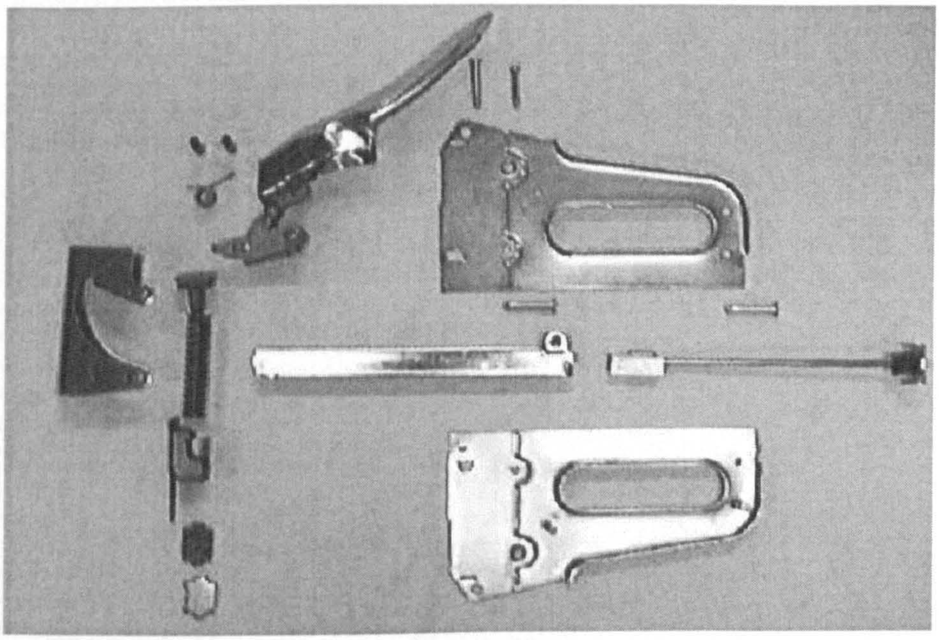


Fig 5.6 Heavy Duty Stapler Assembly

5.3.2 Analysis of Heavy Duty Stapler by Boothroyd & Dewhurst DFA

Table 5.3 outlines the results of the Boothroyd and Dewhurst DFA analysis done on the stapler [63] and shows some suggestions so as to reduce the number of part from 29 to only 14 parts, which can be implemented if the manufacturing cost can be justified.

1	2	3	4	5	6	7	8	9
Part No	No. of operation	Manual handling code	Manual handling time (s)	Insertion code	Insertion time (s)	Total operation time (s)	Theoretical minimum parts	Part name
1	1	30	1.95	00	1.5	3.45	1	Plastic support
2	1	30	1.95	30	2.0	3.95	0	Hammer guide
3	1	23	2.36	30	2.0	4.36	1	Hammer
4	1	30	1.95	06	5.5	7.45	1	Stapler advance mechanism
5	1	33	2.51	06	5.5	8.01	1	Left Casing
6	2	15	2.25	03	3.5	11.5	0	Rivet
7	1	10	1.5	31	5.0	6.5	1	Bottom Leaf Spring
8	1	10	1.5	00	1.5	3.0	0	Top leaf spring
9	1	33	2.51	01	2.5	5.01	1	Left lifter
10	1	00	1.13	06	5.5	6.63	1	Plastic pin
11	1	33	2.51	01	2.5	5.01	1	Right lifter
12	1	30	1.95	07	6.5	8.45	1	Plastic Handle
13	1	30	1.95	30	2.0	3.95	0	Metal handle
14	1	15	2.25	30	2.0	4.25	1	Pin
15	1	15	2.25	30	2.0	4.25	0	Stud
16	2	30	1.95	06	5.5	14.9	0	Lifter cover
17	1	30	1.95	06	5.5	7.45	0	Spring mount
18	2	05	1.84	06	5.5	14.68	2	Springs
19	1	34	3.0	06	5.5	8.5	0	Metal spring holder
20	1	33	2.51	06	5.5	8.01	1	Right casing
21	1	15	2.25	38	6.0	8.25	0	Pin
22	1	39	4.0	31	5.0	9.0	0	Circlip
23	2	-	-	35	7.0	14.0	0	Riveting operation for rivet in row 6
24	1	33	2.51	08	6.5	9.01	0	Front casing
25	1	15	2.25	38	6.0	8.25	0	Pin
26	1	39	4.0	31	5.0	9.0	0	Circlip
27	1	23	2.36	31	5.0	7.36	1	Locking pin
					Totals	204.18	14	
Total number of parts is 29								
The manual design efficiency is given by EM = 3 X 14/204.18 = 20.60 %								

Table 5.3 DFA Analysis on Heavy Duty Stapler

5.3.3 Analysis of Heavy Duty Stapler by Fuzzy Part Count Expert System

Applying the Fuzzy Part Count Expert System on the heavy duty stapler produces results that are consistent with the results reported in Table 5.3. Since the approach investigates the concept behind the design, this product need to be reengineered back to its basic form concepts. This is shown in table 5.4 together with the result from the Part Count Reduction analysis.

Concept Component Description		Part Count Analysis
1.	Staple advanced mechanism with casings	3
2	Hammer with springs and projections	1
3	Handle with integral leaf spring	1
4	Handle with casings	0
5	Locking (pins, screws)	6
		11

Table 5.4 Fuzzy Part Count Expert System Analysis on Heavy Duty Stapler

The underlying basic concept for the mechanism has been identified to 5 descriptions, which include the locking mechanism of the pins and screws.

In this approach, the number of parts has been reduced from 29 to 11, which is less than the number reported by the Boothroyd & Dewhurst DFA analysis in section 5.3.2

5.4 Comparison of Results

The results obtained from the approach was compared to that obtained from the Boothroyd and Dewhurst part count analysis. This is essential since the premise of the three evaluating criteria were based on Boothroyd and Dewhurst method. This way these results were validated using industrially accepted method. Thus both methods leads to part count reduction, with the difference being that the Boothroyd Dewhurst method is post design DFA while the approach advocated in this thesis is more a conceptual method

While the results shows similar characteristic, in that the part count reduction can be achieved, the knowledge of the parts in the assembly is still reliant on knowledge about the assembly, specifically the assembly and disassembly sequence. This knowledge is required for the third analysis regarding the relative positioning of the part with regards to the other parts in the assembly. The parts movement analysis also require information regarding the part relative to other parts. The only analysis that seem advantageous is the examination of materials of parts where this knowledge can be supplied by a knowledge base, like that of Jones and Hua [58].

5.5 Case Study Discussion

The results from the case study has brought out several issues which can be stated thus:

- The confidence (rconf) value was initially set arbitrarily. After several iterations this value was revised to match value from the modified membership function.
- The membership function structure was tested only with linear function, but other function structure could also potentially be explored.
- The rules in the analysis need to be constantly reviewed to continuously update new information and knowledge as it becomes available.
- The representation of the design concepts here in this analysis assumes knowledge of the form and function of the parts in the assembly. Hence the design concepts representation here are basically more towards sketches or preliminary design drawings.
- These concepts are mapped into the analysis through intimate knowledge about the design by the designers themselves. Thus it is placed upon the designers to provide the knowledge base as seen in Fig.4.5 . Even though other form of knowledge bases, such as that provided by databases, data models, exists, it is nowhere near close enough to compare with that of a domain expert.
- Data input into the analysis is done manually, i.e. the user need to have intimate knowledge of the parts of the assembly. Hence the analysis is ideally done by the designer themselves.
- Output from the analysis can only give recommendation or warnings of the relative imminent superfluous parts, i.e. it is still up to the designer to decide whether the recommendation is relevant to the overall design or not.
- The analysis can also act as a flag to designer to assist them in making decision based on the assemblabilty of parts in the assembly.
- There seems to be a slight discrepancy in the parts of the pump that was analysed manually with the Boothroyd & Dewhurst DFA analysis and the results of the analysis done with this approach. This seems to suggest that conceptual DFA will largely depends on the person analysing it.

- The key component of this analysis is the knowledge base support system which is largely assumed to be the user expert himself. Hence, to take out the amount of guesswork from the user, the knowledge base of the system need to support information that is more substantial.
- The analysis will therefore depend largely on the knowledge base, the design of membership function, the structure of the rules, and on how well the design concepts are represented.

Despite numerous code changes, the implementation used wasn't able to completely capture the characteristic of a true DFA analysis. The results obtained were then verified by use of manually investigating each part by the system inference. While limited in scope to only part count reduction, the system has a fairly satisfactory success. From this we can conclude that to integrate fuzzy logic into DFA analysis, there is a need for further detailed analysis of the design concepts than originally thought of.

The combination of fuzzy logic and DFA while seems plausible due to the nature of the information content at the early stages of design, has provided many challenges and constraint that are proving to be elusive. This however doesn't mean that the integration of DFA and FL is impossible. There seems to be a need to clearly define the membership function of the analysis to enable the approach to be fully supportive of design decisions. To be left to the designers to decide the membership function definition will leave the approach open to interpretation, which might leads to inaccuracy.

5.6 Summary

In this chapter, two investigation was made to demonstrate the usefulness of the Fuzzy Part Count Expert System approach to evaluate design concepts. In the first case study, the redesign of a product was undertaken and the approach has demonstrated that it could be used as an early evaluation tool from the DFA perspective. However, the role of the knowledge base in this approach is very much in the user or designers 'head' rather than been in a medium that can be accessed by others. Therefore the use of tools like Fuzzy Part Count Expert System can streamline the designers thought process in evaluating their product can be advantageous.

In the second case study, an existing product was reengineered back to its basic function concepts, in order to allow the approach to analyse it. This illustrate that the approach can be used to investigate existing product and hence provide supporting evaluating tools not only for design concepts but also for finished products.

Both case studies illustrates that Fuzzy Part Count Expert System can be used to evaluate products at the conceptual stage. However, the development of tools that combine the use of fuzzy logic and further DFA strategies would be useful and should be subject for further investigation.

Chapter 6

Conclusions and Further Research

6.1 Summary

The overall summary of this research can be reflected by way of looking at the objectives as outlined in Section 1.3 as follows:

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.

This thesis has addressed the first objective and has demonstrated that a Fuzzy Logic approach to DFA evaluation is possible when the imprecise and vague information at the conceptual stage is represented by fuzzy variables. These fuzzy representations of the information at the conceptual stage can also be modified as the value of this information changes along with product development, thus addressing the need of the second objective.

6.2 Contributions of the Research

Conceptual design requires that the concepts generated be evaluated against many different criteria. This evaluations are an important step in determining how well a design is shaping up according to the specifications and also how well it will succeed in the final stages of design. Even though evaluations are done throughout the design process, the most influence and impact will come from evaluation that is done at the conceptual stage. If these tools are provided to support the designers at this stage, the complex nature of conceptual design can to a certain extent be formalised.

The research presented in this thesis examined the feasibility of using Fuzzy Logic as a tool to provide support for DFA evaluation for design concepts. Hence the possibility of using this evaluation together with other evaluation tools, can complement this process, to provide for the highest impact.

The approach was also developed and implemented to test the issues outlined above. More specifically, the contributions of the research are:

- A fuzzy approach to the Part Count Reduction strategy in Design-for-Assembly is a novel and useful approach to evaluate the criteria needed to determine whether the part will be suitable for elimination or combination with other parts in the assembly.

- A technique to represent the imprecise information at the conceptual design in the form of membership functions. These functions can be readily adjusted according to the needs of the designers and also the changes in information with the progress of product development.

- A technique to represent the evaluating criteria as a set of rules that conform to the need of DFA, specifically the Part Count Reduction strategy. These basic rules could be the starting point from which more rules can be added later to confine the design evaluation space even further.

The combination of these two techniques in the approach as demonstrated in the application known as Fuzzy Part Count Expert System, allows designers to evaluate design concepts and hence support them in bringing DFA consideration into the conceptual stage. The research presented here will also provide more tools at the disposal of the designers to help them make important decision at the early stage of design where the impact of these decision will have the most influence on the whole product development and product life-cycle.

6.3 Recommendations for Further Research

While the research here has made some insights into the DFA area in terms of its approach using Fuzzy Logic, there are many other issues that could be further investigated to make Fuzzy Logic use in DFA more robust. Fuzzy Logic had always been difficult to be accepted by the design research community until only recently. The recent success story of Fuzzy Logic in other field had however, prompted renewed interest, which would make the use Fuzzy Logic in engineering design complementary to other approaches. The results from the use of Fuzzy Logic in the Part Count Reduction analysis of the DFA procedure has raised a number of further issues which warrant further investigation. These issues are discussed further in the next section.

6.3.1 Extending the Framework

The framework presented in this thesis was the basis of the whole work. While it has been shown to support part count analysis, further DFA consideration could be made for the system to be more integrated. Work done by Coma *et. al.* [64] has investigated the use of Fuzzy Logic with handling and insertion analysis, while work done by Hsiao [61] has presented an approach to integrate Fuzzy Logic within the functional analysis of DFA. While work done here are arguably meant for the latter stages of design, it is possible to bring all three together into one integrated approach that will use the common DFA techniques available with Fuzzy Logic as its common denominator. The most promising approach would be to integrate the use of standardised parts in the DFA analysis, as this would be possible to be done at the conceptual stage, as discussed in Chapter 3

6.3.2 The Knowledge Base

In the framework presented in this thesis, the knowledge base is the common body of knowledge that all the other components referenced. With the human expert or designers left to be the knowledge bearer as they are intimate with the design concepts, this opens up the question of consistency. The wealth of knowledge and experience varies from designer to designer and this knowledge base needs to be more streamlined to fully support the evaluation. There are various ways that this can be achieved, i.e. through the use of design practice and rules, design taxonomies and the like.

6.3.3 Design Concepts Representation

The input into the approach here are design concepts in the form of design sketches or basic CAD models. This means that the system does not support other forms of design concepts representation such as mathematical models, functional models, behavioural models and assembly models. It would be interesting how these kinds of inputs would affect the analysis.

6.3.4 Output of Fuzzy Part Count Expert System

The output from the approach only gives indicators and suggestions as to whether the part or component in the assembly is really necessary. This gives adequate warnings to the designers in helping them make decisions about the design. However, if several design alternatives exist, it would be more prudent if there were a matrix or ranking of several concepts that can let designers know which design concepts is more 'assembly-wise'. At the present moment, only single design concepts can be analysed by the approach. Thus to make it more robust, a matrix or ranking system would be advantageous.

6.3.5 Other Fuzzy Approaches

The Fuzzy Logic domain has expanded to include many branches apart from fuzzy expert system as advocated in this approach. Further research could also explore the use of fuzzy outranking preference, fuzzy synthetic evaluation, neural network based fuzzy reasoning, fuzzy weighted wedge mechanism. Whilst some authors have attempted this approach [39, 43, 50, 58, 68] in other areas of the design process, it would be more advantageous to bring these approaches to the conceptual stage of design.

6.4 Conclusions

The approach suggested by this thesis in tackling the important issue of design evaluation covers only a tiny proportion of the amount of research area possible in this field. While it is not intended to compete with other accepted approaches, its use can complement and diversify the use of evaluating techniques for design concepts. Expert system such as the one used in this approach will most likely not replace human experts. Aside from the fact that tacit knowledge cannot be imbedded in a computer modelled system, human experts are needed to produce and constantly update the fuzzy logic engines behind these expert systems. However, it is still advantageous in the sense that it will extend the human capability and allow A.I. techniques to be developed to the next level. It is hoped that this approach will lead to further advancement of design evaluation techniques. In the end, any approach is only valid if it is accepted by the design community at large.

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Appendix A

FLOPS Code for Fuzzy Part Count Expert System

A.1 Introduction

This appendix gives an example of the code generated using FLOPS in implementing the Fuzzy Part Count Expert System :

```
:*************************************************************
:program PCR1.FPS - optimise concept for assembly ?
:all knowledge stored in rules
:total rules = 14 = number of nodes in decision tree + 3
:number of rules goes up as complexity of tree increases
:*************************************************************

string = "DFA\: part count reduction analysis.\n" ;
string + "Pcr1.fps has 14 rules - expert knowledge in rules.\n";
string + "compiling program pcr1.fps...\n" ;
message "<string>";

declare Answer
  reply str
  verify str ;

declare Hypothesis
  working str ;

:++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++

:tests whether part is main component
:rule r0
rule rconf 999 (goal Check whether part is the main component)
  IF (Answer)
    (in Hypothesis working.cf = 0)
  THEN
```

```
    reset ,
    input "Is the part in question the main component of the assembly (y/n) ?\n"
      1 reply lcase y n ,
    in 1 verify = "y" ,
    in 2 working = "part is main component" ;

:tests whether part is a functional part
:rule r1
rule rconf 999 (goal Check if functional part)
  IF (in Answer reply = <R> AND verify = <R>)
    (in Hypothesis working = "Is the part in question a functional part (y/n) ?\n")
  THEN
    reset ,
    input "can feature be transferred to other parts (y/n) ?\n"
      1 reply lcase y n ,
    in 1 verify = "n" ,
    in 2 working = "part cannot be eliminated" ;

:tests functional part
:rule r2
rule rconf  998 (goal Check if functional part)
  IF (in Answer reply = <R> AND verify = <R>)
    (in Hypothesis working = "Is part functional ?")
  THEN
    reset ,
    input "Is your part functional (y/n) ?\n"
      1 reply lcase y n ,
    in 1 verify = "y" ,
    in 2 working = "next stage" ;

:tests part movement
:rule r3
rule rconf  997
  (goal Check if functional part)
  IF (in Answer reply = <R> AND verify = <R>)
    (in Hypothesis working = "Is part functional")
  THEN
    reset ,
    input "Does part move relative to other parts in the assembly (y/n) ?\n"
      1 reply lcase y n ,
    in 1 verify = "n" ,
    in 2 working = "part cannot be eliminated" ;
```

```
:-----------------------------------------------------------
:tests part movement
:level hypotheses
:rule r4
rule rconf  998 (goal Check if part moves)
  IF (in Answer reply.cf = 0)
    (in Hypothesis working.cf = 0)
  THEN
    reset ,
    input "Does part move relative to other parts in the assembly (y/n) ?\n"
      1 reply lcase y n ,
    in 1 verify = "y" ,
    in 2 working = "next stage" ;


:tests material differentiation
:rule r5
rule rconf 999 (goal Check if part need to be of different material)
  IF (in Answer reply = <R> AND verify = <R>)
    (in Hypothesis working = "is material needed")
  THEN
    reset ,
    input "Does the part material need to be different from other parts in the
assembly(y/n) ?\n" 1 reply lcase y n ,
    in 1 verify = "y" ,
    in 2 working = "next stage" ;

:tests material property
:rule r6
rule rconf  998 (goal Check if material property warrant part material be different)
  IF (in Answer reply = <R> AND verify = <R>)
    (in Hypothesis working = "material warranted")
  THEN
    reset ,
    input "Is the use of this material warranted ?" 1 reply lcase y n ,
    in 1 verify = "y" ,
    in 2 working = "state the most important criteria/property of material" ;

:-----------------------------------------------------------
:tests whether property is important in function of part
:rule r7
rule rconf  997 (goal Check if important)
  IF (in Answer reply.cf = 0)
```

```
  (in Hypothesis working.cf = 0)
 THEN
  reset ,
  input "Can the property mentioned be achieved by other material (y/n) ?\n"
    1 reply lcase y n ,
  in 1 verify = "n" ,
  in 2 working = "next part" ;

:check part can be separate to allow assembly
:rule r8
rule rconf 999 (goal Check if assembly is hindered by part presence)
 IF (in Answer reply = <R> AND verify = <R>)
  (in Hypothesis working = "part is separate")
 THEN
  reset ,
  input "Does the part hinders assembly of other parts (y/n)\n"
    1 reply lcase y n ,
  in 1 verify = "n" ,
  in 2 working = "part is a candidate for elimination" ;

:checks part functionality when considering assembly
:rule r9
rule rconf 998 (goal Check if part is important to function)
 IF (in Answer reply = <R> AND verify = <R>)
  (in Hypothesis working = "no function")
 THEN
  reset ,
  input "Is the part functional (y/n) ?\n" 1 reply lcase y n ,
  in 1 verify = "y" ,
  in 2 working = "important part" ;

:checks for part separateness
:rule r10
rule rconf 999 (goal Check if part separate)
 IF (in Answer reply = <R> AND verify = <R>)
  (in Hypothesis working = "separate")
 THEN
  reset ,
  input "Is the part separate from others in the assembly ?\n" 1 reply lcase y n ,
  in 1 verify = "y" ,
  in 2 working = "candidate for elimination" ;

:-----------------------------------------------------------
```

```
:report part for elimination

:rule r11
rule rconf  0  (goal Terminal hypothesis verified - print trouble)
  IF (in Answer reply = <R> AND verify = <R>)
    (in Hypothesis working = <H>)
  THEN
    message 'The part is a candidate for combination/elimination <H>\n' ,
    stop ;

:report failure to find trouble
:part important
:rule r12
rule rconf  0  (goal Hypotheses all rejected - can not find trouble)
  IF (in Answer reply.cf = 0)
    (in Hypothesis working.cf = 0)
  THEN
    message 'The part is essential for the function of the assembly\n' ,
    exit

:------------------------------------------------------------

:backtracks if answer not verified
:rule r13
rule rconf 999 (goal Backtracks if hypothesis rejected)
  IF (in Answer reply = <R> AND verify <> <R>)
    (in Hypothesis working = <X>)
  THEN
    reset ,
    write 'Checked <X> NG  and backtracking\n' ,
    delete 1 ,
    delete 2 ;

:++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++

make Answer ;
make Hypothesis ;
message 'PCR1.FPS ready to run -\n' ;
:run ;
:**********************************************************************
```