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**Design space exploration using multi-instance modelling and its application for SMEs**

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# **Design space exploration using multi-instance modelling and its application for SMEs**

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A thesis submitted for the degree of Doctor of Philosophy

University of Bath

Department of Mechanical Engineering

March 2008

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## **Abstract**

Small and medium sized enterprises (SMEs) provide the backbone to the world's economy nowadays. These enterprises represent more than 90% of all the enterprises around the globe and are a major source for providing employment and entrepreneurship. They contribute as much value to the gross world product (GWP) as larger enterprises. However, when it comes to productivity growth, SMEs are falling behind.

The focus of this thesis is on machine-manufacturing SMEs especially those which design and develop packaging machinery. Their lack of productivity growth is partly due to the fact that these enterprises have relied upon natural evolution of their existing machine designs and often do not have the resources to fully analyse them. For this reason, their design knowledge regarding products is often limited. The design process models, which are normally successful in larger manufacturing firms, are often not utilised in SMEs due their inherent complexity and the longer development times required. SMEs need simpler techniques to develop and refine their products that can be easily understood and implemented in these firms.

This thesis presents a novel and easy to use technique which is based upon one-off instances (variants) of established working designs. It investigates how the design space around these instances can be represented and explored. The exploration can help in increasing design knowledge regarding current products and this can further lead to: identifying similar and dissimilar designs, locating better design solutions, determining design sensitivity and providing a basis for refining existing designs. This process strongly depends upon forming a “representation” of the design space and clearly the greater the level of detail of the representation, the better investigation that can be performed. The approach has been successfully demonstrated with a number of case studies.

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## Terminology

The following table introduces description of some of the terms that have been used in this thesis.

Term	Description
<b>Design Knowledge</b>	Design knowledge encompasses the performance requirements, physical constraints, economic drivers, technological issues and any decision processes that have influence over the current product design (Hicks <i>et al.</i> 2001b)
<b>Design Space (Solution Space)</b>	Design space is the space in which all possible solutions (feasible or unfeasible) lie. It may or may not be bounded by limits imposed on design parameters.
<b>Design Variants (Instances)</b>	Variants of a design can be formed by varying certain aspects of a design such as the sizes and arrangements of parts and assemblies within the limits set by previously designed product structures (Pahl <i>et al.</i> 2007).
<b>Topology</b>	It is the description of how spatial features are connected to each other in any design.
<b>Morphing (Parametric morphing)</b>	Morphing can be defined as a process of generating in-between design solutions among the given design variants and is accomplished by interpolating between the key parameters of these variants. The given variants possess same topology.
<b>Interpolated Space</b>	Interpolated space is the solution space generated as a result of parametric morphing.
<b>Design space exploration</b>	It is the activity of searching design space in order to identify (discover) better solutions.
<b>Rationalisation</b>	Rationalisation of a design can be defined as the organisation of its variants according to their performance capabilities so that redundant variants are eliminated.
<b>Sensitivity</b>	The ability of a system to accommodate small changes in setup parameters or dimensional tolerances without changing its output or performance values.

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<b>SMEs</b>	SMEs stands for small and medium sized enterprises employing less than 250 people and annual turnover less than 50 million Euros (European Commission 2005).
<b>Visualisation</b>	Visualisation (often referred as Scientific visualisation) seeks to provide insightful representations for difficult and complex problems and helps in solving problems (Jones 1994).

---

## Chapter 1: Introduction

Small and medium enterprises (SMEs) play a vital role towards the world's economy by contributing to entrepreneurship, employment and innovation (Morrison *et al.* 2003). This claim can be backed up by the fact that most of the businesses around the globe are small to medium sized enterprises which employ less than 250 people. There are around 23 million SMEs in the European Union, which provide 65 million jobs and represent 99% of all enterprises (European Commission 2005). In the US, more than 99% businesses are small (Small Business Administration 2007). In Australia, these enterprises add to around 96% of non-agricultural industries (Australian Bureau of Statistics 1999). In the UK itself, at the start of 2006 there were an estimated 4.5 million business enterprises, 99.9% of which were small to medium sized (DBER Reform 2007). SMEs account for 58.9% of all UK employment and 51.9% of UK's estimated business turnover of £2,600 billion. Thus these enterprises make up a significant portion of the world's economy.

SMEs have certain strengths when compared to larger firms (Ghobadian & Gallear 1997). These enterprises operate in a very flexible and dynamic environment where changes can be introduced within very short timescales. The results of these changes are also more visible within a short span of time in these companies. They are comparatively less bureaucratic and have simpler and effective communication channels. There is people oriented culture of learning and change. Management is more likely to be directly involved with the customers and thus provide rapid execution and implementation of decisions (Antony *et al.* 2007). Overall these enterprises are more innovative and responsive to changing market needs.

The focus of this thesis is the manufacturing sector among SMEs. In the UK, the manufacturing sector among these SMEs represents 325,875 enterprises (DBER Reform 2007). Even in the USA, there are around 400,000 small manufacturing firms that employ less than 500 employees (US Department of Commerce 1998). These enterprises contribute as much value as larger enterprises, however, they do not experience same productivity gains (Stauffer & Kirby 2003). Some researchers (Maupin & Stauffer 2000) believe that their productivity growth is almost half when



compared to larger manufacturers. This is mainly due to a number of challenges that these enterprises face as described in the following section.

## **1.1 Manufacturing SMEs: current challenges and issues**

The major challenge that SMEs face in relation to their lower productivity growth is the lack of resources available to these firms (Stauffer & Kirby 2003). There is often a lack in terms of cash flow which means that there is limited budget for infrastructure (Information Technology, for example), staff training, and incentive or reward programs (if any) for employees. Due to inadequately trained workforce, there are cases when a single person fulfils multiple job duties (Maupin & Stauffer 2000). In larger manufacturers, on the other hand, these jobs would be handled by various trained engineers thus increasing the overall productivity and quality of products.

As far as product development is concerned, many of the SMEs have relied upon the natural evolution of their existing product designs (Hicks *et al.* 2001a). The products are often developed based upon the empirical knowledge gained through years of experience. The product development processes in many cases are ill defined and may not explicitly exist at all (Stauffer & Kirby 2003). Traditional trial and error methods are still employed which involve continual refinement and development of particular aspects of an existing machine design to achieve a revised set of performance requirements. Changes to part of original design in isolation can lead to problems with other machine assemblies, which then may be solved in isolation and this process continues.

These enterprises are also opportunistic in nature which means that they are more individual customer focused than market focused. There is often a common practice for the introduction of new products for every new customer requirement with little regard for compatibility with other products currently in production (Berti *et al.* 2001). Also little attention is given to product development or long-term planning to bring new products to the market. This often leads to a collection of essentially one-off designs (or a large portfolio of products (Maupin & Stauffer 2000)), which then have to be supported during their operational lives.

Finally, due to the short timescales available to the design teams of these enterprises, the design activities and associated design changes are not properly documented, which means that vital information regarding product's life cycle is not available for

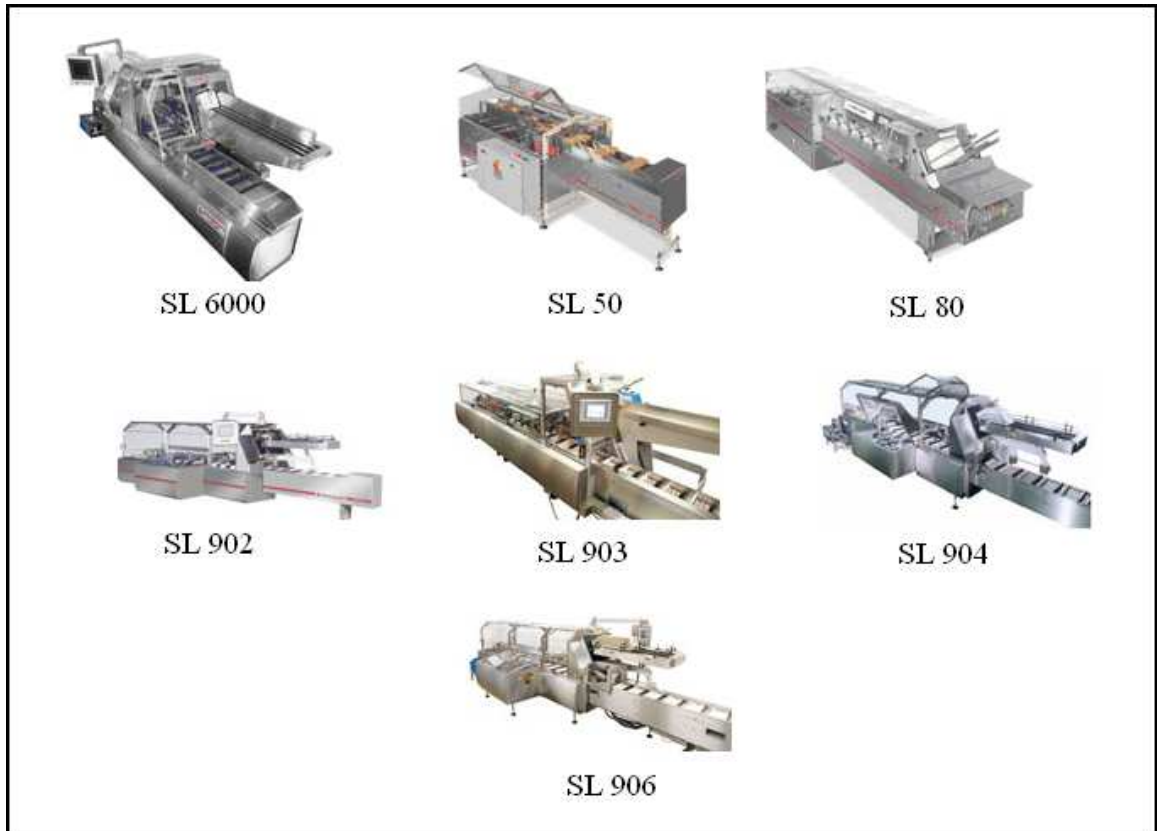
future refinements (Hicks *et al.* 2001b). The situation is exacerbated by the lack of human resources and expertise. Some of these companies also rely on key persons' knowledge and expertise for supporting design activities. This can result in serious problems when these individuals are no longer part of the design team and the design knowledge is unavailable.

### **1.1.1 Packaging machinery manufacturers**

One example, where the above stated issues are prevalent, comes from the packaging machinery manufacturing industry in the UK. It is mainly dominated by small and medium enterprises with over 350 manufacturers and its market has been valued at around £429.4 million pounds (Market and Business Development 2005). Packaging is a big business in the UK with a turnover of 9.6 billion pounds (The Packaging Federation 2006). It represents approximately 0.7% of total UK GDP (gross domestic product) and 5.5% of the manufacturing sector GDP.

Packaging machinery manufacturing is also a highly competitive global industry with machines being constantly redesigned to accommodate ever changing packing styles. There is little time to make these changes (Buske and Liu 2005) and once re-commissioned there is no room for error. Many of the machines produced are the result of incremental improvements which are mainly driven by empirical experimentation (McPherson *et al.* 2004). Thus the fundamental understanding about how these work is largely absent.

There are often cases of particular design variants which are specifically created to satisfy individual customer needs. This can result in a large portfolio of products without any real rationalisation. The variants are normally supported throughout their operational lives which puts extra burden on the internal costs that these companies incur. Figure1-1 shows such an example of seven design variants of an end load cartoning machine that are currently being supported by a packaging machinery manufacturer. The main purpose of these variants is to erect packaging cartons from a pre-folded, flattened state and the machines essentially differ in the production rates, size of cartons that can be handled and degree of automation (further discussed in chapter 5).



**Figure 1-1 Design variants of an end-load cartoning machine source: [www.bradmanlake.com](http://www.bradmanlake.com)**

Changing government legislation and environmental issues are also forcing these manufacturers to reduce waste and use recycled material for packaging (Mullineux *et al.* 2007). There is a usual practice to redesign current machine designs in order to accommodate products made up of thinner/lighter grade of materials. Redesigning existing machines can be a difficult task due to their inherently complex designs. This process is also frustrated by the difficult and ill-defined properties of the products which are handled with these machines. This may require significant levels of resources in order to re-establish the necessary elements of design knowledge regarding a particular machine and process (Halon *et al.* 1998). There is also a lack of supportive design/redesign methods available to these companies that can provide rapid investigation, modelling and analysis of existing machines and new or altered machine configurations (Hicks *et al.* 2001b).

## **1.2 Research aims and objectives**

Machinery producing SMEs have to constantly redesign their products due to several factors including changes in customer requirements and government legislation. Redesigning existing products can be a difficult task owing to the complex machine designs and lack of supportive tools. These enterprises not only struggle with the limited resources but also lack in-depth knowledge regarding their products. This thesis presents a novel technique that can help SMEs to increase their fundamental knowledge about their products and helps to provide a sound basis for redesign activities. The technique is specifically tailored to meet the needs of SMEs. The main idea underlying this research work is that the existence of examples of workable designs (variants) can be used to perform a simplified investigation of the design space (formed by base designs) involved. Such an investigation, which is based upon design space exploration, can aid a designer in better understanding the existing designs and further help in locating better design solutions (Singh *et al.* 2007a).

### **1.2.1 Aim of the research**

The overall aim of this thesis is to propose and demonstrate a novel and easy to use technique which can help SMEs to investigate their designs and the related design space with the intention of increasing their current design knowledge.

### **1.2.2 Objectives**

In order to achieve the above stated aim the following key objectives have been identified and are discussed in this thesis.

1. To investigate current product development practices of SMEs with the aim of capturing factors that are hindering their development processes and to identify their current needs.
2. To investigate and critically appraise previous research work that has been undertaken to improve product development in SMEs.
3. To investigate different tools and techniques which are available to analyse machinery design in general, and their relevance to support product development activities in SMEs.
4. To investigate the suitability of design space exploration and various visualisation techniques for assisting product development in SMEs.

5. To propose an easy to use approach that can help SMEs to increase their current design knowledge and provide a basis for improving/refining their product designs.
6. To investigate and demonstrate the applicability of the proposed approach to meet current needs of SMEs through case study examples.

### 1.3 Overview of the thesis

The structure of this thesis is discussed below and a graphical overview of the chapters is depicted in figure 1-2.

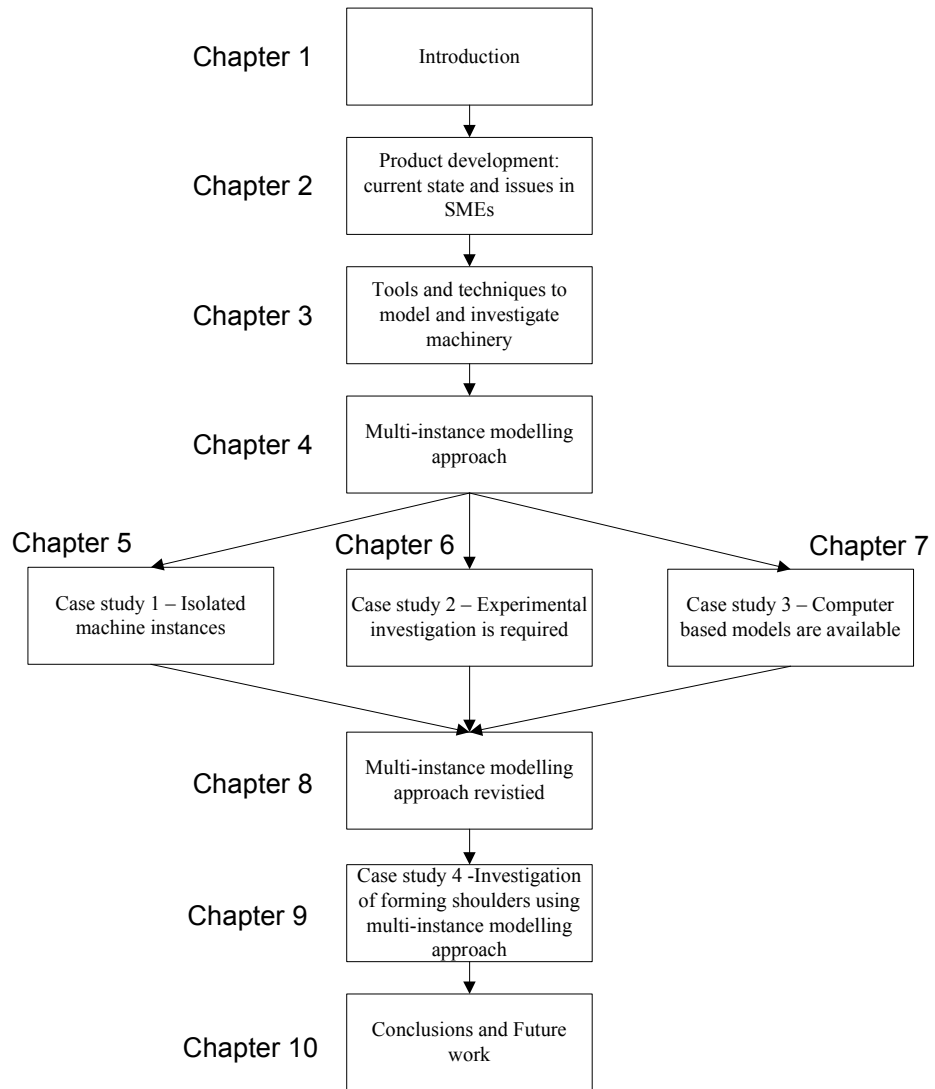


Figure 1-2 Structure of the thesis

The following gives an overview of each chapter in the thesis:

## **2. Product development: current state and issues in SMEs**

This chapter initially describes the need for following a systematic product development approach to realise a successful product. The current design practices of SMEs are then highlighted. Various factors that are hindering effective product development in these enterprises and their current needs are identified. The chapter then explores several techniques and methods that can be employed to improve product development in general. The suitability of these techniques in the context of SMEs is then examined. [Objectives 1 & 2]

## **3. Tools and techniques to model and investigate machinery**

This chapter discusses various tools and techniques that are useful to model and investigate machinery. The suitability of these tools for SMEs is also examined. Finally a survey of design visualisation techniques is presented to highlight the application of effective visualisation in aiding a designer's decision making capabilities. The chapter also comments on the implications of these techniques for SMEs and what is ideally required if such a technique has to be implemented in an SME. [Objective 3 & 4]

## **4. Multi-instance modelling approach**

This chapter introduces a multi-instance modelling approach. A parametric morphing technique is initially introduced to generate interpolant designs between available instances of a design. A complementary visualisation technique is also proposed here, which is used to represent the design space constituting the generated interpolants. This technique represents the design space in the form of one or more surfaces. Both the morphing and visualisation techniques are then combined in a multi-instance modelling approach. This approach helps in exploring the design space existing around various variants of a design and can further assist in identifying better solutions. Three different situations are also identified in this chapter to which the proposed approach can be applied. These situations are: isolated machine instances, when experimental investigation is possible and computer based models are available. These are dealt with in the following case study chapters. [Objective 5]



## **5. Case study 1 – Isolated machine instances**

This case study describes a situation when isolated machine instances are present. However the design knowledge regarding these instances is not fully available to a designer. An investigation based upon the proposed approach is applied here that helps in identifying the redundant variants. [Objective 6]

## **6. Case study 2 – Experimental investigation is possible**

This case study highlights the use of proposed approach in a situation when machine instances are present and experimental work can be undertaken to establish their performance characteristics. A single machine system is investigated here for this purpose. Initially a simplified investigation (using a limited set of data) is made which shows how the system behaves. A “model” of the system is then generated and this provides the basis for a greater level of investigation. In particular, it is used to explore the sensitivity of the machine to changes in its set-up parameters. The proposed approach is applied to this situation by considering known working set-up configurations of the machine as different instances of a successful design. [Objective 6]

## **7. Case study 3 – Computer based models are present**

This chapter presents the application of the proposed approach when computer based models are available to the designer. These models can predict the performance characteristics of a machine/mechanism system. The applicability of the proposed approach in this case is illustrated by the instances taken from a catalogue of standard mechanisms to find a close match to a given requirement of path matching. The proposed approach helps in identifying similar and dissimilar designs, finding better design solutions and determining design sensitivity. [Objective 6]

## **8. Multi-instance modelling approach revisited**

Based upon the findings from the case study examples, this chapter provides an overview of the proposed approach. The application of the approach, in the three scenarios identified in chapter 4, is also discussed here. [Objective 5]

## **9. Case study 4 – Investigation of forming shoulders using multi-instance modelling approach**

This chapter presents an application of the proposed approach where all three scenarios identified (chapter 4) are present. A vertical form fill and seal (VFFS) machine is investigated for its performance capabilities. The proposed approach helps in understanding how the thickness of a certain material affects the performance of a particular forming shoulder which is a crucial component of the VFFS machine.

[Objective 6]

## **10. Conclusion and future work**

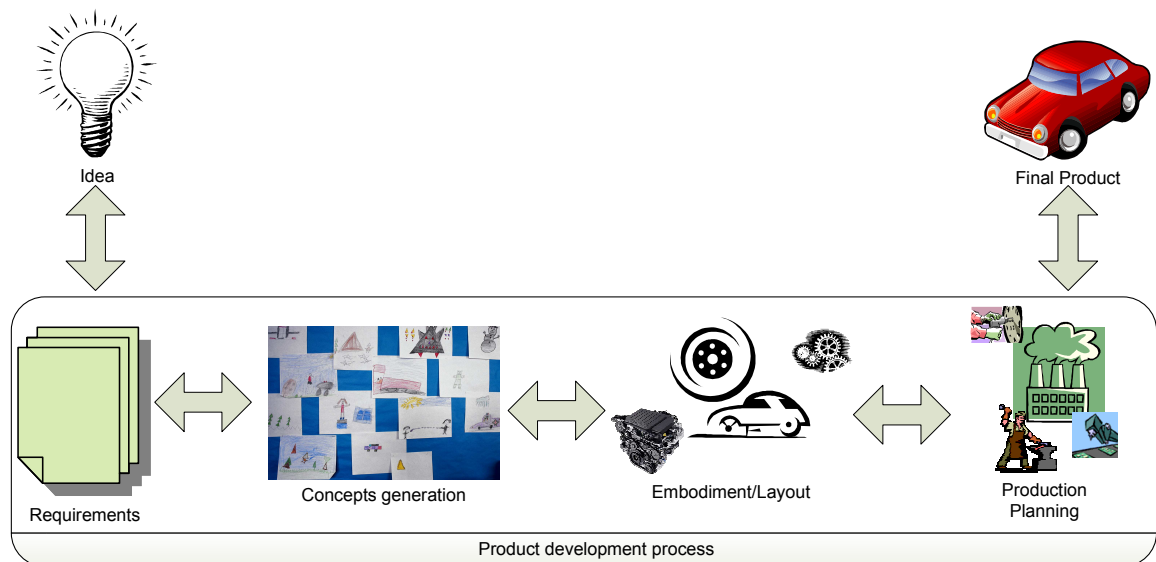
This chapter draws conclusions regarding the current work and discusses them with respect to the aim and objectives. The limitations of the proposed method are highlighted and potential areas for further research are identified.

## **Chapter 2: Product development: current state and issues in SMEs**

The main area of concern of this research work is the product development in SMEs (Small and Medium Enterprises) especially machine manufacturing firms. This chapter presents background literature that is relevant to the current research work. The chapter begins with a brief description about the product development process as engineering is essentially concerned with developing and supporting a product that satisfies some of the human needs. The views of several authors about this development process are presented here. The chapter then identifies the current design practices of SMEs. Several factors hindering a successful product development are identified. A survey of the techniques proposed to improve product development in SMEs is done. The chapter concludes by discussing the suitability of available techniques to support product development in SMEs and what further needs to be done.

## 2.1 Product development

Product development in engineering design is the process of converting an idea to an actual product (figure 2-1). This process normally starts with a list of requirements that a customer wants to see in a final product. The designer follows a number of procedures to conceive different ideas that are capable of fulfilling the requirements. These ideas are then evaluated against initial requirements and a best idea is chosen. This idea (often termed as a ‘concept’) is then given a definitive layout. A production plan is generated and full scale production is finally commenced. This design process is iterative in nature and design knowledge is generated as a designer proceeds through a number of iterations. The solution thus produced at the end has evolved through various stages of the design process and also strongly depends upon the designer’s own knowledge, available resources and experience of the field.



**Figure 2-1 Product development process**

Normally a systematic approach or a model (sequential or iterative) is followed to realise a product. This systematic approach is often termed a design process model. There are different design process models proposed in the literature such as those of French (1971), Pahl *et al.* (2007), Pugh (1991) and Ullman (2003). The aim of these design process models is to guide a designer through a number of procedures so that a successful product can be realised, quickly and directly. The number of activities in these models varies depending upon the methodology used as every author interprets

the design process differently. However, often there is a degree of commonality that can be seen across these models. Generally there are four stages present in all of the models proposed.

### **Clarification of the task or specification**

This is the first activity of any design process model which normally aims at identifying customer requirements about the final product and constraints on the design process such as technology, material availability and economical considerations (Pahl *et al.* 2007). A requirement list or, in other words, a product design specification (Ullman 2003) is usually formed at the end of this stage which serves the basis for the following activities. The design solutions, formed later, are evaluated against this requirement list. Some of the models such as Ullman (2003) and Pugh (1991) also explicitly advocate the need for conducting market analysis and data collection before the development of a product can be initialised which is essential to see if the product launch can be successful, in time and profitable for the company in the long run. It also involves assessing the competition that will be faced in the future.

### **Conceptual design**

Once the task is clarified, a conceptual design of the product takes place. This activity aims at identifying the principle solution and this is achieved by determining functions and their structures. The overall function and sub-functions are derived from the specification and their solution principles are identified. These solution principles can then be combined in accordance to the function structure which results in a principal solution (often referred to as a 'concept'). A number of concepts may be generated here and these are then compared to the original requirement list produced earlier on. The concepts that do not conform to this list are dropped. The rest of them are then compared according to specific criteria such as technical nature or rough economic factors (Pahl *et al.* 2007). The best concept is then taken to the next stage.

### **Embodiment design**

This stage is concerned with the development of the chosen concept by determining its layout and form. A preliminary layout of the concept is initially created. The

designer may come up with a number of variants, which may then be compared and evaluated against the list of requirements. The most promising layout is selected and may further be improved by adding geometry and technology for secondary functions. The end result of this stage is a specification of a layout.

### **Detailed design**

The concept is finalised in the last of the four identified stages which is often referred to as detailed design. Here details such as dimensions, surface properties, assembly sequences and production processes that are required for production to take place are determined. The output of this stage is normally detailed drawings and part lists in the form of production documentation.

These four stages of the design process model can be found in most of the sequential design process models proposed by various researchers. One of the first authors to model the design process as a series of discrete stages was French (1971). His proposed model is shown in figure 2-2 (part a). A widely acclaimed design process model (across continental Europe) is proposed by Pahl and Beitz (1984) (figure 2-2, part b). This model is divided into four stages which are almost in agreement with the four stages described earlier. Another design process model, given by Pugh (1991), is shown in figure 2-2 (part c). He describes the 'design core' as a central activity that constitutes a product development process. There are six stages to this process model that are market, specification, concept design, detail design, manufacture and sell.

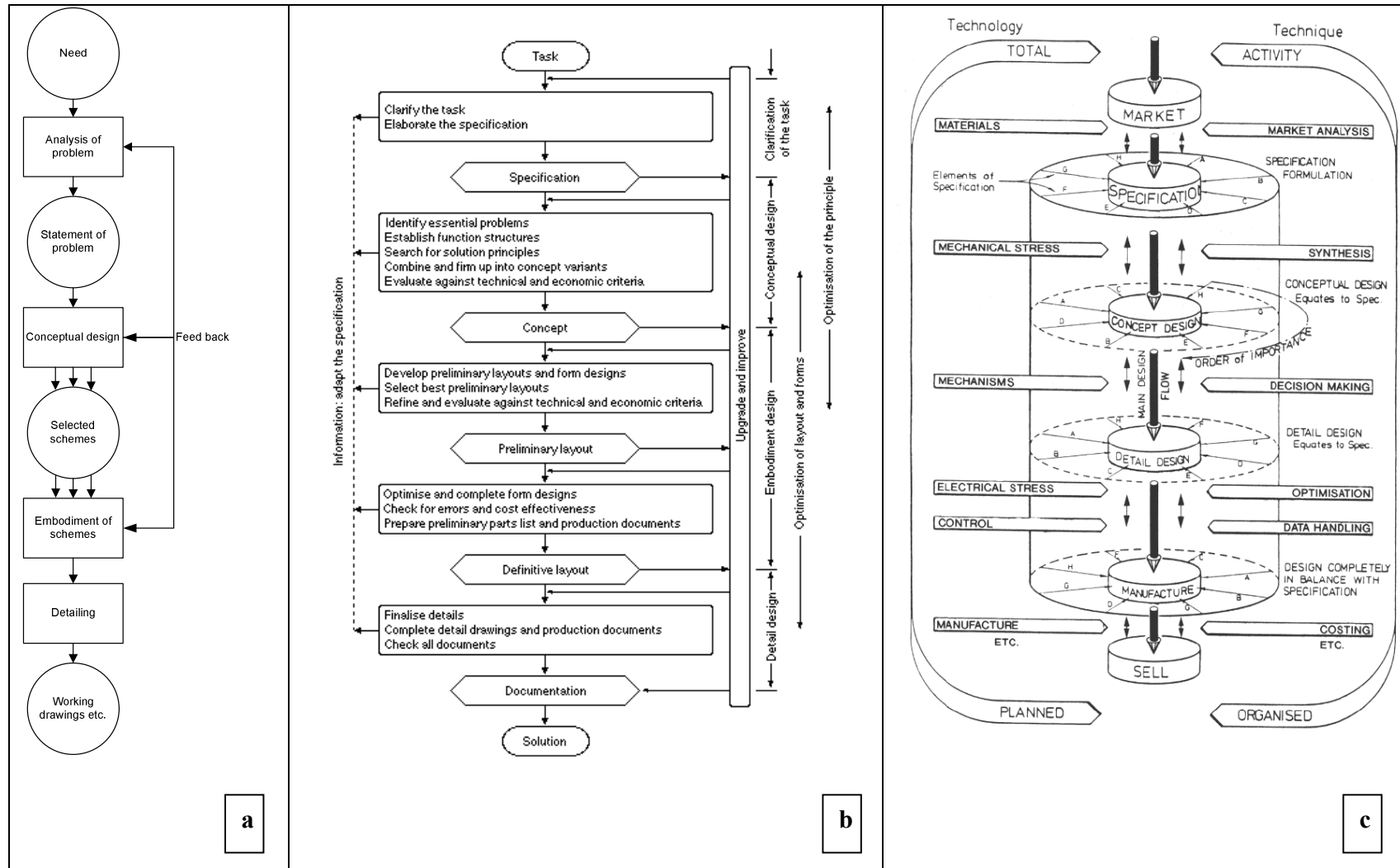


Figure 2-2 Various design process models sources: (a) French (1971), (b) Pahl & Beitz (1984), and (c) Pugh (1991) respectively

### **2.1.1 Benefits of following a systematic product development process model**

Some of the benefits of following a systematic design process model, highlighted in the literature, are listed below. A systematic design process model:

1. Helps to organise the design process effectively and efficiently by providing procedural tools to the designers.
2. Helps in improving the product quality by providing a step-by-step approach of constant testing and evaluation.
3. Helps in reducing the time to market by improving the quality and speed of the designer's work.
4. Helps in reducing the product development cost by using efficient methods and optimising the resources.
5. Helps in generating alternatives and their evaluation against the requirements.
6. Helps in keeping better records and more accurate knowledge for the reasons of the past work.
7. Provides an effective way to rationalise the design and production process.

Thus a systematic design process model is useful in realising an effective and efficient product development. The need for having such a model has been highlighted by various researchers throughout the literature. It is also important to understand the nature of the design activities carried out in various parts of the industry. These can be different, depending upon the type of the design problem involved. The designer may follow some stages of a design process model and omit others. For example, while carrying out a redesign work on previous design, the designer may not need to generate new concepts. He or she can simply adapt to the older concept and do certain changes to the subsystem level. However, it is not easy to clearly define the boundaries of different types of design activity as there is always some overlap. The following section aims at capturing the extent of different design activities carried through out the industry.



### **2.1.2 Types of design activities**

Numerous researchers have tried to categorise different design activities carried out in industry according to their interpretation of the design process. The various categories proposed by different researchers include original design, adaptive design, and variant design (Pahl *et al.* 2007), static product and dynamic product (Pugh 1991), evolutionary design and non-evolutionary design (French 1988), selection design, configuration design, parametric design, original design and redesign (Ullman 2003). Hicks (2001) evaluates and categorises some of these definitions by combining them according to similarities and removing the duplicates. Various classes of these activities are summarised in the table 2-1. He proposes the following three types of primary design activities that encompass most design activities.

#### **Original or creative design**

This class of activity involves elaborating or developing an original solution principle for a process, component, plant, machine or assembly previously not in existence.

#### **Adaptive, non-routine design or redesign**

This activity involves adapting a known system or the modification of an existing product to a changed task. It often requires original designs of individual assemblies or components.

#### **Variant or routine design**

In this class of activity, all the design and the performance variables are known *a priori*. The aim is to determine the values for the structural variables. Here function and the solution principles of a system remain unchanged. However, the size and arrangement of certain aspects of it may change.

Other activities such as dynamic or non-evolutionary design and static or evolutionary design are merely a combination of original and adaptive or adaptive and variant design respectively (figure 2-3). This classification of a design task also depends on whether the

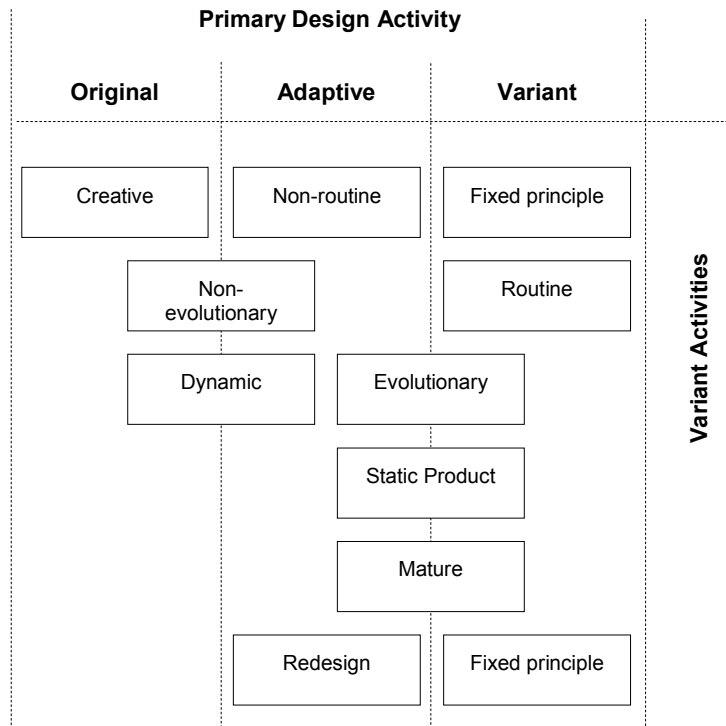
design specification relates to a system, an assembly or even a subassembly. For example an overall product can be of adaptive design in nature but some of its individual subassemblies may require original design.

The spread or division of the design activities has been studied by several authors. Prebil *et al.* (1995) argue that the adaptive and variant design activities correspond to 70% of the design work that is carried out in industry. Pugh (1991) indicated that 80% of a typical design is adaptive design. Pahl and Beitz (1984) suggested this division as 55% adaptive design, 25% percent on the original design and the remaining 20% is variant design. Tseng and Jiao (1997) note that evolutionary (evolving from existing products) product design is frequently adopted in practice instead of designing a product from scratch. This enhances the reusability of knowledge. Wang *et al.* (2005 a & b) argue that variant design is a common practice across the industry to relieve the designer from iterating similar design processes, hasten product development, reduce cost and finally enable manufacturing companies to develop individualised product based upon existing mature designs. This is also backed up by the fact that design uncertainty (uncertainty related to knowledge of a product design's final attributes such as materials, geometries and manufacturing processes) is largest for entirely original designs and least for variant design (Fitch & Cooper 2005). Thus it is not surprising given that the most of the products that are launched in the market are modifications of existing design concepts.

From the above discussion, it can be concluded that adaptive and variant design form the major portion of the design work that takes place in industry. The following sections are concerned with product development in small and medium enterprises (SMEs). The research focus is mainly on manufacturing firms that design and produce machinery. The aim here is to identify the extent to which systematic product development practices are being adopted in these firms, the types of design activities that are mainly carried out and factors that are hindering their success.

**Table 2- 1 Classification and definition of design activities Source: Hicks (2001)**

Type of Design Activity	Definition	Author/source							
		Pahl & Beitz	Ullman	Pugh	French	Gero	BS 7000	VDI 2221	Ulrich & Eppinger
Original	Elaborating an original solution principle for a system with the same, a similar or new task	•	•					•	
Adaptive	Adapting a known system to a changed task	•						•	•
Creative	An original design solution to an existing or new problem		•			•			
Variant / customized	Varying the size and/or arrangement of certain aspects of a chosen system	•							•
Fixed Principle	Solution principle and design are the same dimensions of individual parts are changed	•							
Redesign/ Development	The modification of an existing product for a new set of requirements		•			•		•	
Routine	Design of the artefact can be represented by a system/network of rules and equations		•						
Non-routine	Not all of the design and structure variables, performance and behaviour variables are known at the outset					•			
Mature	Complete knowledge about the design problem exists and design focuses on aesthetics and optimisation		•						
Static Product	Design changes are incremental or non-existent			•			•		
Dynamic Product	Design changes are innovative and frequent			•			•		
Evolutionary	Continuous product improvement to meet slowly changing needs or evolving science and technology.			•	•		•		
Non-evolutionary	Deliberately innovative design using new technology				•				
Catalogue	Selecting and assembling of catalogue items						•		



**Figure 2-3 Primary design activities and their combinatorial variants Source: Hicks (2001)**

## **2.2 Product development in SMEs**

Product development in SMEs has been an area of concern for a number of researchers (Berti *et al.* 2001; Cederfeldt & Elegh 2005; Hicks *et al.* 2001b; Maupin & Stauffer 2000; Stauffer & Kirby 2003). These researchers have highlighted a number of issues that need to be tackled in order to increase the productivity and profits of these firms. The issues include: lack of resources available to SMEs; their lack of design knowledge regarding products; ill defined product development processes and their large portfolio of products. These are further discussed in the following sections.

Stauffer and Kirby (2003) conducted a survey on smaller US manufacturers. The objective of the study was to gain a better understanding of the product-development needs of smaller manufacturers. There were 61 smaller manufacturing companies surveyed in 10 states across the US. These companies were from mechanical and electro-mechanical domains and employed from 20 to 200 employees. The important finding of their research work is that in order to increase the competitiveness of these manufacturers there is a need to improve project management and product refinement along with reducing the cost of the product and processing. Stauffer and Kirby also highlighted the fact that lack of resources and often ill defined product development processes are hindering the productivity of these firms.

Cederfeldt and Elgh (2005) conducted a study on the current state, potential need and requirements of design automation at eleven SMEs. They argue that one way to gain competitive advantages is to adopt an approach where products are based upon a prepared design. This means that if some of the work related to these products and design tasks is automated, the design process can become more effective and efficient. Their study revealed that there is currently a varying state of design automation in SMEs. This ranges from the systems where design knowledge is fully integrated and orders are automatically processed with generation of machine code for manufacture and BOM-lists for assemblies, to the use of spreadsheets for specific design tasks. The study also expressed the need for a more efficient and effective design processes.

Maupin and Stauffer (2000) highlight the problem of product proliferation in SMEs. They argue that these manufacturers are often less profitable when compared to large manufacturers. There is a common practice of instant introduction of new products, which is done with a little regard for compatibility with other products in production. The result is a large portfolio of products. The other challenges to SMEs highlighted by Maupin and Stauffer include lack of resources, lack of an adequately trained workforce and ill defined product development processes. They also indicate the need for simple and easy product development processes. The complex design processes that are normally successful in larger manufacturing firms are not utilised in smaller firms. One reason for this is that their technical team want to see immediate reduction in product cost or time required, which may only be long term goals with available design process models.

The problem of product proliferation in SMEs is also illustrated by Berti *et al.* (2001). According to them, these enterprises are more customer focused (concentrating on getting product to the customer) than market focused. There is little attention given to product development or long-term planning to bring new products to the market. This results in a large product portfolio without any real rationalisation. The improvement of product development practice can be reached only with less complex modification of processes suitable to small manufacturers who are usually short of financial resources and lack a broad range of technical skills. Yan *et al.*(2007) expressed their concern on growing complexity within product development process due to ever changing needs of customer and the high pace of change of current product markets. They suggest that the problems for SMEs are amplified due to their common practice of instant introduction of products.

Schofield and Kelly (1997) highlight the lack of a formalised database and product coding/classification system in SMEs that results in a tendency for designers to create new designs instead of utilising existing ones. This means increased cost of manufacture and inventory. They argue that product rationalisation based upon effective

coding/classification techniques, on the other hand, can reduce lead times, reduce manufacturing costs and facilitate a more effective spares operation.

O'Donnell *et al.* (1996) describe the lack of company-wide product structuring models in many small manufacturing enterprises. They also discuss the issues of unnecessary number of variants in these firms. The variants, which are determined during the initial design phase, can increase dramatically and in a poorly controlled manner due to efforts to satisfy every potential customer and the increasing global market requiring country specific products. They highlight the need for a corporate product structure model that can provide help to manage variants, promote design reuse and support the tasks of configuration design and management.

Hicks *et al.* (2001b) state that majority of machinery manufacturing SMEs have relied upon natural evolution of their existing machine designs to meet the performance requirements demanded by the customers. This natural evolution involves continual refinement and development of particular aspects of existing machine design. However, the problem with this traditional approach is that revisions to the designs are often carried out within shortened development times, with a little consideration being given to the effect of the changes on other aspects of the machine. It often leads to problems with other machine parts or assemblies, which again may be solved in isolation. Lack of documentation is another impeding factor here. Due to shortened time scales the important design activities and associated changes are not necessarily documented in these firms. Thus the company becomes reliant on key persons' knowledge regarding the history of a particular machine development. This design knowledge is lost when these individuals leave the enterprise and can result in serious problems.

### **2.2.1 Important findings from the literature**

The following points summarises the factors mentioned above, which are hindering effective product development in SMEs:

1. SMEs, in general, lack in resources in terms of cash flow, number of employees and adequately trained workforce.

2. These enterprises are opportunistic in nature and very much individual customer focused. Due to this, there is often a practise of instant introduction of products with little regard for compatibility with other products in production. This results in large portfolio of products.
3. There is also a lack of design knowledge due to natural evolution of product designs (mainly redesign and variant design activities carried out) which is normally based upon trial and error approach. This is further exacerbated by lack of documentation and reliant on key persons' knowledge regarding the history of a particular design development which is lost when these individuals leave the enterprise.
4. The design process models (discussed in section 2.1) which are normally successful in larger manufacturing firms are often not utilised in SMEs due their inherent nature of complexity and longer development times required.

There are also some basic needs of SMEs that have been highlighted in the literature reviewed above. These can be summarised as following:

1. Most of the researchers agree that there is a need for a simpler technique to develop products that can be easily understood and implemented in these firms.
2. Such a technique should also help designers to investigate existing ranges of products in order to tackle product proliferation.
3. These enterprises also need to increase their understanding (design knowledge) regarding their current product designs.
4. Some authors have stressed a need to improve current product refinement methods adopted by these enterprises.
5. Several authors have advocated the need to promote design reuse. This means that new designs should be based upon existing designs. It can help in cutting the internal costs incurred by these firms.

The following sections discuss some of the relevant techniques that can be used to improve product design and development in SMEs. Some of these techniques are successfully implemented in larger manufacturing firms. The aim is to capture the extent to which these techniques can be helpful to SMEs.



## **2.3 Relevant techniques to improve product development**

There have been several techniques proposed in the literature in order to improve product development in manufacturing companies. Whilst most of these techniques are aimed at larger companies, some of them have been applied to SMEs. The following sections discuss a few of these techniques.

### **2.3.1 Standardisation**

This is the basic approach that has been adopted worldwide for reducing product variety and thus manufacturing costs. Standardisation means the use of the same component in multiple products (Ulrich 1995). By standardising different parts of a product, one can easily automate its production. Standardisation also helps in after sales service, part interchangeability and re-manufacturing. This concept was first introduced by Henry Ford, who revolutionised production by drastically cutting manufacturing costs. The lower cost is possible as standardised components can be produced in high volumes.

### **2.3.2 Modular design**

Using this concept, a complex product design is broken into smaller groups of standard components. These modules (developed in the early design stages) are reusable in different variants of the product and can be manufactured independently. Hence the number of products that can be developed using the modules depends upon the number of module versions and variants and their physical coupling characteristics (Jose & Tollenaere 2005). This concept of modularity was first introduced by Star (1965). There are several methods for grouping or distinguishing modules (Dahmus *et al.* 2001; Hata *et al.* 2001; Sudjianto & Otto 2001) and representing a modular system (He *et al.* 1998; Kusiak & Larson 1995) proposed in the literature that cover different domains and dimensions of manufacturing engineering.

### **2.3.3 Product platform development**

Meyer and Utterback (1993) define a product platform as “a platform that encompasses the design and components shared by a set of products”. A similar description in terms of product rationalisation is given by Ericsson and Erixon (1999), “*The product platform*

*philosophy mainly concentrates on rationalisation by identifying parts or subsystems of the products that should be kept as common units*". Thus a platform is a standard module that can be used among different products, and it consists of several other parts that are common in different products across the family. Other components are then added onto a platform to generate different varieties of the products. A simple example of the product platform is a suspension system that is used by car manufacturers among the different varieties of the cars. Using the platform based product design, one can emphasise the use of common technology, manufacturing process and knowledge that is shared among the different products in a family. Hence the platform provides a technical basis for catering to customization, managing varieties and improving existing capabilities (Jiao & Tseng 1999).

#### **2.3.4 Development of a product architecture**

Robust product platform architecture can bring an important competitive advantage to a company (Martin & Ishii 2002). The product architecture is defined by Ulrich (1995) as the "*scheme by which the function of a product is allocated to physical components*". The author further describes the product architecture as: 1) the arrangement of functional elements; 2) mapping from functional elements to physical components; 3) the specification of the interfaces among interacting physical components. There are two distinct platforms identified by Ulrich namely modular and integral. In modular architecture, there is a one-to-one mapping from functional elements in the function structure to physical components of the product. De-coupled type interfaces are specified so that changes made on one component do not lead to changes in other. Integral architecture, on the other hand, exhibits a more complex (one-to-many or many-to-one) mapping from functional elements to physical components and the interfaces between components are coupled. The modular architecture is suitable for supporting product variety as it provides the flexibility of carrying out localised design changes with the minimum possible number of components involved. These design changes are often associated with the product's function. In actual practice, however, a mixed type of architecture may be found in the products (Ulrich 1995).

## **2.4 Application in SMEs**

The following sections briefly discuss how the above stated approaches have been implemented in the SMES.

Schofield and Kelly (1997) describe the development of an in-house software system to support product rationalisation and lead time reduction for ball valve production. For the purpose of rationalisation, they initially identified a standard range of ball valves using a parametric approach. A spreadsheet was developed that determined the parameter values for each of the nominal sizes. The next stage was to develop a coding/classification system that facilitated the retrieval of similar designs. For this, the material types for valve body and other parts used in the assembly were classified. A new product code was also developed that formed the basis for design retrieval. A software system was developed to implement the computer based support. Using this system, the designer can input the parameters required by customers in final design such as pressure, temperature, construction and materials. There is a standard set of values shown to the designer for each parameter. The designer, however, has the ability to override these values if necessary. After completing the input, the system generates a valve configuration and a product code. It also creates the drawings of the resulting designs which can be used for production purposes. According to Schofield and Kelly the system effectively halted unnecessary proliferation of products and components.

Maupin and Stauffer (2000) present a methodology that can help small manufacturers to reengineer a product family. The methodology presented is based upon the application of four metrics: simplicity, standardisation index, direct cost and delayed differentiation index. These metrics help designers to evaluate their progress while reengineering a product family. Simplification helps reducing the complexity of a product and it can be achieved by removing redundant components and integrating (consolidating) component functions into a few components. Standardising components and operations provides cost reduction. Direct cost provides a measure of materials and labour cost. The aim is to reduce the direct costs by minimising the number of components, operations required to assemble the product family, required handling and insertion times. Delayed

differentiation is a concept where manufacturing starts with making a generic product which is later differentiated into specific products. It helps in tackling uncertainty in the demand of products.

Yan *et al.* (2007) argue that modularity within a product can help facilitate enhanced design reuse, reduce lead times, decreased cost and higher level of product quality for SMEs. They introduce a methodology, named GeMoCURE, which can provide an integrated total solution to modular design based on reuse of identified modules from similar previous designs. It contains four methods namely generalisation, modularisation, customisation and reconfiguration. The generalisation process is aimed at creating generalised and generic product development primitives (PDP) by studying existing similar products. The output of this process is a series of PDP models and knowledge for each PDP. Modularisation is the next stage of the methodology which aims at generating and structuring a family of generic modules derived from generalisation. These modules are used at the next stage of customisation in order to meet new requirements. The relevant modules are first identified and then tailored to suit a new design solution. Reconfiguration is the last stage where available modules are utilised and rearranged in different forms to investigate spatial and structural configurations.

Berti *et al.* (2001) developed a method to support the design of modular products in SMEs. This method is also based upon digital spreadsheets linked to a CAD system. The basic idea behind their methodology is to support the definition of functional structure by providing well-documented studies of product types for an application field. The different product types are decomposed according to various functions. The functional groups thus identified can serve as a basis for selecting modules for new products. A library of modules is thus created that can be used by the designer. The system developed supports the configuration of single modules and their assembly. The designer enters the design parameters relating to product geometry in the spread sheet. This spreadsheet contains all the design knowledge such as design rules, dimensioning relations and standard component dimensions. This spreadsheet is connected to a three dimensional CAD system and a semi-automatic parametric design can be achieved using this system. The

system can be further connected to down stream applications such as FEM (Finite Element Method) and CAPP (Computer Aided Process Planning).

Buske and Liu (2005) provide computer integrated support for design and manufacture of packaging machinery. They argue that thousands of machines have been developed over the years to automate every aspect of the packaging industry and these machines must be constantly redesigned to accommodate ever changing packing requirements. For SMEs especially there is little time to make these changes and no room for error. Buske and Liu's aim is to automate the entire customisation process of complicated packaging machines. They accomplish this by embedding a knowledge base into solid modelling software. The knowledge base contains information regarding different parts such as parametric descriptions regarding parts and their assembly and material types. The designer can create a custom machine by entering the different input parameters according to the changed requirements. The knowledge base is capable of checking for errors in the user input, part interferences in the assembly and sends warning signals in the event of a problem. It also contains algorithms capable of creating new parts numbers and CNC tool paths can also be generated automatically using this system.

### **2.4.1 Challenges for SMEs**

Most of the work identified in the literature (reviewed in the previous section) has stressed the need for effective design reuse. This essentially means deriving knowledge from existing products and applying it to new products. The common factor in different approaches is the identification of standard parts or components (in the form of modules) that serve different functions. A generic product model (product platform) can be generated from them. These parts (parametric descriptions) are then stored as a database that can be accessed during similar product development processes. In the case of the ones reviewed earlier, this has been normally accomplished by generating specific product codes, developing an expert knowledge base and connecting it to a CAD system with the help of a spreadsheet. The designer is presented with standard components which he or she can choose and if required, their parameters can be overridden with new values. The new components thus generated become standard parts for future product developments. Most of the approaches reviewed are based upon the modularisation concept. These are useful for generating custom designs based upon the existing designs and also make sure that there is always a consistent assembly generated. These can certainly help to lower product costs, support product variety and promote the use of standard components. However, there are some limitations associated with these techniques.

- These approaches (based upon the modularisation concept) consider the cases where the functional requirements of a design are well defined before the actual design is created. This may not be true for most of the SMEs. One example comes for packaging machine manufacturers in the UK. As mentioned earlier (section 2.2), the machine designs in these SMEs are evolved through empirical knowledge gained during years of work. The design knowledge regarding design decisions made is often limited. The underlying designs often adopt an integral type of architecture which means that changes made to any component may affect other components in the assembly.

- Developing a new product by incorporating these techniques in design methods can be a one-off task. But redesigning current products can be a difficult and cumbersome process. Sometimes a complete redesign of existing products is required in order to make a design modular. In such cases these methods are beneficial in the long run but initially require a lot of redesign effort. Yan *et al.* (2007) describe a case where the concept of modularity was applied to a mechanical products producing SME. It was hard to reconfigure the product as its design was well founded and evolved (having been in production for twenty years).
- Another drawback of adopting modular architecture is highlighted by Ulrich (1995). He says that a modular architecture can help in optimising local performance characteristics but fails to address global performance characteristics, which can only be dealt with using an integral architecture. Local performance here relates to performance characteristics arising from only a local region of the product (such as the tail light of a car which can fixed independently of other parts of that car) and global performance stands for performance characteristics arising from the physical properties of most components of a product (such as mass, shape and material that is constituted by all components of any machine). These techniques provide no direct support for evaluating or modifying (refining) the design for changes in global performance requirements such as optimising accelerations produced and increasing efficiency.
- Also, it is not always efficient to spend time and great effort to match modules to develop different products when the product variety is low (Jose & Tollenaere 2005). Optimising and developing products in the individual form (integral architecture) can be a better option in these cases.

Apart from the limitations associated with the application of modularisation techniques within SMEs, the overall work done (discussed in the previous section) for improving product development in these enterprises does not address all of their needs. Some of the

needs such as increasing design knowledge of existing products and improving methods for product refinement still seem to remain unanswered.

Based upon the factors that are hindering productivity of SMEs and their needs as highlighted in the literature reviewed earlier (section 2.3), it can be deduced that a supportive technique is still required in order to develop and refine products in SMEs. Such a technique should have following characteristics:

1. It must be simple to understand and easy to implement.
2. It should help in increasing the design knowledge of any existing product; in particular, the performance capabilities of current designs should be made known to the designer.
3. It should help in rationalising the current ranges of products by identifying their performance capabilities. Thus controlling product variety as new products must only be launched when existing designs are unable to cope with the changed requirements.
4. It should help in improving/refining current product designs.

The focus of this research work is on machine manufacturing SMEs. It can be beneficial to explore and incorporate existing tools that are useful in general to model and investigate machinery while developing the above stated technique. The following chapter discusses such tools.



## **Chapter 3: Tools and techniques to model and investigate machinery**

The previous chapter identified current design practices of SMEs with a focus on machine manufacturing enterprises. Various factors that are hindering effective product development in these enterprises were highlighted and their current needs were identified. It was also observed that most of the design activities that take place in these SMEs fall under redesign (adaptive) and variant design umbrella as there is natural evolution of machine designs. This chapter is focused upon the tools and techniques that are useful to model and analyse machinery. The aim is to investigate the extent to which these tools can be utilised for tackling the current issues faced by SMEs. The identified tools are essentially classified into two categories namely computer based tools and practical tools. The computer based tools are helpful in modelling and analysing machinery. The practical (experimental) tools on the other hand provide strategies to conduct experiments on actual machines and are further required to validate computer based models.

The following section discusses the use of computer based tools to model and analyse machinery. The scope of the current work, however, is restricted to the final stages of a product development process when concepts are already generated and possibly redesign or variant design activities are undertaken. Thus the discussion is limited to CAD and design optimisation tools for their capabilities and uses for the engineering design process.

### **3.1 Computer based tools for the purpose of modelling and analysis of machinery**

Computers have been helpful to engineers in automating many of the activities of a design process. They are present as various tools that range from a simple mathematical tool such as a calculator to sophisticated mainframe computers to carry out complicated engineering related tasks. The application of computer support in engineering has a wider span on the overall product life cycle. Computer Aided Design (CAD) is one among these tools that is widely used in various engineering streams. These systems help designers in solving complicated engineering related tasks that involve 3D modelling, assembly, virtual prototyping and manufacturing. Some of the features of CAD systems are briefly discussed in the following sections.

#### **3.1.1 Computer aided design (CAD)**

Research work on CAD can be traced back to mid sixties (SKETCHPAD, Sutherland (1963)). Earlier CAD systems were developed for the purpose of digitization of paper drawings and relied solely upon a 2D wire frame approach. The CAD systems nowadays are fully parametric and incorporate both feature based and constraint based support in order to create and manipulate geometry. Some of these features are discussed in the following sections.

##### **Parametric CAD modelling**

A parametric solid can be regarded as one whose shape is defined by parameters and relations between them. These parameters can be modified at any stage to alter the shape of the solid. The CAD system must solve the equations that are present relating the parameters in order to evaluate the shape of the artefact. Following the technique of parametrics, it is also possible to define the entire class of shapes that can be instantiated when required. This gives the designer a flexibility and ease of work. Hoffmann & Joan-Arinyo (2002) describe these parametric solid models as a class of specific solid models, which include meta-structure from which specific solid models can be derived as instances. In modern parametric solid modelling systems, solid models are defined using sketches, constraints and features. These are briefly discussed in the following sections.

### **Constraint based CAD**

Most modern CAD systems incorporate constraints in their interface for the purpose of geometry creation and manipulation. In these systems, the process of geometry creation starts with the creation of a 2D sketch. The designer draws a rough sketch using different geometric entities available such as points, lines and circular arcs. The sketch is then sent to the underlying geometric constraint solver to check for its integrity. The purpose of the geometric constraint solver is to solve the constraint problem. The geometric constraint solver then highlights the conflicting constraints if the sketch is over-constrained or shows a number of possible arrangements of the design in case the sketch is under-constrained. Similarly the constraint solver also helps in solving different constraints and maintaining various relationships that arise while creating, manipulating and assembling 3D geometries.

### **Feature based CAD**

Features are nowadays an integral part of parametric modelling. Features are generic shapes that contain information relating to their behaviour and engineering significance (Hoffmann & Joan-Arinyo 2002). Features are defined by different people depending upon their relevance (Shah 1991). These features can be broadly classified as features for design and features for manufacture. Features for design provide necessary information regarding design tasks and performance analysis by capturing engineering attributes and relationships for the product definition. Bosses, webs, holes and slots are examples of design features. Features for manufacturing on the other hand provide information that is required to generate manufacturing information and process planning.

### **Benefits of using CAD systems**

There have been continuous developments in the field of CAD. These developments include parametric design support, constraint based CAD, feature based CAD and more recently collaborative working environments (Hoffmann & Joan-Arinyo 2002; Li *et al.* 2005). These systems help designers in automating many design related tasks. Some of the major advantages these systems are listed below:

- The major application of CAD is in 2D and 3D modelling. Using these systems, different parts of a machine system can be modelled separately and then assembled together.

- The assembly thus generated can be further analysed for studying kinematics and dynamics of the overall system and one can easily identify any interference or collisions present in the motion.
- These systems also help in virtual prototyping so that validation/verification of design can be done against the given specifications and design rules without any need to build physical prototypes.
- There can be further provisions, in these systems, for promoting design reuse by maintaining libraries of standard parts and assemblies.
- Finally, CAD systems help in generating manufacturing information in the form of engineering drawings and CNC part programming.

CAD is widely used across the industry and even these systems are being utilised in machine manufacturing SMEs. However, their functionality is normally limited for 2D and 3D machine modelling purpose only. Once a model is created (or retrieved) using any CAD system, it must be evaluated further to satisfy any new design requirements and possibly needs modifications for this purpose. One way to accomplish this is using specialised design optimisation tools. The technique of design optimisation and a tool (Constraint modeller) based upon this technique is discussed in the following sections.

### 3.1.2 Design optimisation

Design optimisation is an important activity carried out by designers in engineering. It incorporates numerical algorithms and techniques that assist the designers to improve a system's performance, weight, reliability and cost. These methods can be either applied during the product development stage to ensure that the finished design conforms to the desired performance levels or to the existing product design in order to evaluate it for new design requirements and to improve its performance. The optimisation process normally aims at finding an ideal solution by meeting all the design requirements and satisfying all the constraints. Alternatively, in case of conflicting constraints, a best compromise is sought.

The optimisation process can normally help at any stage of a typical design process by optimising the sub-problem being addressed at that stage. However, following conditions are necessary to incorporate this process (Spicer 2002):

1. The optimality criteria and the constraints are well defined and computable.
2. Analysis codes to compute these are available.
3. The design evaluation sequence is well defined.

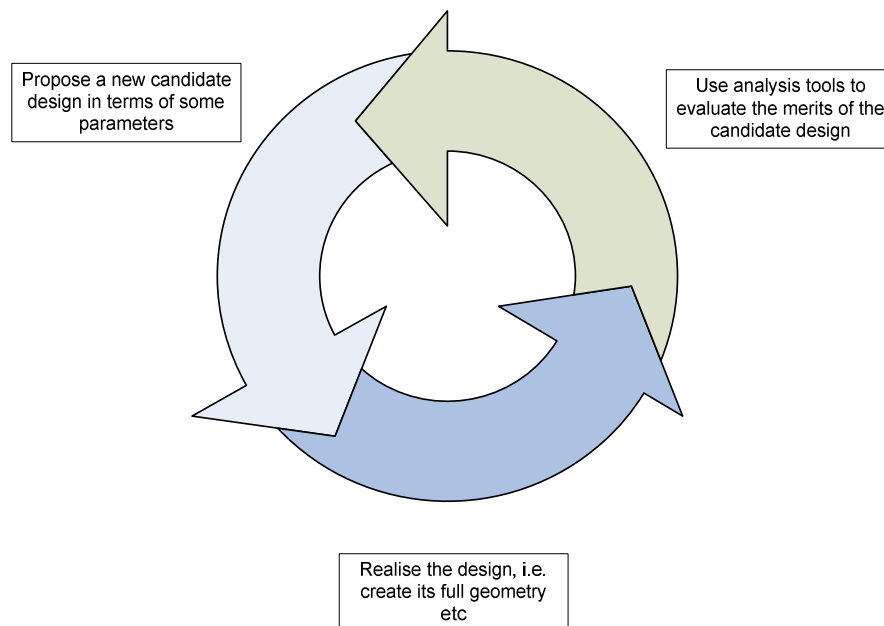


Figure 3-1 Optimisation process structure Source: Spicer (2002)

This process of optimisation in itself is iterative and follows a basic Generate-Realise-Evaluate structure (Spicer 2002) (figure 3-1). Initially, it can help in selecting a candidate from a family of designs. This may be accomplished using sophisticated search algorithms. The design thus selected is usually characterised by a small number of parameters and hence incomplete design information is available. The optimisation process then helps in realising the full geometry of the candidate design that includes geometry and materials. Finally the optimisation process also helps in evaluation of the design generated. This evaluation is normally done against some criteria to find out a best design.

There are several methods available that can be employed for the process of optimisation such as direct search, genetic algorithms, simulated annealing and particle swarm method. Each method has its own benefits and limitations. However, it is not the aim of this thesis to compare and comment upon these methods. Using any of these methods, a designer normally seeks to minimise or maximise an objective function which represents the design requirements. These optimisation problems can be broadly classified as single objective optimisation and multi-objective optimisation.

Multi-objective optimisation problems involve finding a solution (or number of solutions) to a set of objective functions. These objectives can be competitive, cooperative or have no relationship at all (Agrawal *et al.* 2004). The aim is to find an acceptable solution by finding compromises or trade-offs of all the objective functions. A single-objective optimisation on the other hand requires the designer to specify relative preferences (weights) of design requirements to construct the objective function. In such cases, if the resultant solution is not optimal then the weights are modified and a new objective function is used. The optimisation process is repeated until a desired solution is found. This process is iterative and computationally expensive. These drawbacks of a single-objective optimisation are overcome by multi-objective optimisation where there is no need to identify trade-offs beforehand and multiple solutions can be generated with the help of search strategies (Valliyappan & Simpson 2006).

### 3.1.3 Constraint based modelling

The application and usefulness of optimisation techniques in machine design is shown by Mullineux (2001). He introduced a constraint based modelling technique which involves identification and resolution of all the constraints known to be acting on a system. In this approach, the design requirements are converted into constraints and the various design parameters that affect these are identified. Various procedures can be used to manipulate the parameters in order to resolve the constraints including graph-based searches and optimisation. The approach is open so that users can add new constraints and relax existing ones when required. Hence it can be tailored to specific applications.

Constraint based modelling has been proved useful in different design applications. These areas include redesign of packaging machinery (Hicks *et al.* 2001b), mechanism design (Mullineux 2001), human modelling (Mitchell *et al.* 2006) and manufacturing capabilities (Matthews *et al.* 2005). In particular, the technique is useful for studying mechanism and machine systems as it can represent diverse types of machine components such as cams, linkages, rotary and linear actuators from the pneumatic, electrical and mechanical domains, within a single environment. This ability of the constraint modeller is useful for evaluating interactions between different machine components and thus a complete machine system and process can be studied. Some of the main features of this environment are listed below.

- The models constructed in this environment are driven purely by the constraints rules. Hence by simply inverting these rules one can also modify the input parameters. For example, in case of a cam and follower assembly, normally a cam profile is specified and then the resultant motion is analysed. However, in the constraint modeller environment the desired motion can be specified and a cam profile can be created from it.
- The constraint modelling environment provides the flexibility of customisation. The designer can add further constraints depending upon the nature of the problem involved.

These features offered by the constraint modeller are normally absent in most CAD systems. CAD systems, as discussed earlier, are highly suitable for 3D modelling, performing engineering analysis and generating manufacturing information for the designs. One possible area of research can be to combine the constraint modelling approach within a CAD system. Incorporating constraint modelling techniques within a CAD system can give designer combined benefits of both the systems. This integration has been successfully accomplished using Unigraphics NX3 and constraint modeller (Singh *et al.* 2006; Singh *et al.* 2007a).

However, there is an inherent limitation with implementing such a (design optimisation based) tool in SMEs. This is the expertise required to be able to interpret current design problem in way that it can be modelled and analysed with these tools. SMEs, which may already be struggling with limited resources and expertise, can be reluctant to use such tools. One way to overcome this is to provide these enterprises with a simple step by step approach to tackle their current design problems. It can help designers to model and analyse current design problem with the available tools and further helps in improving their designs. Such an approach (redesign methodology proposed by Hicks *et al.* 2001b) is discussed in the next section.

Another important aspect about computer based analysis is that it is always incomplete until the model is validated by practical experimentation. For this purpose, SMEs may need some sort of practical strategies to conduct experiments on actual machines. There are some practical approaches such as design of experiments, which can be useful along with computer based analysis, discussed in the following sections.



## **3.2 Practical tools for the purpose of modelling and analysis of machinery**

This section discusses some of the practical techniques that can provide strategies regarding how to conduct experiments on actual machines and help in validating/verifying computer based models. There are two techniques discussed here namely a redesign methodology for machinery (Hicks *et al.* 2001b) and design of experiments techniques. The redesign methodology is particularly suitable for SMEs for analysing and improving their existing machine designs and design of experiments is more general technique to conduct and analyse experiments. It helps in reducing the number of experiment runs that are required to predict the response of a system. Both of these techniques are briefly discussed in the following sections.

### **3.2.1 Redesign methodology**

Hicks *et al.* (2001b) propose a constraint based methodology for the design and redesign of packaging machinery. This methodology incorporates constraint based modelling technique (described in section 3.1.3), which involves identification and resolution of all the constraints known to be acting on a system. The methodology is essentially similar to the design process models discussed in chapter 2 (section 2.1), evolving and iterating through different design stages. It is argued that the requirements of SMEs for support during redesign (such as the need to represent and manipulate design knowledge, model and analyse systems and provide support over conceptual, embodiment and detailed phases of design process) can be met in part or in full using constraint based modelling techniques. The design knowledge is gained through the process of refining constraints and models. The results and implications about the design decisions are embodied in the various sets of constraint rules, which are later resolved in order to achieve a successful solution.

The main feature of their proposed methodology is its incorporation of two parallel activities: practical and analytical (computer based). The practical (experimental) investigation helps to identify and develop design constraints and to validate the modelling and analysis data resulting from the analytical study. This approach is very useful especially for redesign activities carried out in SMEs. A computer model (constraint based model in this case) can always be generated by identifying the main

design constraints embodied in the existing design. The model can be further validated and refined through comparing predicted results with those obtained from experimental investigation. Once a successful computer based model is obtained, it can be tested with different redesign strategies such as adaptive and variant. The designer can interact with the system to change design parameters and investigate their effects. Thus the key parameters can be identified and an assessment of the robustness of the design can be made. Optimisation techniques can then be applied to search for improved designs.

This methodology proposed by Hicks *et al.* (2001b) is very useful for carrying out design/redesign activities in SMEs and can provide a basis for further research in this area. However, their approach is limited to investigating a single design only. It does not address the issues relating existing variety in products. The following section discusses a more general approach to conduct and analyse experiments.

### **3.2.2 Design of experiments**

Design of experiments is a methodology for conducting experiments on a physical system with the aim to understand its response to input conditions (factors). It is essentially an information gathering exercise which uses statistical techniques for planning and conducting experiments as well as analysing and interpreting results. It is a superior approach than traditional trial and error way of conducting experiments (Umetri, 1998). In traditional methods, one normally relies upon one-factor-at-a-time approach where only one factor is varied at a time while others are kept constant. When interactions are present, the one-factor-at-a-time experiments need to be repeated at different levels of the other factors. Thus the number of experiments that need to be conducted increases drastically. Hence traditional methods are not cost effective for conducting experiments. Whereas statistically designed experiments are more efficient for predicting behaviour of complex interactions. The interaction between the factors can be estimated systematically and with a limited number of experiments using the techniques from design of experiments.

Broadly speaking there are two types of design of experiment strategies available: screening design (factorial fractional designs) and response surface model (RSM). Screening experiments are useful when large numbers of possible factors are present

and the search is then narrowed down in order to reduce the factors to a relatively small set (Montgomery, D. C., 2001). Screening experiments can provide an efficient way of determining important factors with minimal number of runs. The response surface methodology (Khuri & Cornell, 1987) on the other hand helps in setting up a series of experiments that yield adequate and reliable measurements of the response of interest. A mathematical model can also be determined that fits the data collected from the conducted experiments. Finally the optimal settings of the experimental factors that produce minimum (or maximum) value of response can be obtained using any optimisation strategy.

The tools and techniques discussed so far are helpful in modelling and analysing machinery. Most of the tools discussed in the previous sections relied upon optimisation techniques to improve product designs. However, there are two major limitations associated with the design optimisation process. First is with the traditional optimisers (single objective optimisation is one example) that these can operate like a black box solver which present the designer with end results from a prescribed input. However, the designer gets no information about the alternative solutions and trend followed by the optimisation process. The second is with multi-objective optimisation where the amount of data generated through these search techniques is vast and it is difficult to analyse the results generated. Also no technique, discussed so far, has provided any clear support to tackle issues relating existing variety in products such as how far the existing range of products can be extended and identifying their performance limits.

It is proposed that these issues can be effectively handled with a proper visualisation technique. Visualisation has a great impact on the designer's decision making process as design decisions often require specialised knowledge about the solution space. Visualisation techniques can be highly effective in identifying a better solution by browsing through the information in the solution space. According to one study, 70% of human attention is dedicated to visual input (Helig 1992 as cited in Eddy & Lewis 2002). The following sections provide some of the research work that has been done to address the above stated issues relating design optimisation process. The basic idea is to be able assist a designer's decision making process with the help of an effective visualisation strategy. An overview of various visualisation techniques is given in the

following sections which are being used by the researchers in order to display and analyse multi-dimensional data. The aim is to understand various techniques available so that a visualisation tool can be proposed that can aid in the designer's decision making process when a number of variants are to be investigated. Ideally, for its suitability in SMEs when several variants of a design need to be investigated, a visualisation technique with the following characteristics is required:

1. It should be able to represent a number of (two or more) design variants in a single plot. Such a plot will help in investigating current product designs and their relative merits.
2. It should be able to represent the solution space that exists between these variants. The solution space will help in identifying better solutions which may exist in that space.
3. It should provide means to plot and compare the performance measures of every design solution created within the design space.
4. It should be easy to understand and identify good design solutions.
5. There should be provisions to zoom into the areas of interest.

### 3.3 Design space exploration and visualisation techniques

Design can be seen as a shopping process as proposed by Balling (1999) ('design as a shopping paradigm'), where the designer, first of all, explores the design space and then chooses an optimal design among the set of possible designs. This activity is analogous to the shopping process, as while shopping a person can look at all the available products and select one that suits his or her needs. Such a selection process in a design context allows the designer to form his/her design preferences after visualising the entire design space and lets them choose an optimal design that is based upon the preferences (Stump *et al.* 2003).

This can be further elaborated with a multi-objective optimisation example. Consider a design problem subjected to two objectives (F1 and F2, figure 3-2). The designer's aim is to find a solution where both of the objectives are minimised or at least best compromise is obtained. In such situations, a designer can end up with a number of optimal solutions. These solutions (points) are known as Pareto-Optimal points. (A point in the design space is Pareto-Optimal if no feasible point exists that would reduce one objective without increasing the value of one or more of the other objectives (Papalambros & Wilde 2000)).

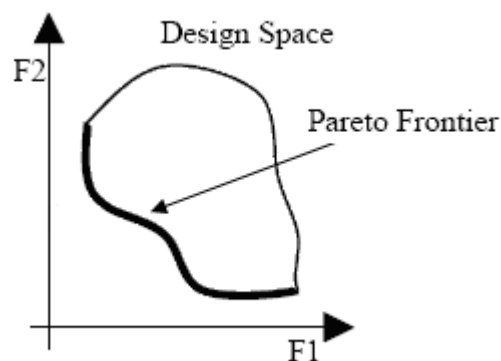


Figure 3-2 Pareto Frontier

Thus the designer can select any solution from this set of solutions (referred to as 'Pareto set' or 'Pareto Frontier', figure 3-2) that are equally important and global optimal solutions. This concept is highly useful in aiding designer's decision making process as by visualising the optimal set of solutions, the designer can articulate his

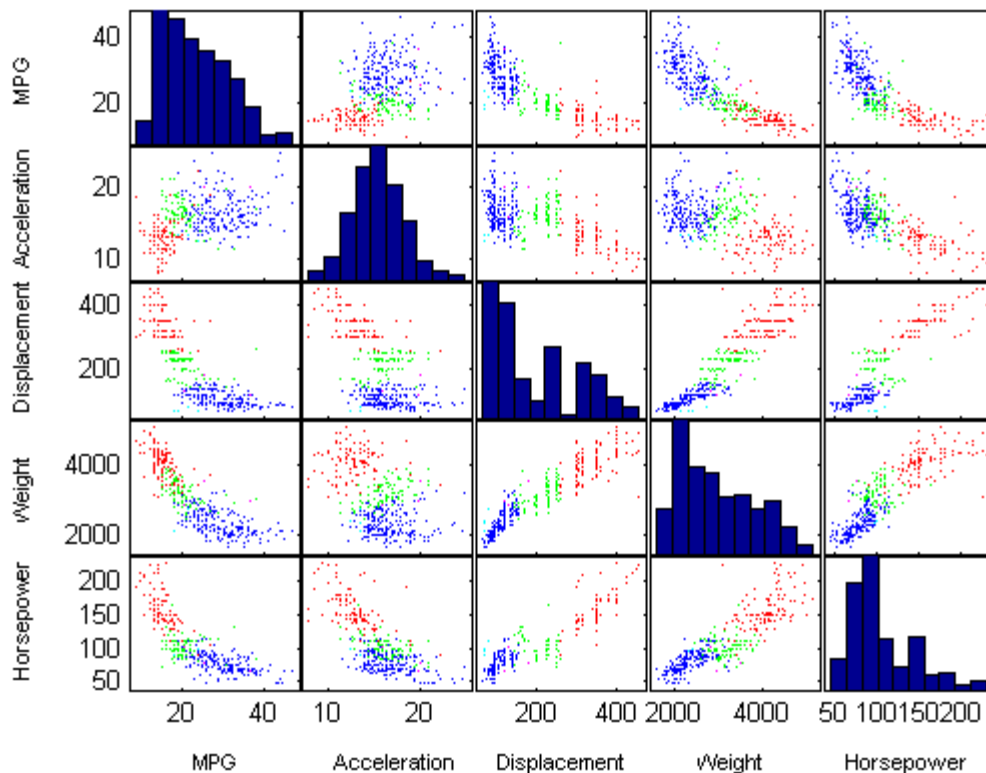
preference pertaining to the different objectives. Balling (1999) also highlighted the need for interactive graphical (visualisation) computer tools that can display these solution points to assist designers in this shopping process (design space exploration).

This section summarises such visualisation techniques that can be adopted by the designers for the purpose of design space exploration. There are numerous methods available that can be used for this purpose. These methods include some basic techniques such as bar charts, pie charts, histograms, scatter data plot (2D and 3D) and surface plots. These representations are widely adopted due to their simplicity and ease of understanding. However, these techniques are only helpful when the number of variables to be plotted is only two or at the most three. Often in many design problems more than two design variables affect the overall performance of the system. One way to add an extra dimension to the conventional methods used is to incorporate visual aids like colour, shape and relative size. However, there is still a need for multi-dimensional data representation that incorporates heuristics and design knowledge (Eddy & Lewis 2002). In the following sections, some of the techniques developed for exploring high dimensional problem spaces in the engineering design are presented.

### **3.3.1 Scatterplot matrix**

As the name suggests, a Scatterplot matrix presents a grid structure (matrix) of scatter plots to represent multi-dimensional data. In such a plot each element of the matrix is an individual scatter plot and variables are plotted against each other at least once (Stump *et al.* 2004). This technique can be used to represent any number of variables. Figure 3-3 shows an example of a scatterplot matrix.

Here five variables are plotted against each other using this technique along with a univariate histogram for each variable. The advantage of using this method is in its ease of interpretation. However, with an increase in the number of variables, the space available for each element decreases and thus it is suitable for representing only a small number of variables.



**Figure 3-3 A scatter plot Source:**

[http://www.mathworks.com/products/demos/fullsize.html?src=/products/demos/shipping/stats/mvplotdemo\\_01.png](http://www.mathworks.com/products/demos/fullsize.html?src=/products/demos/shipping/stats/mvplotdemo_01.png)

### 3.3.2 Glyph plots

The glyph plot is a way of adding extra dimensions to a normal scatter plot diagram. In this technique more than two variables can be represented by using a glyph symbol (Stump *et al.* 2003). The additional variables are represented by physical characteristics of that symbol such as shape, colour, texture, size, length and direction.

Figure 3-4 shows such a glyph plot, representing 7-dimensional information. It uses the spatial position of a glyph symbol (icon) to represent three variables and the other four variables are represented by the size, colour, orientation and transparency of the symbol. A glyph plot is a good way of plotting multi-dimensional data. However, this representation is limited to the number of data elements that can be displayed on the available space and also it can be difficult to visually compare glyphs that are separated in space.

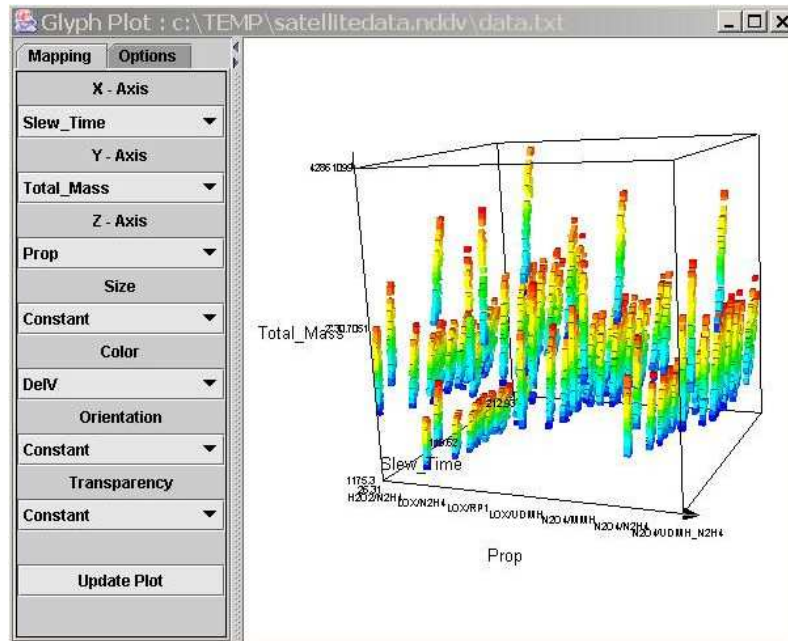


Figure 3-4 A glyph plot Source: Stump *et al.* (2004)

### 3.3.3 Parallel coordinates

Parallel coordinates, introduced by Inselberg (1990), is a way of representing multi-dimensional geometry. In this technique, the axes are drawn parallel to one another and are equally spaced as opposed to Cartesian coordinates where all axes are mutually perpendicular to each other. The observations are plotted in this case as a series of connected line segments. Figure 3-5 shows such a representation for a six dimensional point (1, 3, -1, 4, 2, -3).

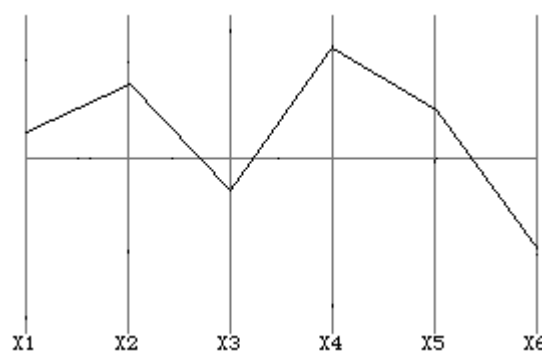


Figure 3-5 Parallel coordinate representation of a six dimensional point

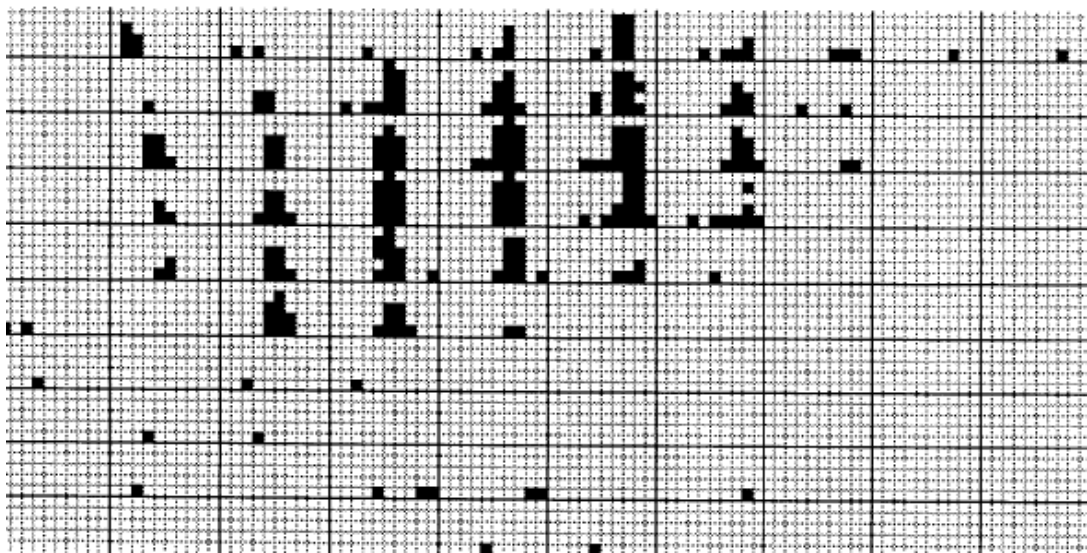
It is possible to represent multi-dimensional geometry including multi-dimensional lines, hyper-cubes and high dimensional spheres on a 2-D plane using this representation. This technique has been widely applied for visualising high dimensional space in industry as theoretically it is possible to represent as many



dimensions as one wants. However, with larger problems the plot size increases and it becomes difficult to interpret the results.

### 3.3.4 Dimensional stacking

Dimensional stacking is a hierarchical technique of displaying multi-dimensional data by recursively embedding dimensions within other dimensions. In this technique initially, each dimension range is discretised (also known as assigning a number of buckets for a dimension or cardinality) and an orientation is assigned to it (vertical/horizontal). The next step is then to assign an ordering to these dimensions as these are said to have unique “speeds” (Ward 1994). The outer-most dimension is the slowest and the inner-most is the fastest. A virtual screen is divided into sections with the two dimensions having slowest speeds. The cardinality determines the number of sections generated horizontally and vertically. Each of these sections is then used to define the virtual screen for the next two dimensions (slowest of the remaining dimensions) and the cardinality is used to determine the break up of the virtual screen. The process is repeated until all the dimensions are embedded. An example of this representation technique is shown in figure 3-6.



**Figure 3-6 Four dimensional data set representation using dimensional stacking** Source: Ward (1994)

The figure shows a four dimensional data set (3D drill-hole data with a fourth dimension representing ore grade at that location) representation using dimensional stacking. Each data point here maps into a unique bucket, which in turn maps to a

unique location in the resulting image. This technique is essentially suited for representing dense data sets as in the case of sparse data, the screen space expands rapidly with increase in the data dimensions (Ward 1994). Another limitation of this technique is in determining spatial relationships between points in non-adjacent dimensions as two points, which are closely located in space, may get projected to far apart screen locations.

### **3.3.5 Dimensional reduction**

Dimensional reduction is another approach used in visualising multidimensional data. In this approach, data is processed in such a way that dimensionality is reduced without losing the integrity of its meaning. The dimensionality is normally reduced to two or three dimensions that can be displayed using conventional visualisation techniques such as scatterplots. Carreira-Perpinan (1997) gives a comprehensive review of techniques that are used for dimensional reduction. One of the major drawbacks of dimensional reduction is that it can result in loss of meaning, a loss of the concept of a neighbourhood, and an associated loss of an ability to understand the representation in an intuitive way (Agrawal *et al.* 2004).

### **3.3.6 Nested performance charts**

Performance charts are helpful visual aid for designers for the purpose of exploring design space. In such types of charts, normally, performance is plotted against the design variables. Using these charts, a designer can understand the effect of a certain design variable on the overall performance of the system. The drawback of this technique is that it is limited to one or two design variables. Figure 3-7 shows such a performance chart.

To overcome this problem Burgess *et al.* (2004) present a new type of chart known as a nested design chart. The proposed method is similar to dimensional stacking. Using this chart the designer can visualise the whole design space on one single design chart as performance can be presented as a function of more than two variables. Indeed the method is capable of representing more than four variables. Figure 3-8 shows a nested performance chart with four (two discrete and two continuous) variables.

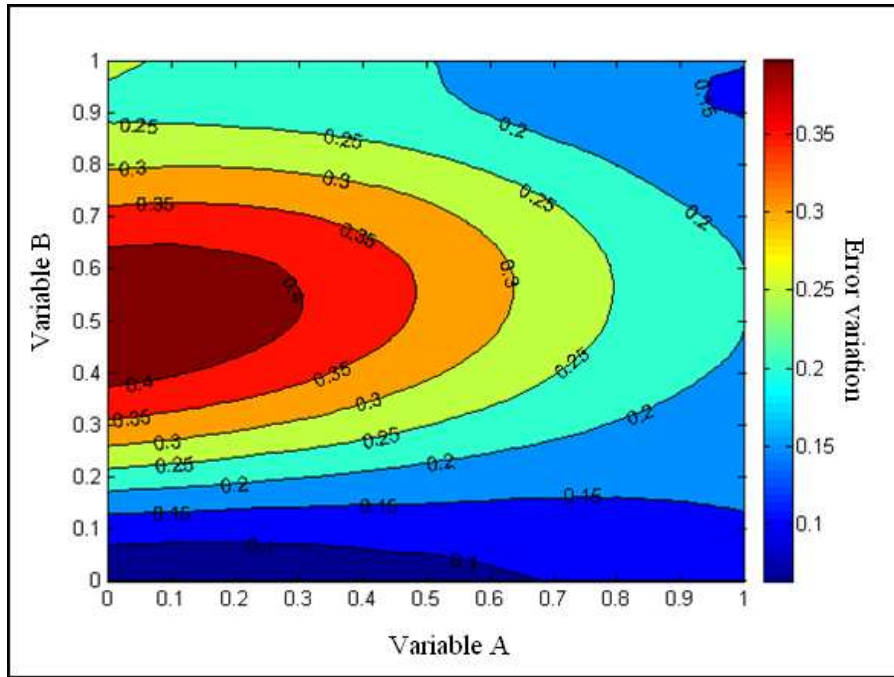


Figure 3-7 An example of a performance chart

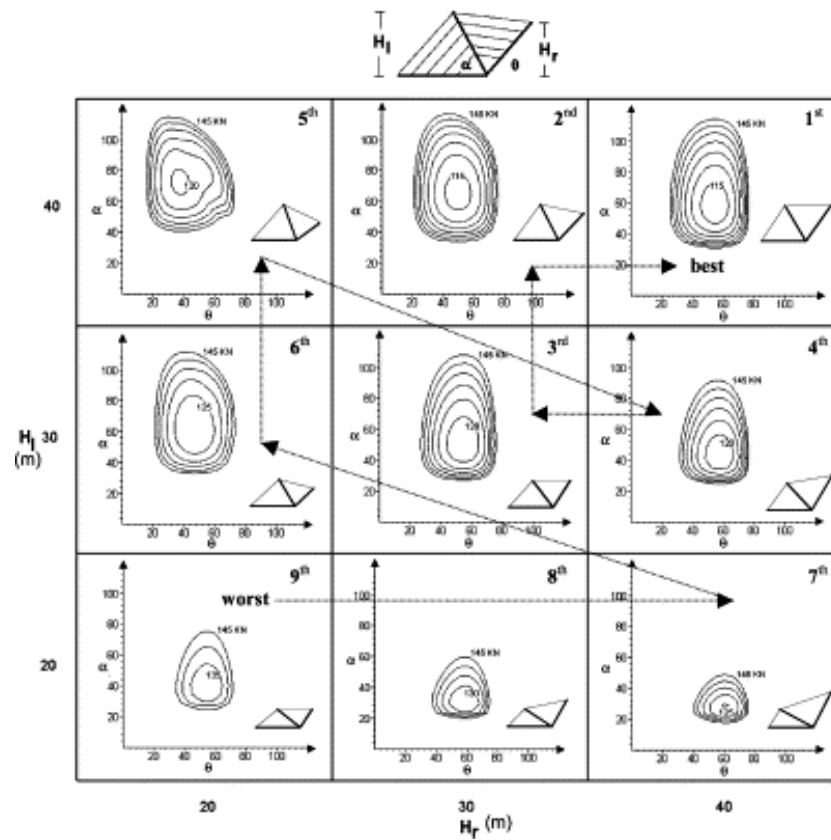


Figure 3-8 An example of a nested performance chart source: Burgess *et al.* (2004)

### **3.3.7 Design visualisation in optimisation**

One way to overcome the drawbacks of the traditional optimisation process, where algorithms can blindly run their course to completion, is with the use of computational steering (CS). It can be defined as the interactive control over a computational process during execution (Mulder *et al.* 1999). Computational steering provides ability to the designer to visualise how the solution procedure is progressing. Using this method the designer can actually alter the parameters during the analysis. If the solution seems to be diverging, the designer can redirect and even terminate the optimisation process. Hence this method enables the designer to steer the solution in the desired direction and saves the solution time as well.

There are numerous CS applications and systems described in the literature such as SCIRun (Parker & Johnson 1995), VASE (Jablonowski *et al.* 1993), Magellan (Vetter & Schwan 1997), CUMULVS (Geist *et al.* 1997), and VIPER (Rathmayer & Lenke 1997). These environments can be classified according to the specific domain and application of use. Mulder *et al.* (1999) recognises three uses of CS in the area of scientific and engineering simulations which are model exploration, algorithm experimentation and performance optimisation. In model exploration, CS can be used to explore parameter spaces and simulation behaviour. Algorithm experimentation allows the designer to adapt program algorithms in runtime that means the user can experiment with different numerical solving methods. Finally performance optimisation can be used to improve an application's performance.

There is one major drawback associated with CS as it requires very high computational power for its calculations and data transfer. Winer and Bloebaum (2002) highlight some of the shortcomings of CS that include requirements such as highest networking capabilities, high-performance computers, high-end graphics boards and specialised tools for every application.

### **3.3.8 Implications for SMEs**

This chapter has highlighted some of the visualisation techniques adopted by different researchers for representing multi-dimensional design space. The comparatively simple visualisation techniques such as scatter matrix, glyph plots, parallel coordinates are helpful in visualising multidimensional data but do not possess

capabilities to alter the design optimisation process. Other intelligent techniques that possess these capabilities such as computational steering techniques are computationally expensive, need sophisticated computer hardware to run and are sometimes difficult to understand. The area of application of each technique, in engineering, may be different from others but these are helpful in adding to the decision making process of a designer if considered as a solution tool rather than a means to present results.

There had been no explicit work published on visualisation techniques for SMEs specifically. However, SMEs and other organisations can benefit from a good visualisation technique. It can help them to better develop their products and can further assist in meeting their current needs in the following ways.

- It can provide a simple and convenient way to represent and analyse product performance.
- It can aid a designer's decision making process when a number of design options are to be evaluated.
- It helps in increasing their design knowledge regarding current products.
- It can provide basis for carrying out redesign activities.

For SMEs especially, such a technique needs to be simple to understand and easy to implement. One of the objectives of this thesis is to propose, demonstrate and test a visualisation technique, which allows the design space between a number of design variants to be represented and hence explored. None of the visualisation techniques, discussed in the previous section, provide such a support. A visualisation technique with required characteristics (described earlier in section 3.2.2) is discussed in the next chapter.

## **Chapter 4: Multi-Instance modelling approach**

The previous chapter highlighted the need for having an effective visualisation strategy in order to explore and analyse different product designs in SMEs. Using such a strategy various design options and their relative merits can be evaluated. For this purpose, a multi-instance modelling approach is presented in this chapter. The overall approach is divided into two stages namely parametric morphing and visualisation. These stages are described in the following sections.

## 4.1 Parametric morphing

The idea which underlies the parametric morphing approach is that designers often can obtain information from known (successful) designs. Such information can be already present in the form of documents or can be generated by modelling the existing designs and understanding their functionality. It can be beneficial to use such information as a guide to what the full design space looks like. The design space usually has a large number of dimensions, corresponding to the number of design parameters, which can easily become unwieldy. Additionally, very many combinations of the design parameters lead to infeasible designs. Basing design exploration upon successful instances can mean that relationships implicitly required between the parameters are imposed without the need for a formal investigation of what these may be. In this way, although a large number of design parameters are likely to be present, the fact that the existing instances are good designs suggests that some of the required relations between the parameters are already satisfied (albeit on a heuristic basis). An assumption is made here that the instances share essentially the same “topology” although the “geometry” of each is different.

It is also necessary to have one or more performance metrics by which any design instance can be evaluated. Such metrics might include: cost, weight, ability to reach target values. A suitable computer-based model of the design is also required which is parametric. This allows different instances to be investigated and the performance metric(s) evaluated.

Given a collection of “base” instances, the next stage is to investigate the effect of interpolating or “morphing” between them. This starts with identifying the relevant parameters. These parameters determine the functionality of a machine system. If  $p$  is a particular parameter of the design and there are  $n$  instances, then there are  $n$  values of the parameter among the base instances. Denote these by  $p_1, p_2, \dots, p_n$ . To find a new morphed instance, a set of weighting values  $\alpha_1, \alpha_2, \dots, \alpha_n$  are taken whose sum is unity, the same set for all the parameters. The new value of parameter  $p$  is then taken as

$$p = \alpha_1 p_1 + \alpha_2 p_2 + \dots + \alpha_n p_n$$

and the similar combination for all the other design parameters. These new values can be used within the parametric model and the morphed instance (interpolant) created and its performance metric(s) determined. This can be done in discrete steps, for different choices of the weights  $\alpha_i$ , and the performance evaluated for each new instance. For example in the case of two instances if  $h$  is taken as the step size, the weights  $\alpha_1, \alpha_2$  are changed to  $\alpha_1+h$  and  $\alpha_2-h$  so that their sum remains 1. The step size can be reduced to perform a finer search. The reduction in step size results in an increased number of interpolants generated which then have to be analysed individually for their performance values.

Depending upon the step size used for morphing, one can end up with a vast amount of data to be dealt with. One way to do this is by using a suitable visualisation technique. Such a technique for the visualisation of design space among design variants is described in the next section.



## 4.2 Visualisation

The literature survey in the previous chapters highlighted the need for an effective visualisation technique. The simplest case of visualisation representation for parametric morphing is between just two instances which can be plotted as a curve of performance measures. This can be extended to morphing between three base instances by creating a surface of performance measures. The surface thus plotted can be taken as being over an equilateral triangle whose vertices represent the base instances (design variants). The height of the surface gives the value of the metric. Any morphed instance corresponds to a point within the triangle and the weights ( $\alpha_i$ ) can be regarded as the barycentric coordinates of this with the respect to the triangle.

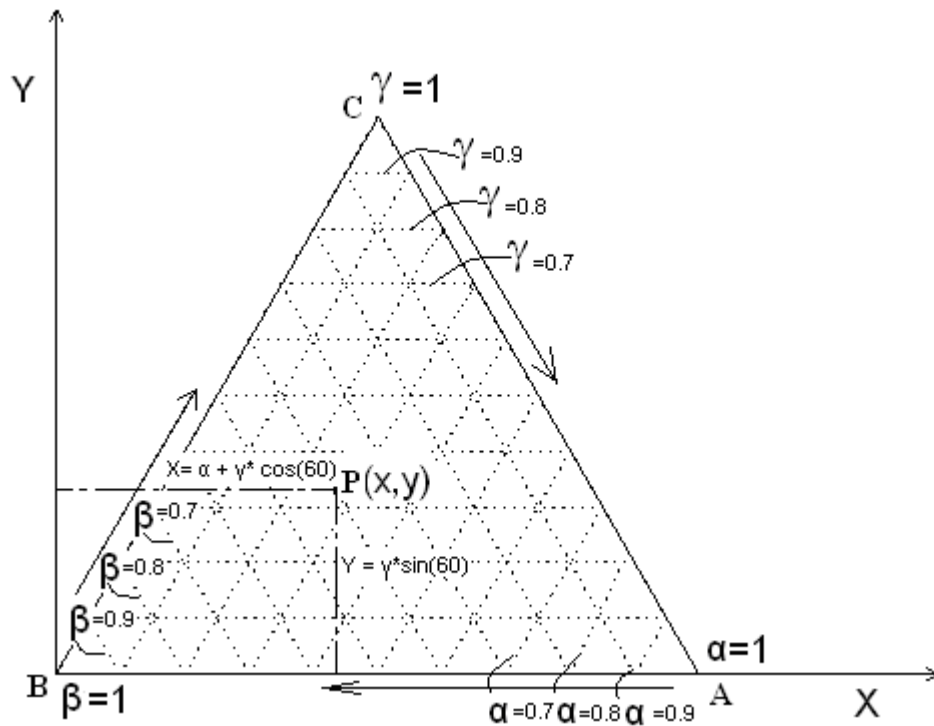


Figure 4-1 Triangular representation for three instances

Figure 4-1 shows such a triangular representation. Three points  $A$ ,  $B$  and  $C$  represent three design variants here. There are three weights  $\alpha_1=\alpha$ ,  $\alpha_2=\beta$  and  $\alpha_3=\gamma$  with

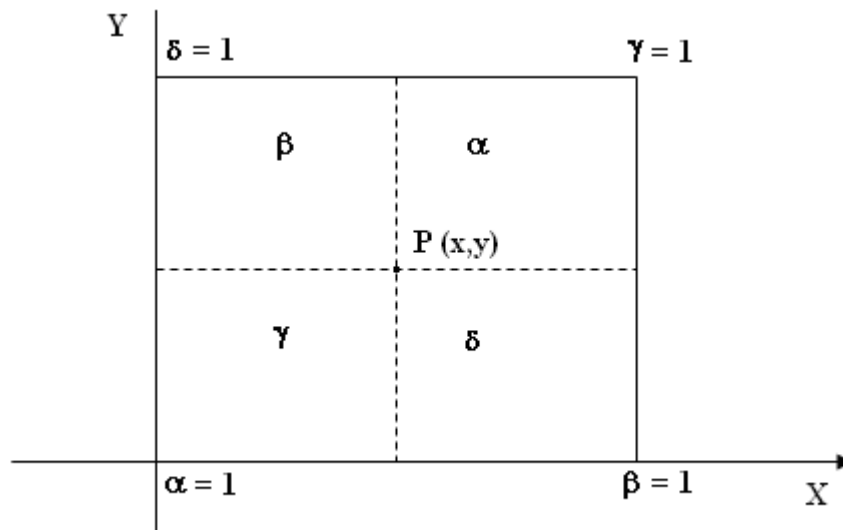
$$\alpha + \beta + \gamma = 1$$

and at each corner just one of the weights is unity. These weights, considered as barycentric coordinates, determine a point  $P$ .

$$P = \alpha A + \beta B + \gamma C$$

The performance values are then plotted in the Z-direction. The various interpolants can thus be found inside the triangular surface. If the weights are all non-negative, then the new instances lie within the triangle. The weights can of course be taken as negative, although, in this case, one is extrapolating away from the base instances rather than interpolating between them.

It is also possible to morph between four or more base instances. This can be represented in a higher dimensional space, for example a tetrahedron can be used to represent four instances. However for ease of visualisation a surface in three dimensions is used. Here the surface is again plotted over a (regular) polygon whose vertices represent the base instances.



**Figure 4-2 Square surface representation for four instances**

Figure 4-2 shows a square surface representation for four base instances. The weights for the point  $P(x,y)$  are given by the following equations.

$$\alpha = (1-x) (1-y)$$

$$\beta = x (1-y)$$

$$\gamma = x y$$

$$\delta = y (1-x)$$

so that

$$\alpha + \beta + \gamma + \delta = 1$$

It needs to be noted that with four or more base instances, there is more than one choice of weights that can specify any given point within the polygon. Conversely, a single surface cannot capture all the possible combinations of the base instances. In particular, another ordering of the instances changes the plot (to some extent).

### 4.3 Illustration with different surface examples

The next step is to analyse the design space represented with the help of a surface. The surface may be continuous and reasonably “flat”. This suggests that the base instances used all lie within a single “family” of possible designs. The optimal member of this family can be found as that new interpolant which provides the best performance value(s). It also suggests that this optimal design is relatively insensitive to variations in its parameters. Figure 4-3 shows an example of such a surface. It is assumed here and elsewhere that the performance measure plotted in the vertical direction becomes smaller as the design improves.

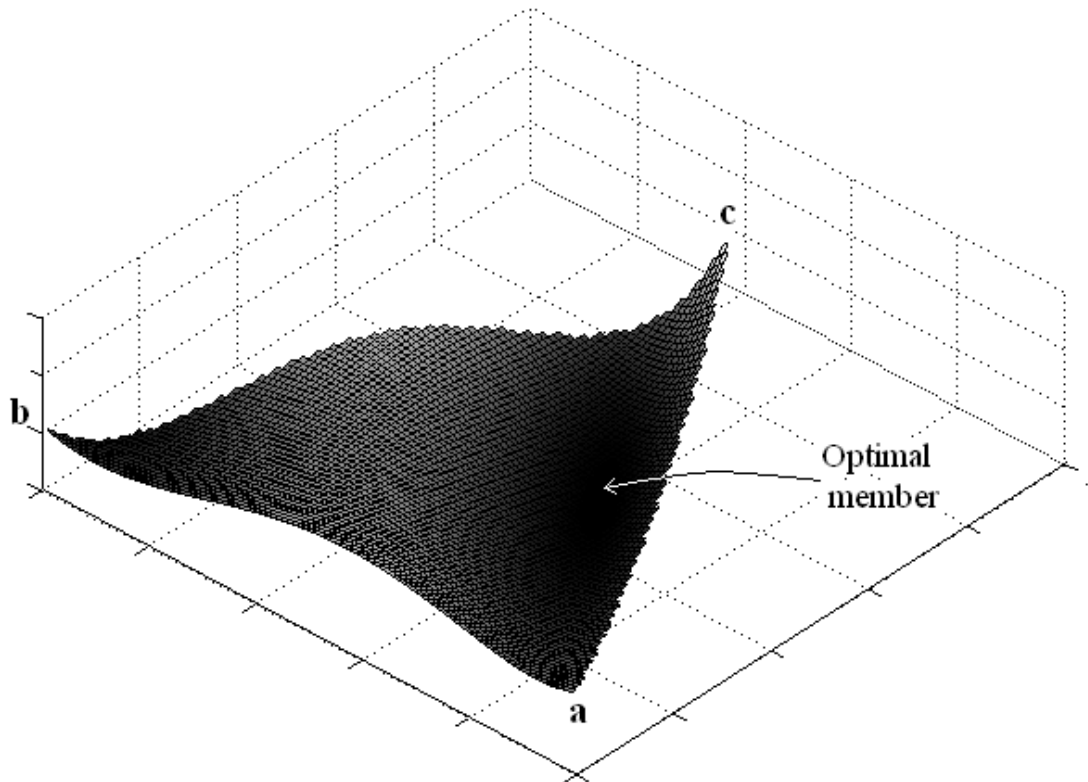
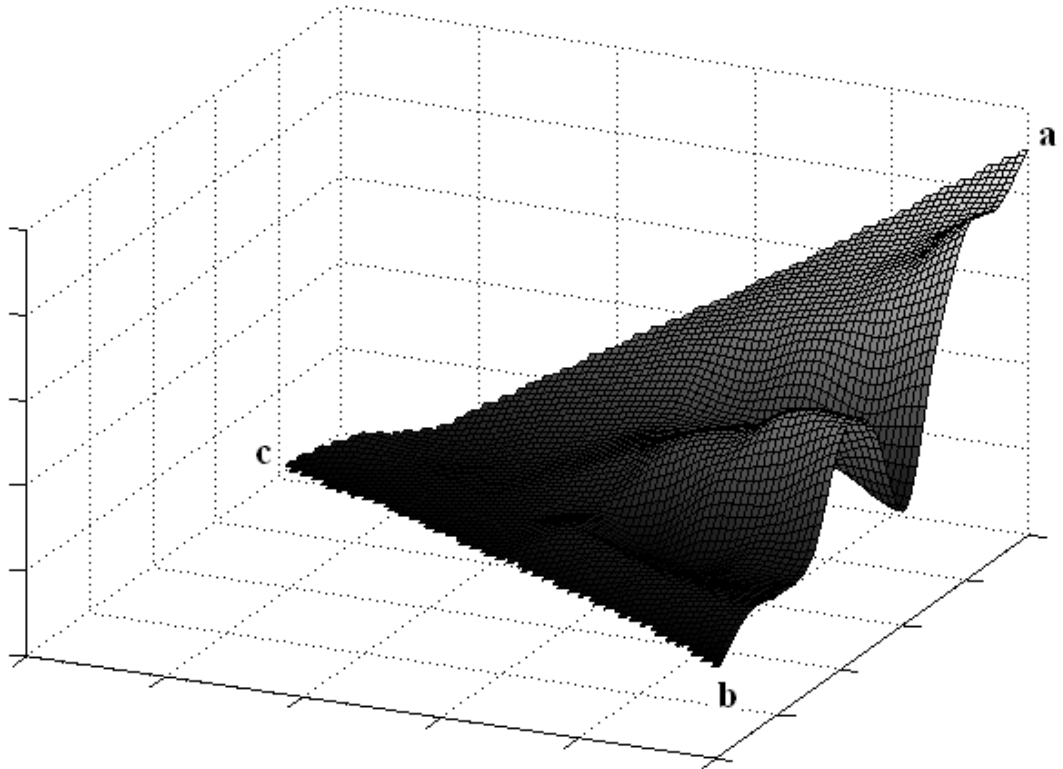


Figure 4-3 Example of a flat surface

If the surface rises steeply between some of the vertices, this suggests that the original base instances lie in different families and there is some fundamental difference between these designs. The sensitivity of the base instances to changes in the parameters is likely to be high. Such a surface is illustrated in figure 4-4. An extreme case is when the surface is discontinuous or has holes in it. This suggests that there are situations where the design has failed and the base instances are definitely distinct in some way.



**Figure 4-4 A steep surface**

When a better solution is found, the designer may want to focus on the region of interest where this better solution lies. The proposed visualisation approach helps in achieving this by subdividing the design space. In the case of three instances, the triangular surface can be subdivided into a number of small triangular surfaces around a region of interest. This division is carried out by selecting the appropriate weight values and generating new instances at the points where the division is required. The instances thus generated can now be considered as new base instances and further parametric morphing can be carried out between them. Figure 4-5 shows an example of triangular subdivision of a triangular surface. The surface shown in part (a) is divided into four triangles numbered as 1, 2, 3 and 4, part (b). The minimum lies in region (2) which is further morphed by taking A', B' and C as base instances. The resulting surface is shown in part (c).

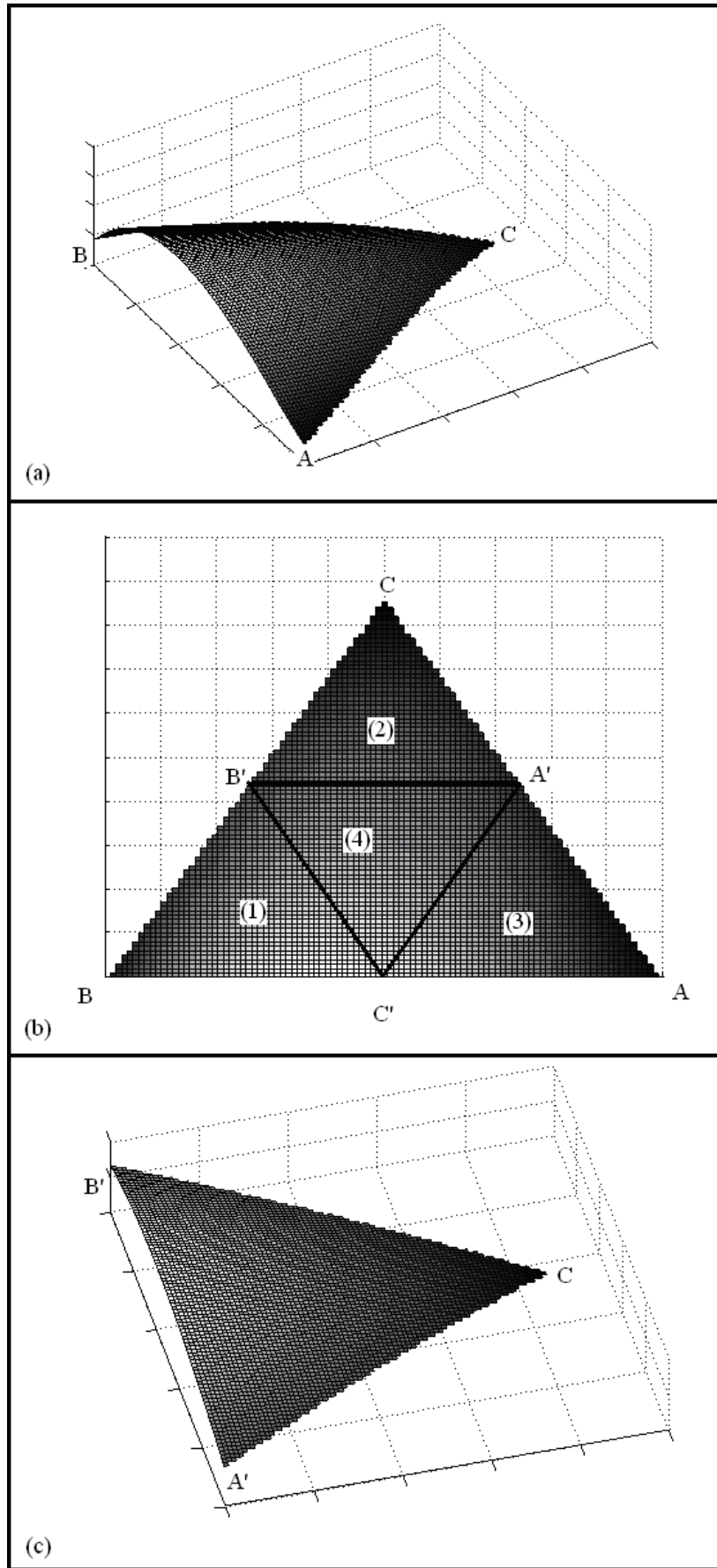


Figure 4-5 Triangular surface division

Similarly in the case of four instances, the square surface can be divided into smaller square or rectangular surfaces. This strategy is helpful in focusing on the region where the good design solutions lie. Figure 4-6 shows a square surface subdivision where a surface (part (a)) is divided into four regions 1, 2, 3 and 4, part (b) and further morphing is carried out on region (3) (part (c)). This application of the proposed visualisation technique and division of the resulting surfaces is further illustrated by case study examples in the following chapters.

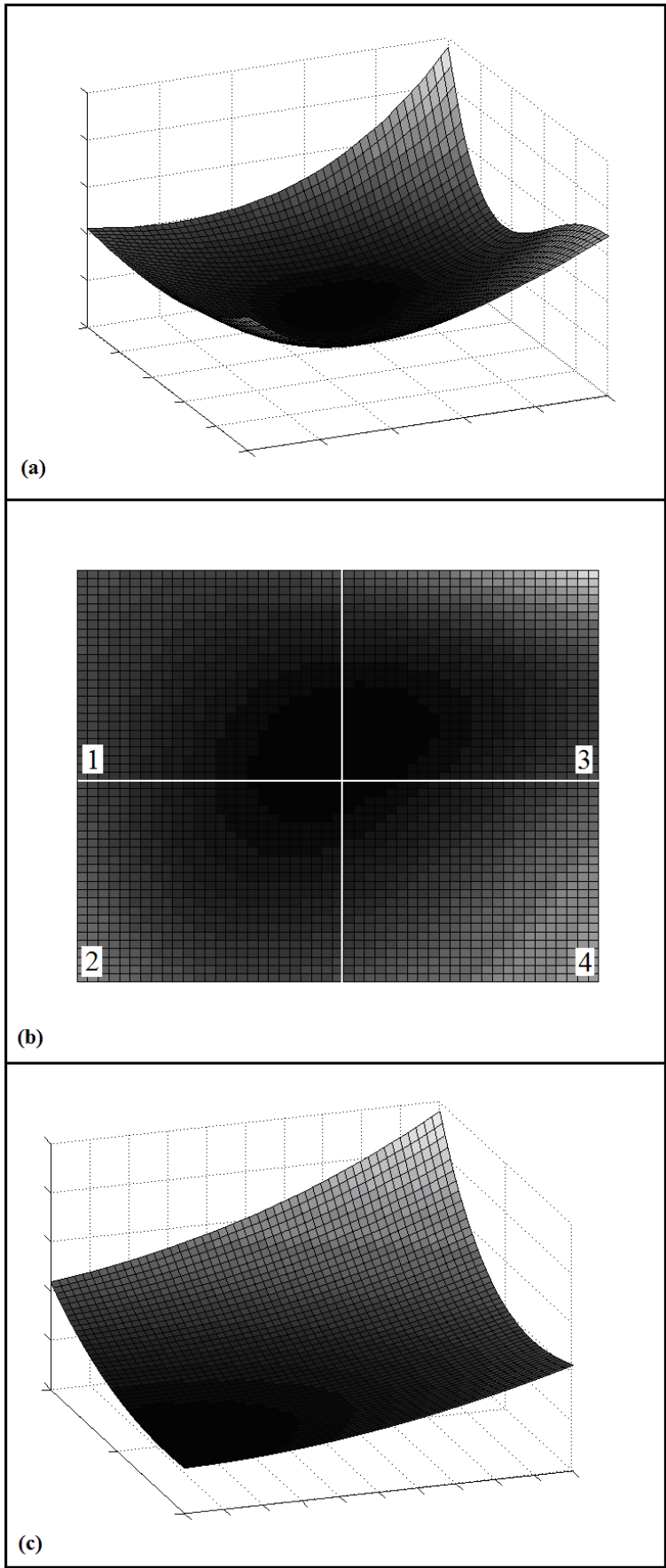


Figure 4-6 Square surface subdivision



## 4.4 Application of the proposed approach in SMEs

The underlying idea of the proposed approach is to be able to represent and thus explore the design space which lies between different design variants. Such an approach has implications in the areas of achieving product rationalisation and can help in meeting the current needs of SMEs (identified in section 2.3, chapter 2). Some of the possible advantages of implementing such a technique in these enterprises are listed below:

1. It is simple technique to understand and implement as the design space between various variants of a design can be represented and understood with the help of simple surfaces.
2. The design knowledge regarding current products is increased using this approach as the performance capabilities of current product designs are made known to the designer. In many cases the designer may need to follow an experimental strategy beforehand, which also helps in gathering fundamental knowledge regarding current product designs.
3. If a company produces a range of variants of a particular design, it may be interested in knowing whether that range can be reduced or otherwise rationalised. If several instances create a roughly flat surface, then, as suggested previously, there is commonality between them. The best morphed design based upon these may be capable of fulfilling the tasks of the original ones and hence these can be replaced by a single design. On other hand, if the surface produced rises steeply between instances, it shows that there are some fundamental differences in the base designs and helps in differentiating products into families. Thus issues related product proliferation can be tackled by the proposed approach.
4. It further helps in refining/improving product designs. This is accomplished by determining the sensitivity of a design to small changes in its parameter values which is represented with the help of surfaces. The design is more robust when it is less sensitive to its setup parameters. Better design solutions can also be identified, which may lie within the design space investigated. If found, these designs can replace the current designs and perform better.

These points are further elaborated by the case study examples in the following chapters. The proposed approach helps in analysing different design variants and evaluating their relative merits. These variants can be present in SMEs in many forms such as isolated machine instances, choice of setup parameters and components. Most of these situations encountered can be broadly classified into three categories.

1. The first category belongs to the situations when isolated machine instances are present and there is limited design information available to the designer.
2. The second category is when some machine instances are present and the designer can also carry out experimental investigation to establish their performance characteristics.
3. The third category is when some form of a mathematical or computer based model for the machine instances is available, which is capable of predicting the machine performance for a range of instances.

All three categories are discussed in the following sections and the applicability of the proposed approach in these cases is highlighted by case study examples.

#### **4.4.1 Isolated machine instances – no provision for experimental investigation**

This case is encountered when various machine instances are present and are known to operate but there is little or no other design information available to the designer. The aim is to increase fundamental design knowledge about the product designs and if possible, to reduce or rationalise the current variety across the product range. There may not be any provision for the designer to carry out any experimental work to establish performance characteristics of these machines. For example, consider a case of seven design variants of an end-load cartoning machine (discussed further in chapter 5). The goal of these machines is to erect packaging carton from a pre-folded, flattened state. These machines essentially differ in production rates, size of cartons that can be handled and degree of automation. There may not be enough information available to carry out a thorough analysis in this case in order to reduce or rationalise these variants. However, a simplified investigation based upon the visualisation stage of the proposed approach can be performed. This case is further discussed in chapter 5.

#### **4.4.2 Experimental investigation is possible**

In this case, machine instances are present and there are provisions for some experimental work to be undertaken, for example investigating the effects on performance by changing setup parameter values. The proposed approach can be applied to the experimental results in order to gain a better understanding of the system. It can also allow some form of mathematical relationship to be obtained to represent the system behaviour. If the system is complex it is likely that techniques from the design of experiments will be necessary to ensure that a good model is obtained without excessive experimental work.

This category also covers the case where a computer based or mathematical model already exists (FE model for example) but it is not economical to run it frequently due to the amount of computational time required.

Chapter 6 further elaborates this problem and the proposed approach is used here to predict the best setup configuration for the machine to erect carton boards.

#### **4.4.3 Computer based models are available**

This third category occurs where a computer based model is available to the designer that can accurately predict performance capabilities of the current design. This may have been obtained on the basis of experimental results as suggested in the previous subsection. In this case, the proposed approach can help in finding the design instances that exist between current design variants. These instances form the design space around original base designs. Knowledge of the design space may help in identifying a better solution, if one lies within the space. It also provides an insight about how sensitive these designs are in small changes to their design parameters.

Chapter 7 presents a case study example where a computer based model is available and how the proposed approach can be helpful in this situation.

## **Chapter 5: Case study 1 - Isolated machine instances**

The previous chapter (section 4.4) identified three situations where the proposed approach can be helpful to a designer for investigating current design variants. This case study discusses one such example of isolated machine instances taken from the Bradman Lake Group, Bristol. They are a privately owned enterprise specialising in design, development, manufacture and service of packaging machinery and represent a typical SME in the UK. The different types of machinery they produce include cartoning machinery, product handing, feeding distribution and storage systems, flow wrapping and end-of line packaging machinery. A variety of products can be seen across the entire range of packaging machines they offer. One example comes from end load cartoning machinery (SL series) that they design. The purpose of this machine is to erect cartons that are initially supplied in the form of pre-folded, flattened “skillets”, then to insert the product inside these cartons and finally seal them. During its operation, skillets are erected first. The flaps on one end of the cartons are then closed and product is inserted through the other open end. This open side is finally sealed using hot melted glue.

In the SL series of end load cartoning machinery, there are seven types of machines available (figure 1-1, chapter 1). These machines include a single end flap sealer (SL 50) and six end load cartoners (SL 80, SL 902, SL 903, SL 904, SL 906 and SL 6000).

In this particular case all the information regarding these variants was obtained from the group website ([www.bradmanlake.com](http://www.bradmanlake.com)) and is limited by their description. It is interesting to know if the proposed approach can be helpful in analysing these design variants. The following sections discuss further investigation of these variants using the proposed approach.

## **5.1 Investigating current machine variants using multi-instance modelling**

All of the end-load cartoning machine variants essentially have similar topology and can be investigated with the proposed approach. However, for the end flap sealer machine (SL50), the cartons are erected manually by the operators and the machine is different from other machines which come with automatic carton erection mechanism. Thus this variant of the cartoning machine is not considered for further investigation as it only serves limited functionality.

The other six types of machines have the same functionality. However, SL 80 differs from the remaining five designs in the way cartons are erected. It incorporates semi-automatic reciprocating feeder instead of an automatic rotary head. This means the SL 80 incorporates different technology and thus is not suitable for further investigation.

The five remaining cartoning machines are well suited for performing multi-instance modelling. Their description is shown in the figure 5-1 and table 5-1. The figure shows two elevations and a plan of the machine. Carton skillets are placed in a hopper at the right. They are extracted from the hopper and during extraction are opened up. They are then placed between moving lugs on a conveyor. Product is inserted into the open skillets as it moves along the conveyor. The end flaps are then folded and glued.

It is clear from their description in table 5-1 that a higher production speed can be achieved by increasing the number of the rotary heads of the feeding system. However, it seems that the range of carton sizes that these machines can handle at higher production speeds is less than the machines with fewer heads at lower production speeds.

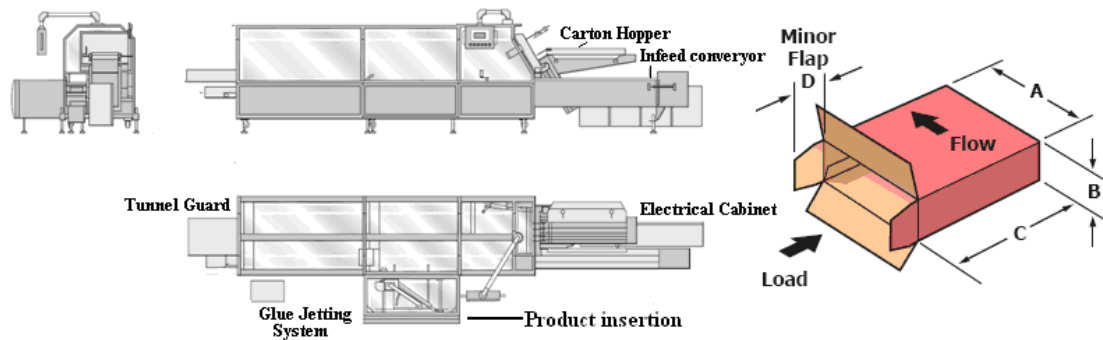


Figure 5-1 End load cartoning machine and various carton parameters Source: [www.bradmanlake.com](http://www.bradmanlake.com)

Table 5-1 Description of end load cartoning machine variants Source: [www.bradmanlake.com](http://www.bradmanlake.com)

Machine model	Type	Speed carton max per min	Carton size		Feed system
			min	max	
SL 902	Automatic 2 head rotary	135	A 50mm B 19mm C 135mm D 19mm	A 254mm B 76mm C 305mm D 40mm	Manual or auto
SL 903	Automatic 3 head rotary	200	A 50mm B 19mm C 135mm D 19mm	A 254mm B 100mm C 304mm D 40mm	Manual or auto
SL 904	Automatic 3 head rotary	270	A 76mm B 19mm C 116mm D 19mm	A 200mm B 115mm C 305mm D 40mm	Manual or auto
SL 906	Automatic 4 head rotary	350	A 76mm B 19mm C 116mm D 19mm	A 254mm B 115mm C 300mm D 40mm	Manual or auto
SL 6000	Automatic 2 head rotary	120	A 50mm B 19mm C 114mm D 19mm	A 350mm B 100mm C 330mm D 40mm	Manual or auto

An important point here is that there is no further information available on these variants. In order to determine the performance characteristics of these machines following assumptions are made:

- The variants can be classified into three categories according to type of rotary head used. Thus three types of machines are available namely 2 head rotary, 3 head rotary and 4 head rotary. These three types can be used as three base instances for further investigation.

- For simplicity, the volume of the carton ( $A*B*C$ , Table 5-2) is considered as the size of the carton (minimum or maximum) that a particular instance can handle.

Finally the variants are classified (Table 5-3) according to the type of rotary head used, maximum production speed, minimum and maximum volume of the cartons that a particular rotary head can handle.

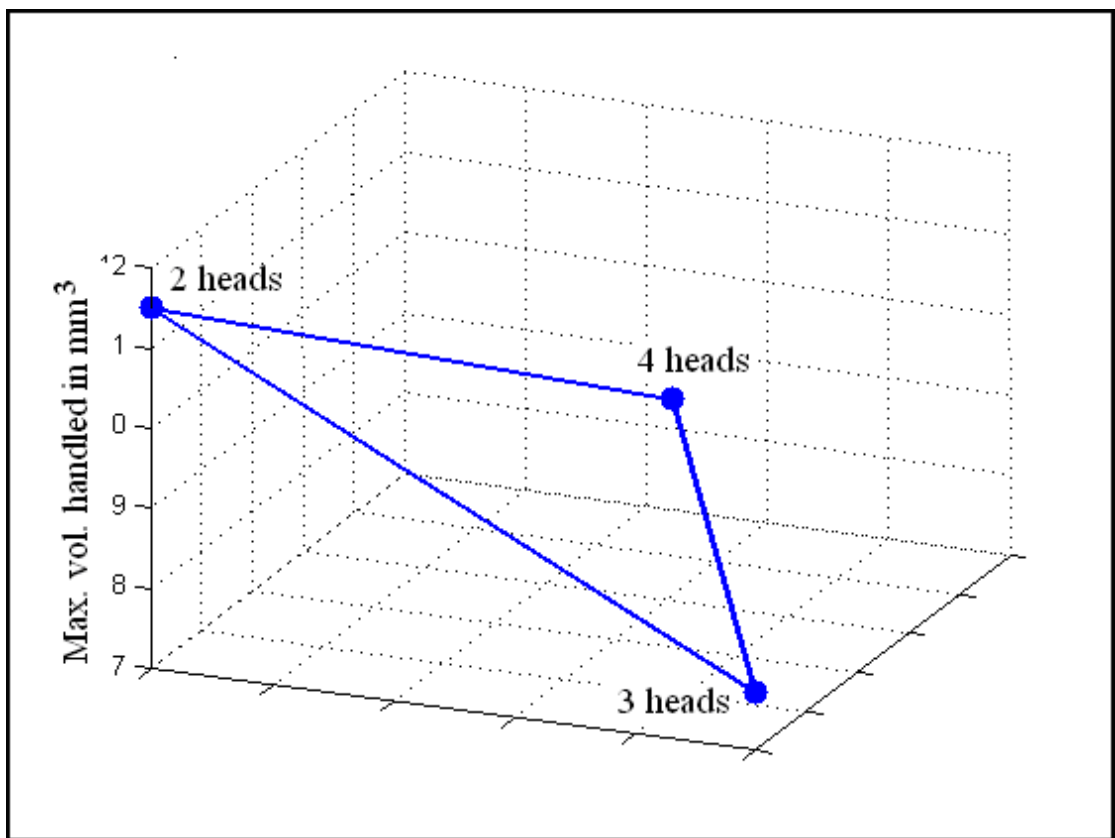
**Table 5-2 A simplified classification of the variants**

<i>Machine model</i>	<i>Type</i>	<i>Speed carton max per min</i>	<i>Carton size in mm<sup>3</sup> (volume A*B*C) (x10<sup>6</sup>)</i>	
			<i>min</i>	<i>max</i>
			SL 902	Automatic 2 head rotary
SL 903	Automatic 3 head rotary	200	0.128	7.722
SL 904	Automatic 3 head rotary	270	0.168	7.015
SL 906	Automatic 4 head rotary	350	0.168	8.763
SL 6000	Automatic 2 head rotary	120	0.108	11.5

**Table 5-3 Further simplification of the variants**

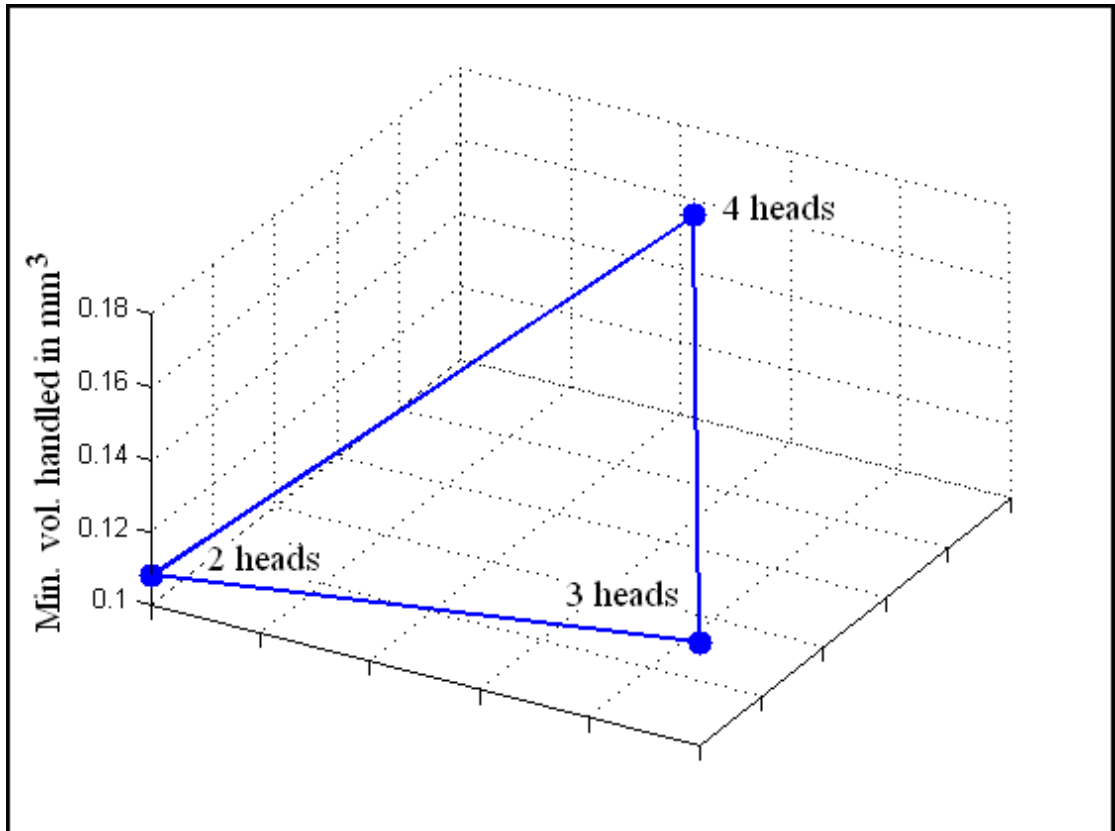
<i>Type of rotary head</i>	<i>Speed carton max per min</i>	<i>Carton size in mm<sup>3</sup> (volume A*B*C) (x10<sup>6</sup>)</i>	
		<i>min</i>	<i>max</i>
		Automatic 2 head rotary	135
Automatic 3 head rotary	270	0.128	7.722
Automatic 4 head rotary	350	0.168	8.763

Now as there is no quantification criterion available for determining the performance characteristics of these machines, so the parametric morphing stage of the proposed approach can be omitted. One can start directly by plotting the base instances as three corner of a triangular surface. For the first plot, the maximum values of the carton size that a particular machine variant can handle are used as a performance criterion and are plotted along the z-axis (figure 5-2). Similarly another simplified triangular surface can be plotted using the minimum carton sizes that these machine variants can handle (figure 5-3).



**Figure 5-2 A simplified surface plot for maximum carton sizes that can be handled**





**Figure 5-3 A simplified surface plot for minimum carton sizes that can be handled**

Now these two surfaces can be combined and represented as a single plot (shown in figure 5-4). The figure shows that the carton size range that the 2 head rotary machine can handle is largest (ranging from 0.108 to 11.5 mm<sup>3</sup>). However, the maximum possible production rate that can be achieved with this variant is only 135 cartons per minute (CPM). Similarly the 3 head rotary machine can handle a smaller range of carton sizes (ranging from 0.128 to 7.722 mm<sup>3</sup>) and is capable of running at the production speeds up to 270 CPM. The 4 head rotary machine, however, does not follow the same trend. It can handle a better range compared to the 3 head rotary system when it comes to handling maximum carton sizes and is not very far away either for handling cartons of smaller sizes either (ranging from 0.168 to 8.763 mm<sup>3</sup>).

Figure 5-5 shows the further plotting of carton size ranges that various variants can handle. It is clear from the figure that at least two machine variants SL 902 and SL 903 are redundant. Their functionality can be achieved by variants SL 6000 and SL 904 respectively, if these machines are made capable of running at their full production speed capabilities.

On the other hand, as observed earlier, the 4 head rotary machine is better at handling maximum carton sizes when compared to the 3 head rotary machine. Also it is not far off from 3 head rotary machine when it comes to handling cartons of smaller sizes. Now it may also be possible to extend the minimum carton sizes range that it can handle to  $7.722 \text{ mm}^3$  from  $8.723 \text{ mm}^3$  without affecting its productivity. If that is possible then the entire 3 head rotary machine range is redundant. There is only a need of two machine variants that can satisfy all the performance demands being met currently.

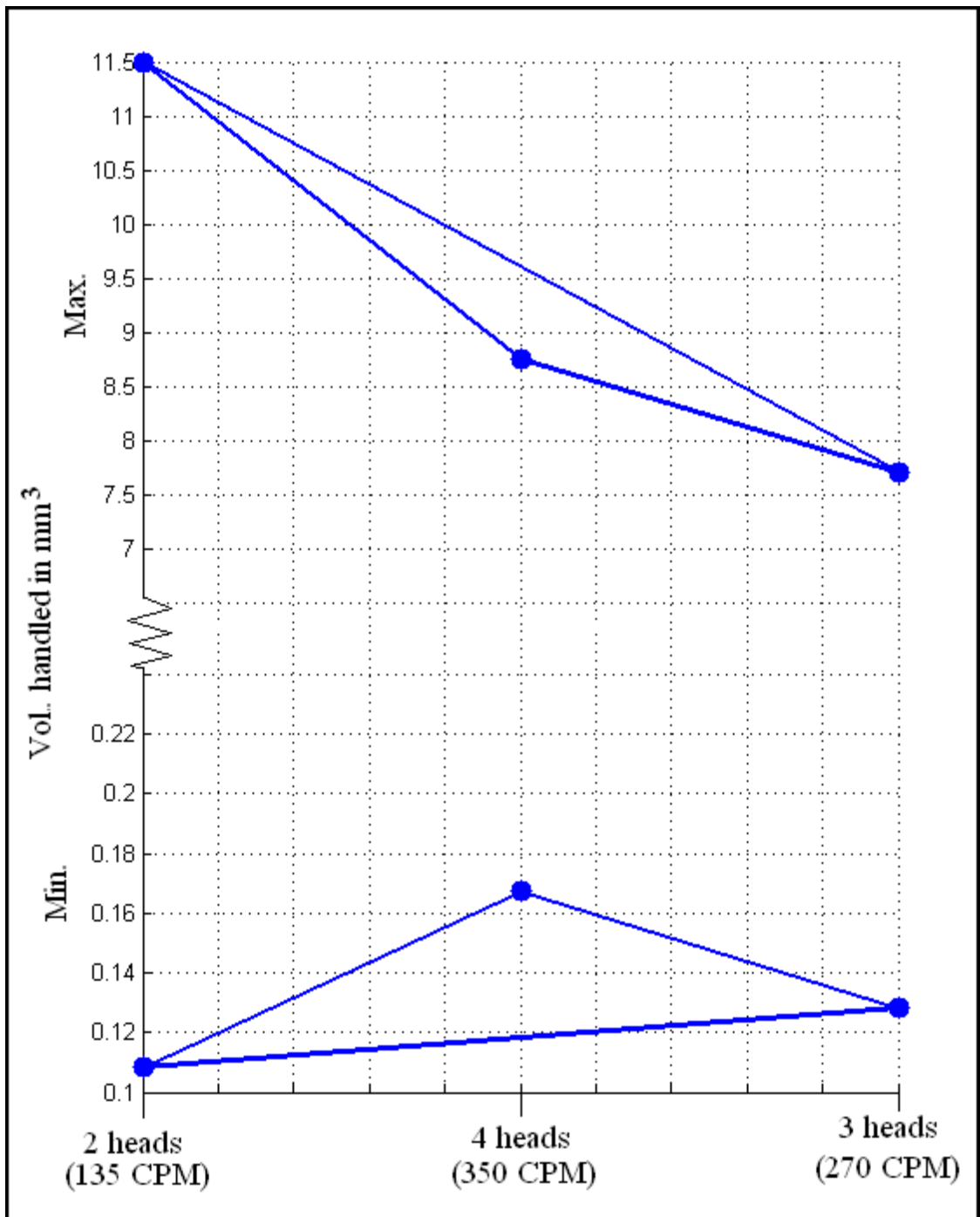


Figure 5-4 Combined plot of the surfaces

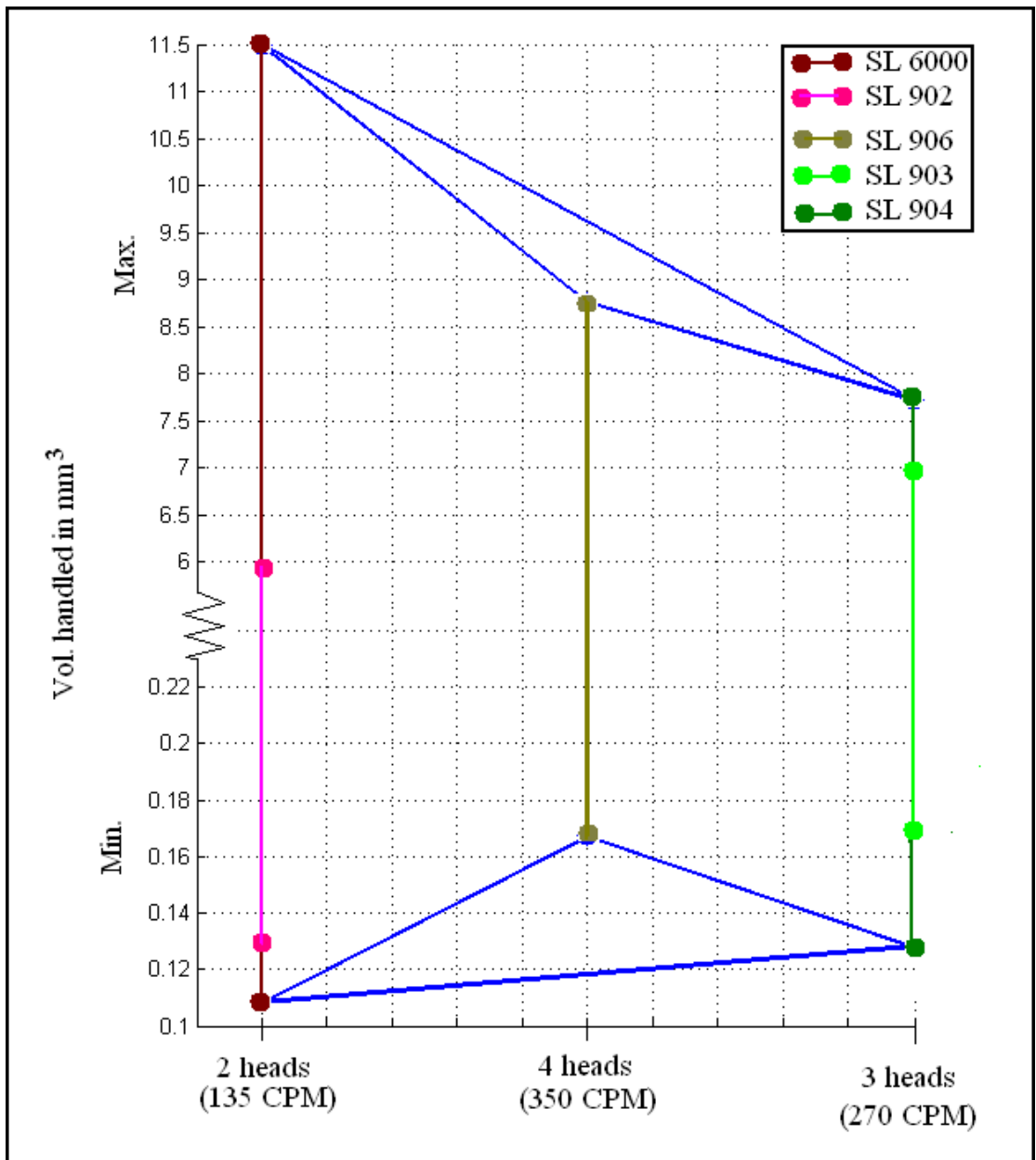


Figure 5-5 Operating ranges of various instances

## **5.2 Discussion**

This case study presents a simplified investigation of the proposed multi-instance modelling approach. In this particular case, the proposed approach helped in rationalising the current range of products by identifying redundant design variants. It is shown here that even in the absence of complete design knowledge, the proposed approach can be applied and current design variants investigated. The designer can get sensible results by re-formulating the limited data available and such an investigation can help the top management of the enterprise as well in deciding their future strategy regarding supporting the current machine variants.

## **Chapter 6: Case study 2 – Experimental investigation is possible**

The previous chapter described a case where the proposed multi-instance modelling approach was applied to an example where only isolated machine instances were available. There was a little information regarding the designs and an investigation was performed using the proposed approach. This chapter introduces another application of the proposed technique when experimental investigation can be carried out to understand the existing designs better.

For this purpose, a carton erection machine is analysed for its ability to erect cartons. This machine is normally supplied by various manufactures (mainly SMEs) with different setup configurations (parameters). The performance of the machine is believed to be directly affected by these parameters. However there is little known about their effects on the machine performance. Thus the setup parameters of the carton erection machine are investigated here. The different available setup configurations in this case are assumed to be base instances for the multi-instance modelling approach and the design space between these configurations is further explored to investigate design sensitivity to its set up parameters and establish best machine settings for erecting cartons.

## 6.1 Background

As described the previous chapter the purpose of this machine is to erect cartons (supplied in the form of pre-folded, flattened skillets), insert product in them and finally seal them. A common method to carry out the skillet erection process is using epicyclic mechanism (figure 6-1).

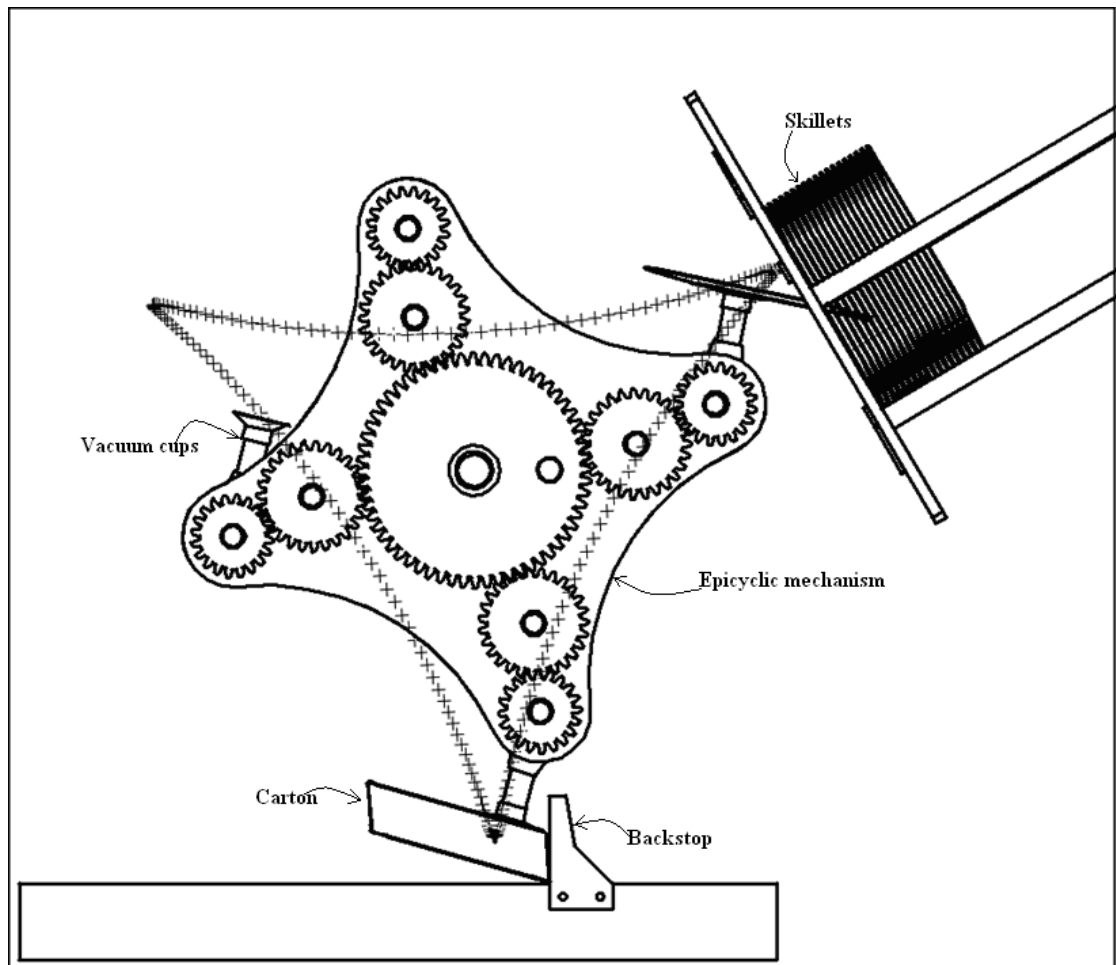


Figure 6-1 Carton erection process using epicyclic mechanism

Ideally skillets should open in a parallelogram fashion as shown in figure 6-1. But under certain conditions these skillets tend to buckle (figure 6-2). Here the process is same as in figure 6-1, but in part (1) there is no initial separation of the sides. In parts (2) and (3) the sides stick together instead of being separated and in part (4) improper opening has occurred. The reasons for this buckling are still not well understood.

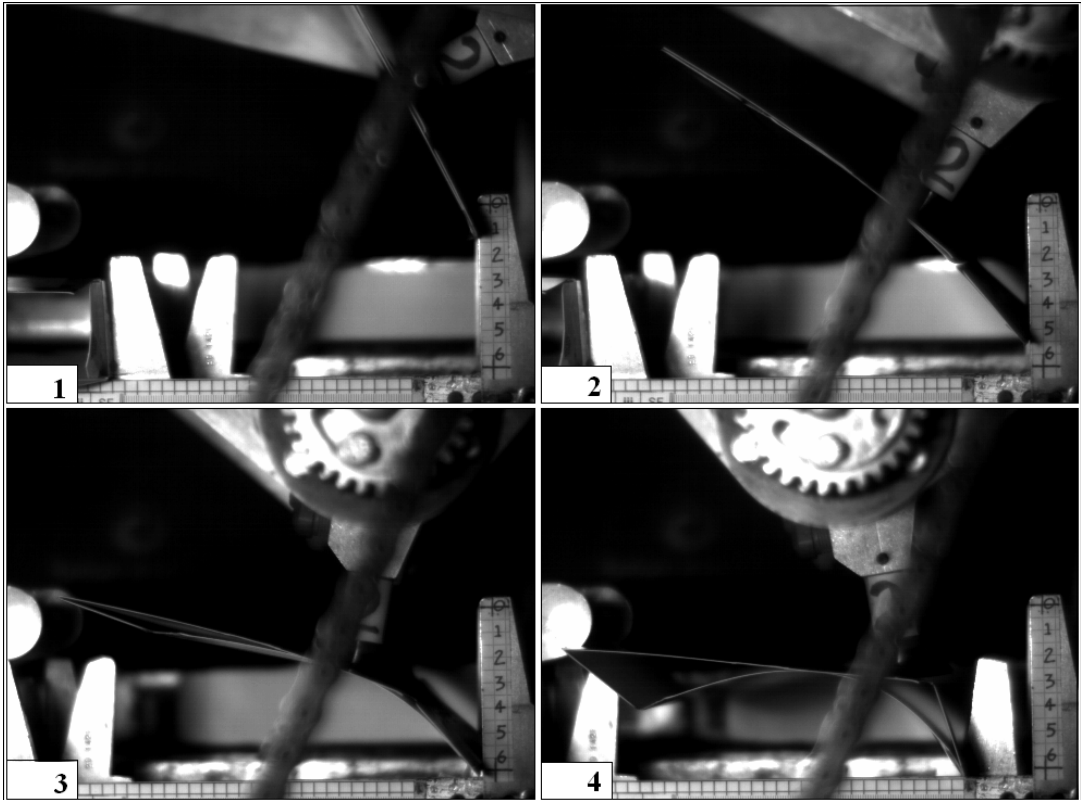


Figure 6-2 Buckling in skilnet erection process

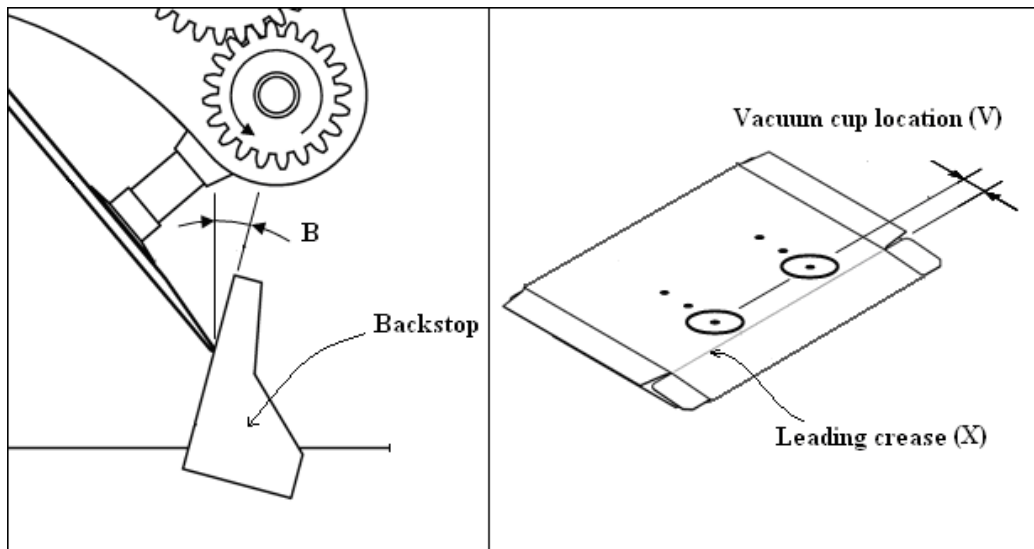


Figure 6-3 Machine settings investigated

Several factors have been identified, in the previous research work (Sirkett *et al.* 2007), which are thought to predispose a skilnet to buckling. These factors include initial opening of skilnet walls (termed “plim”), stiffness of the board and creases in relation to the size of skilnet, the position and orientation of the backstop (figure 6-3, left), positioning of vacuum cup with respect to leading crease (figure 6-3, right) and



production speed. These factors can be broadly classified into three categories: environmental conditions (storage conditions and moisture content that affects plim), material properties and machine setup (production speed, backstop angle and location of vacuum cup with respect to leading crease of skillet). The complex interrelationships between these factors govern the carton erection process. There is little known so far about these complex interactions that take place during the erection process and the reasons for buckling of the cartons. However past experiences show that buckling is more likely to occur at higher production speeds. It is thought that by establishing the best machine settings, buckling of the cartons can be reduced to some extent.

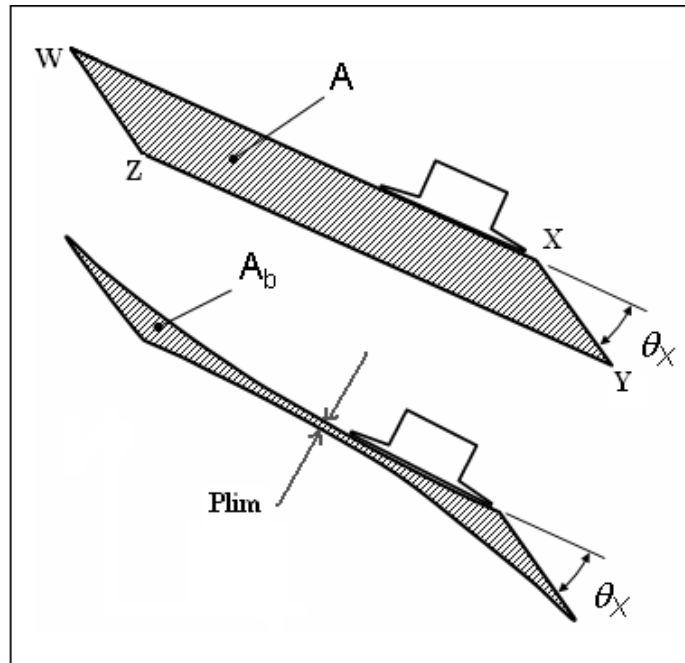
Sirkett *et al.* (2007) created a finite-element computer simulation of carton processing to determine ideal machine settings. This carton model was validated against experimental results and this showed a good agreement with the physical system. The model can be used to study the effects of variation in material properties, pack properties (carton design) and machine settings. Sirkett *et al.* experimented with three machine settings (production speed, backstop angle and vacuum cup position) in order to investigate response (opening of cartons). Their effect on carton erection was studied and validated by analysing the computer model and actual experimentation on the machine. This study provided a valuable insight into the effects of changing machine settings on the carton erection process at various production speeds. However it incorporated one-factor-at-a-time approach, where effects of changing machine settings on carton buckling was studied individually.

In order to investigate the effects of interactions present between different factors, another study (Singh *et al.* 2008b) was conducted. This was essentially an experimental investigation on an actual machine and it is used here to illustrate how the proposed approach can be used with relatively little data and when that data is used to obtain some form of computational model.

The machine settings were tested by varying the three different factors (production speed  $P$ , backstop angle  $A$ , and vacuum cup location  $C$ ). The performance of the system was taken as the “opening ratio”  $R$ . This quantifies the buckling (distortion) in

the skillet walls. It is the ratio of cross sectional area of a partially open carton,  $A_b$ , to the area,  $A$ , of the parallelogram representing a non-distorted carton (figure 6-4).

$$R = A_b / A$$



**Figure 6-4 Quantification of buckling**

A perfectly opened carton has a parallelogram shape without any distortion in the carton walls and the value of the  $R$  in that case would be 1. Any other value less than 1 signifies the presence of buckling. It was shown by Sirkett *et al.* that the settings that produce opening ratio less than 0.6 are less likely to open up during the later stages of the erection process and can cause machine jamming.

The values for the opening ratio  $R$  obtained for various combinations of the factor are shown in table 6-1. These combinations were actually chosen using techniques from the design of experiments but for the moment that fact is ignored. The results are thus simply values of  $R$  for some (arbitrary) combination of the inputs.

**Table 6-1 Box-Behnken design with actual/coded values for various factors and their responses**

Experiment	Production speed (P)	Backstop angle (B)	Vacuum cup location (V)	Opening ratio (R)
1	150 (-1)	0 (-1)	38 (0)	0.8812
2	150 (-1)	30 (+1)	38 (0)	0
3	250 (+1)	0 (-1)	38 (0)	0.3839
4	250 (+1)	30 (+1)	38 (0)	0
5	150 (-1)	15 (0)	30 (-1)	0.9277
6	150 (-1)	15 (0)	46 (+1)	0.9697
7	250 (+1)	15 (0)	30 (-1)	0.1854
8	250 (+1)	15 (0)	46 (+1)	0.7306
9	200 (0)	0 (-1)	30 (-1)	0.47303
10	200 (0)	0 (-1)	46 (+1)	0.6145
11	200 (0)	30 (+1)	30 (-1)	0.5765
12	200 (0)	30 (+1)	46 (+1)	0
13	200 (0)	15 (0)	38 (0)	0.5356
14	200 (0)	15 (0)	38 (0)	0.7080
15	200 (0)	15 (0)	38 (0)	0.5667

## 6.2 Exploring setup parameters sensitivity – a simplified investigation based upon the experimental results

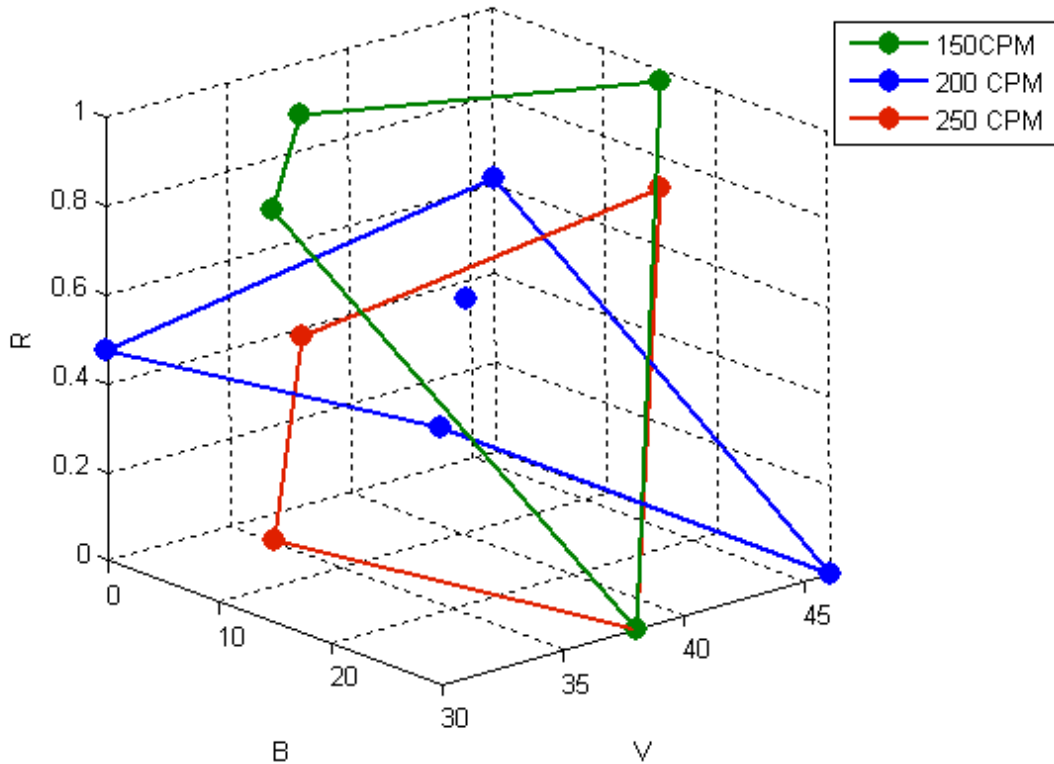


Figure 6-5 A simplified investigation

Using the proposed visualisation technique the results can be displayed as shown in figure 6-5. Here the response values (opening ratio,  $R$ ) obtained for various machine settings ( $B$  &  $V$ ) at different production speeds ( $P$ ) are plotted in the figure. It is clear from the figure that opening ratio decreases with increase in the production speed. Increase in the backstop angle ( $B$ ) also decreases the opening ratio. The increase in vacuum cup location ( $V$ ) increases the opening ratio, however this effect is small when compared to other effects due other two factors. The figure also shows the machine is capable of erecting cartons ( $R > 0.6$ ) at production speeds of 250 CPM when backstop angle is inclined to 15 degrees and vacuum cup location is 46mm.

Thus the diagram provides a rough picture of how the machine behaves. As noted in the last section, the combinations used in table 6-1 are not arbitrary but are based on a Box-Behnken design from the design of experiments. These designs are response surface designs that can fit a full quadratic model (Khuri & Cornell 1987).

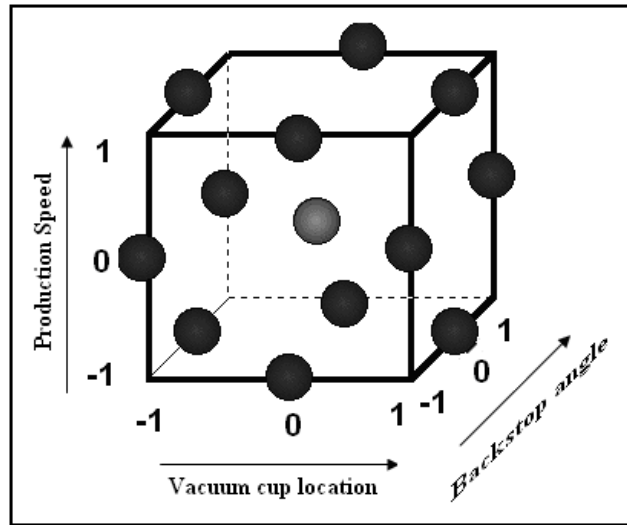


Figure 6-6 Box-Behnken design

In Box-Behnken design, the experiment combinations are designed at midpoints of the edges of the process space and at the centre (shown in figure 6-6). The experiments thus generated (in both coded variables and real world units) are shown in table 6-1. Once results were obtained, the response surface methodology (RSM) was used to derive a mathematical model. The generated (fitted) model is shown below:

$$R = 0.603 - 0.185P - 0.222B - 0.019V + 0.124PB + 0.126PV - 0.180BV - 0.287B^2 + 0.100V^2 \quad (1)$$

where  $R$  is the opening ratio,  $P$  is production speed,  $B$  is the backstop angle and  $V$  is the position of vacuum cup from the leading crease  $X$  of the skillet. The fitted model (equation 1) helped in establishing the optimal setting for erecting cartons at high speeds. The predicted results were further validated by performing production trial runs at the new optimised settings.

### **6.3 Exploring setup parameters sensitivity – a thorough investigation based upon the fitted model**

The creation of equation (1) as a “model” of the system means that a greater level of investigation can be undertaken. In particular, it can be used to explore the sensitivity of the machine to changes in its set-up parameters. Such an analysis can help in refining existing design. The rest of section simply gives some examples of such analysis.

To fit this analysis into the approach of this thesis, the known working set-up configurations are here considered as different instances of a successful design. The machine is originally designed to run at  $P = 250$  CPM (cartons per minute) and there are three known setup configurations of the carton erector machine.

#### **Configuration 1**

This is the initial configuration of the machine with which it was supplied by its manufacturer. The angle of the fixed backstop ( $B$ ) is 15 degrees (to the vertical) and the location of the vacuum cup ( $V$ ) is 30 mm (figure 6-3) from the leading crease of the skillet to be erected.

#### **Configuration 2**

This is the configuration proposed by Sirkett *et al.* (2007). In this configuration the backstop angle ( $B$ ) is inclined at 0 degrees (to the vertical) and location of the vacuum cup ( $V$ ) is again 30 mm from the leading crease of the skillet to be erected.

#### **Configuration 3**

This configuration was predicted by Singh *et al.* (2008b) and is thought to be the optimal configuration for erecting cartons at high speeds. In this configuration the backstop ( $B$ ) is inclined at 8 degrees (to the vertical) and location of the vacuum cup ( $V$ ) is 46 mm from the leading crease of the skillet.

It is interesting to know what the solution space looks like between these configurations. The measure of performance in this case is how efficiently a particular

configuration erects the skillets and for this purpose the fitted model (equation 1) is used to predict the opening ratio  $R$ .

### 6.3.1 Parametric morphing of the given configurations

The parametric morphing is then conducted to generate the interpolated solution space. As mentioned earlier, for the purpose of morphing and obtaining opening ratios for various interpolants, the quadratic model proposed by Singh *et al.* (2008b) is used. As the machine is designed to operate at various production speeds (upper limit is 250 CPM), it is desirable to investigate the setup parameters sensitivity at different speeds. The configurations 1, 2 and 3 are represented as three base instances and weights are taken as  $\alpha_1 = \gamma$ ,  $\alpha_2 = \beta$  and  $\alpha_3 = \alpha$  respectively. The surface resulting in-between them shows the design interpolants. The height of the surface at any point gives the value of opening ratio produced by a particular instance generated at that point.

#### Case 1 ( $P = 150$ CPM)

Consider the first case with the production speed of 150 CPM. The three configurations are morphed and opening ratios for various interpolants are calculated using the fitted model. It is then recorded and plotted according to the proposed visualisation strategy. The resulting surface is shown the figure 6-7.

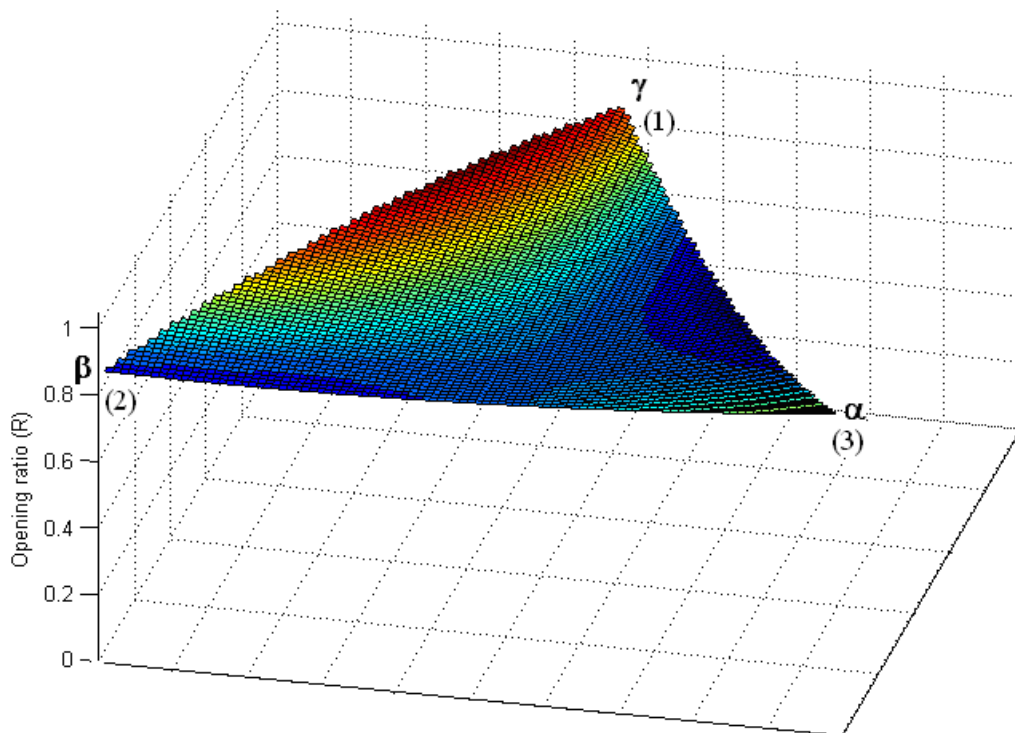
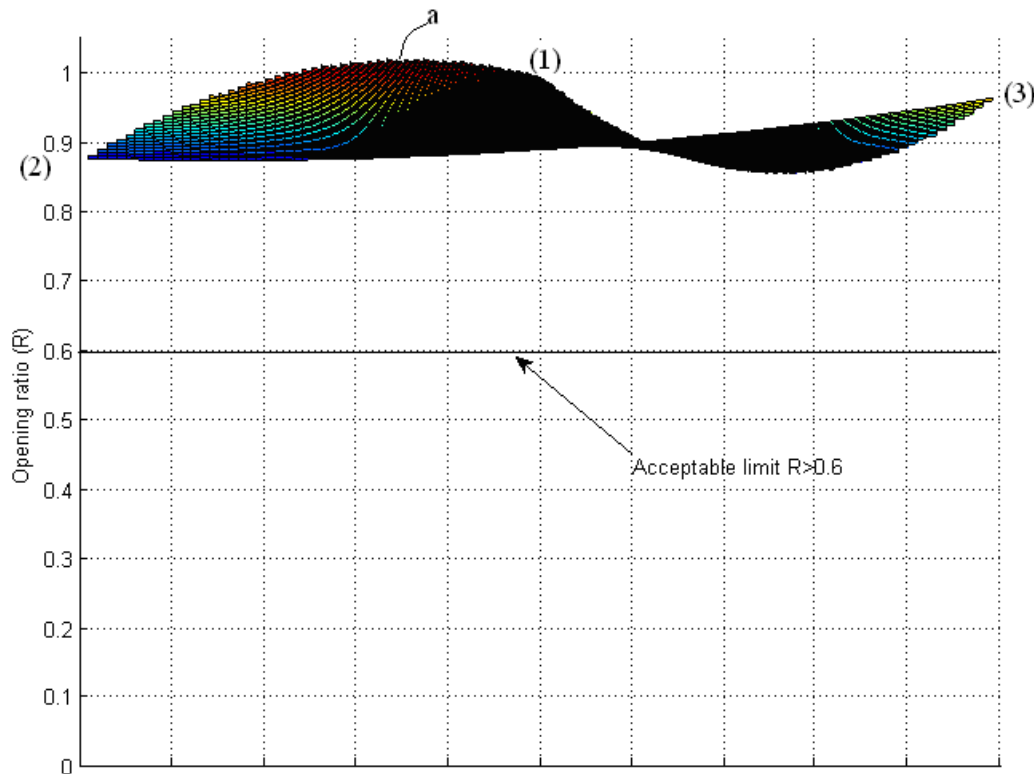


Figure 6-7 Opening ratios for various configurations ( $P = 150$ )



The resulting surface is almost flat. It means that the machine has got a little or no sensitivity towards change in setup parameters. This also validates the observation that machine performs well at low production speeds. Figure 6-8 shows the side view of the same surface as well as the acceptable limit of the opening ratio ( $R > 0.6$ ).



**Figure 6-8 Side view of the surface ( $P = 150$ )**

It is clear from the figure that all of the designs generated as a result of parametric morphing, perform well over the acceptable limits of the required performance criteria. However a better solution (point 'a' in the figure) is found lying between configurations 1 and 2, where the weights at the corresponding instances are 0.3 ( $\gamma$ ) and 0.7 ( $\beta$ ) respectively. The opening ratio found at this point is 1.019.

### **Case 2 ( $P = 175$ CPM)**

The production speed of 175 CPM is considered during the second case. The resulting surface is shown in figure 6-9. This also results in almost flat surface indicating that

machine is still little sensitive to the setup parameters. The overall height of the surface, however, is dropped in this case. This is clearly a sign of decreasing performance values for each of the interpolants generated as a result of morphing.

The side view of the same surface in figure 6-10, shows that all the generated designs are still over the acceptable limits of the performance criteria. This means that any configuration of the machine (within the morphed region) can be used to erect cartons efficiently.

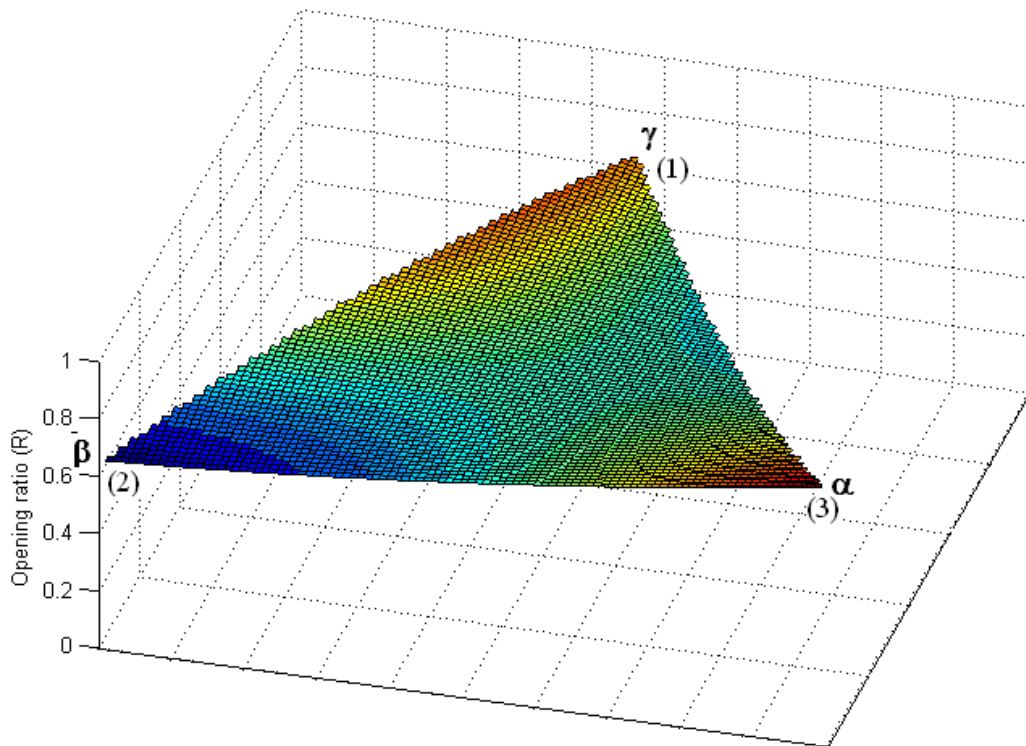
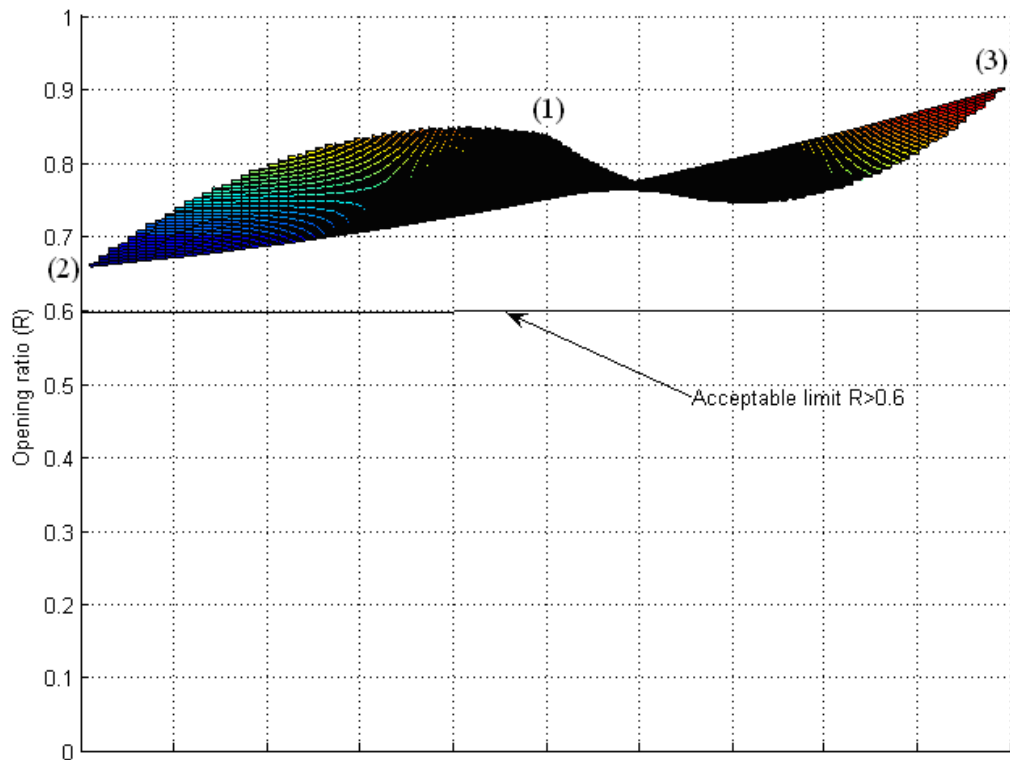


Figure 6-9 Opening ratios for various configurations ( $P = 175$ )



**Figure 6-10 Side view of the surface ( $P = 175$ )**

The best instance found in this case is configuration 3 with an opening ratio of 0.905.

### **Case 3 ( $P = 200$ CPM)**

Now consider the case of production speed at 200 CPM. It can be seen that the surface is comparatively less flat this time (figure 6-11 and 6-12). This is an indication of sensitivity of the machine to setup parameters at higher speeds.

Figure 6-12 shows that not only is the surface less flat but also some of the region on the surface is also lying below the acceptable performance limits. The configuration 2 produces smallest opening ratio and is no longer acceptable for performing the carton erection operation. The other two configurations are still good and over the acceptable performance limits. The acceptable region on the resulting surface is shown in figure 6-13. The best instance found in this case is configuration 3 with an opening ratio of 0.847.

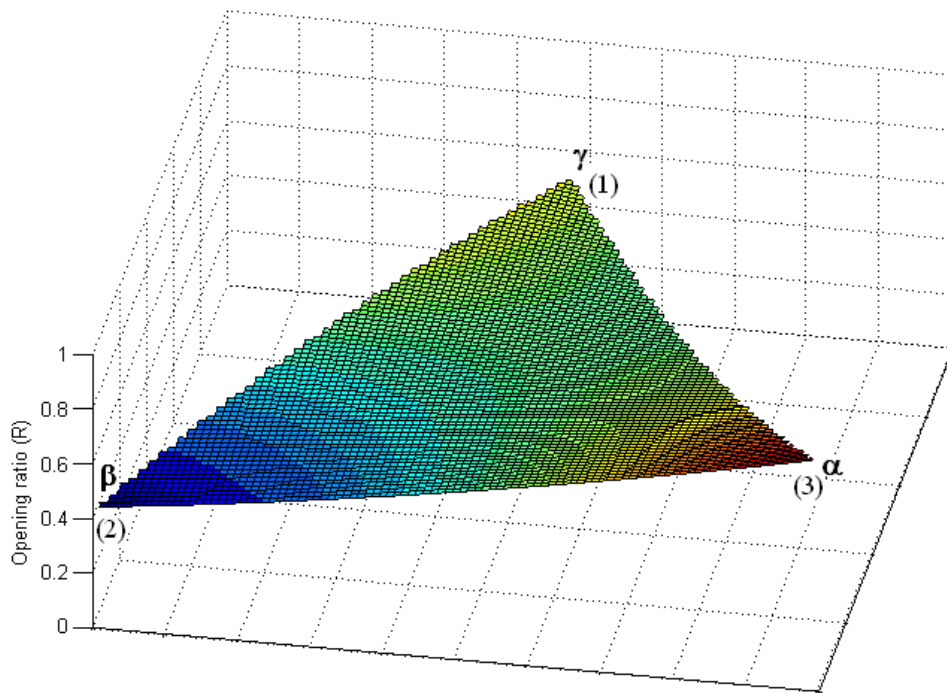


Figure 6-11 Opening ratios for various configurations ( $P = 200$ )

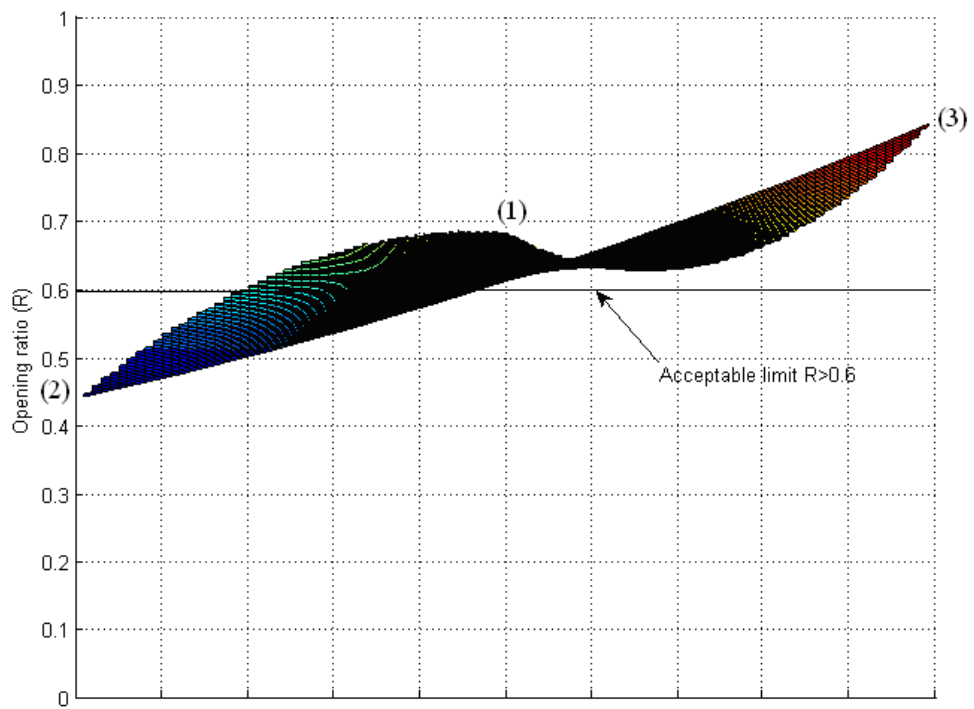


Figure 6-12 Side view of the surface ( $P = 200$ )

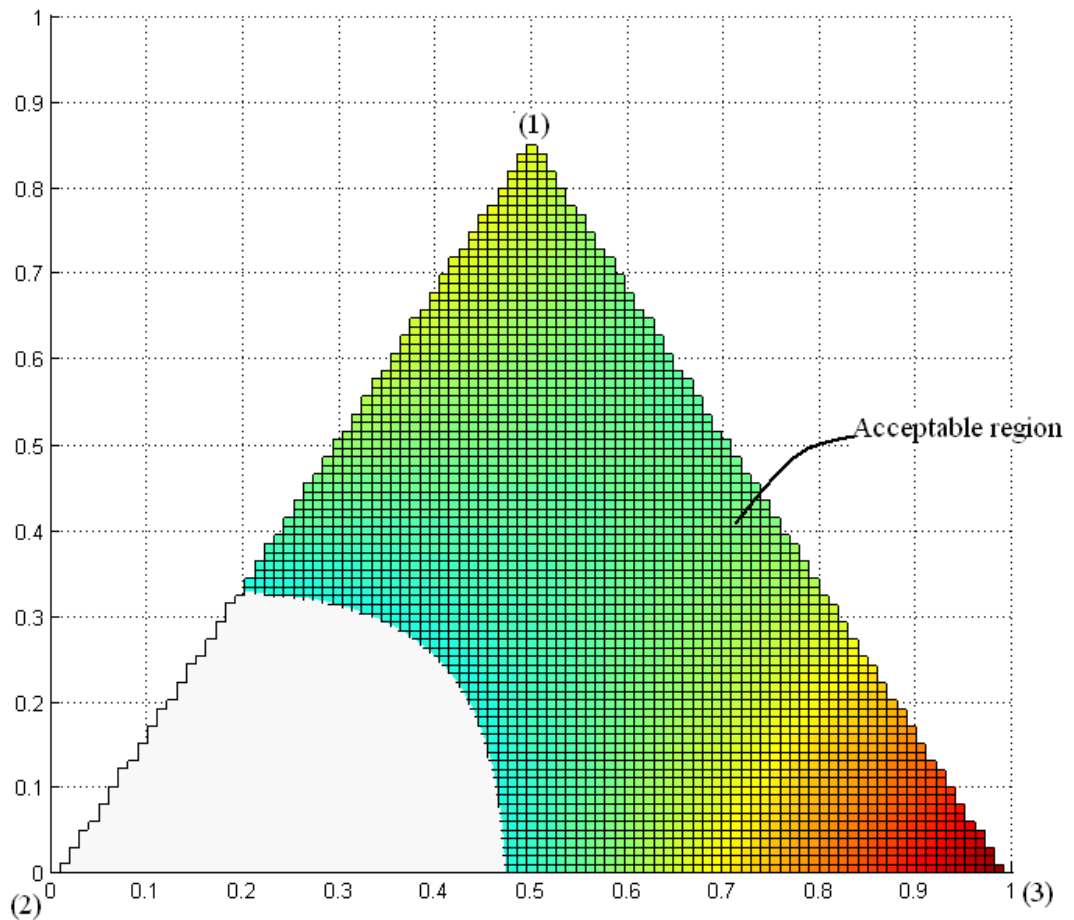


Figure 6-13 Acceptable region ( $P = 200$ )

#### Case 4 ( $P = 225$ CPM)

In this case the production speed is further increased to 225 CPM. The resulting surface is shown in figure 6-14. The flatness of the surface is further decreased now and both configurations 1 and 2 are now lying below the acceptable performance levels (figure 6-15).

It can be seen that the machine is more sensitive to setup parameters now. The acceptable region in this case has substantially reduced as shown in figure 6-16. The best instance found in this case is configuration 3 with an opening ratio of 0.788.

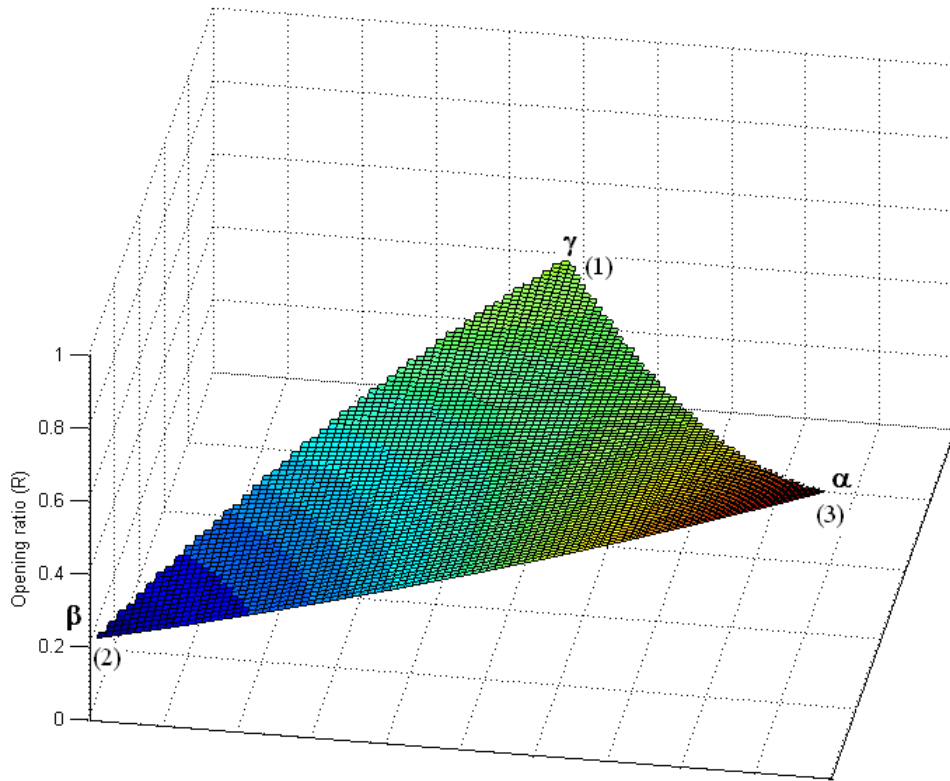


Figure 6-14 Opening ratios for various configurations ( $P = 225$ )

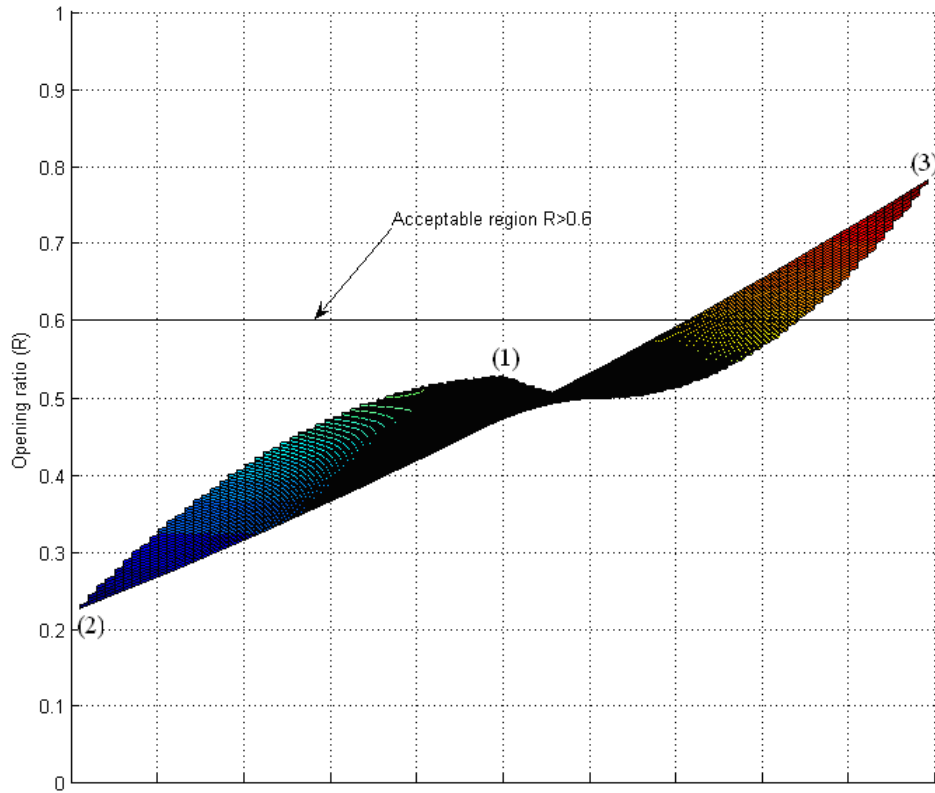
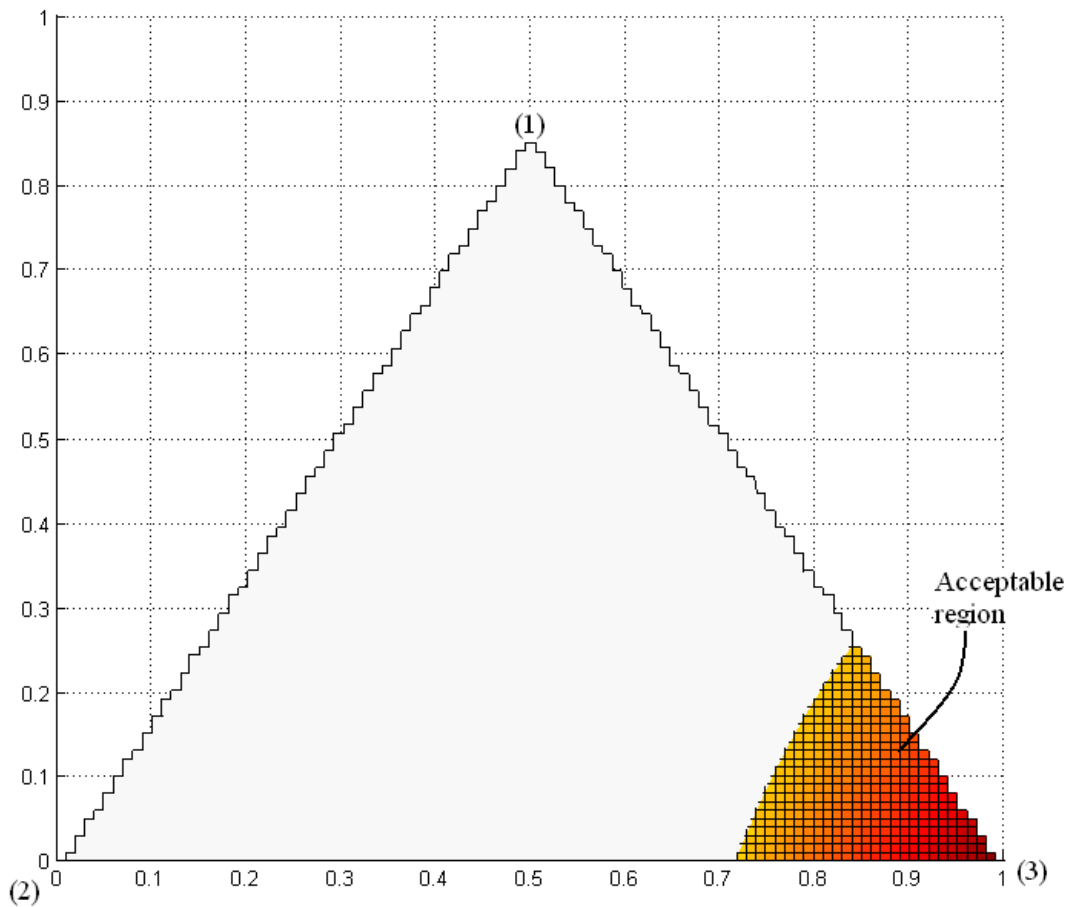


Figure 6-15 Side view of the surface ( $P = 225$ )



**Figure 6-16 Acceptable region ( $P = 225$ )**

### **Case 5 ( $P = 250$ CPM)**

Finally machine setup is investigated at maximum production speed of 250 CPM. The results even in this case are following the earlier trend. The machine is very sensitive to the setup parameters as clear from the resulting surface (figures 6-17 and 6-18).

Both configurations 1 and 2 in this case are also lying below the acceptable performance levels. The overall height of the surface has dropped as well. There is small acceptable region of the interpolated designs is left in this case (figure 6-19). The best instance found in this case is configuration 3 with an opening ratio of 0.730.

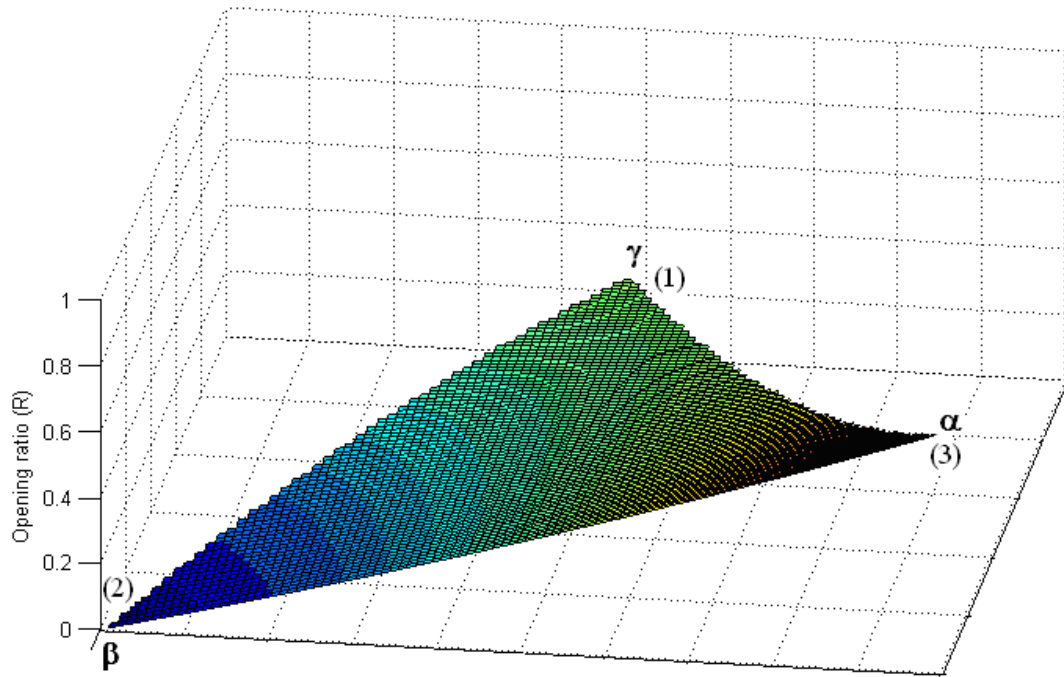


Figure 6-17 Opening ratios for various configurations ( $P = 250$ )

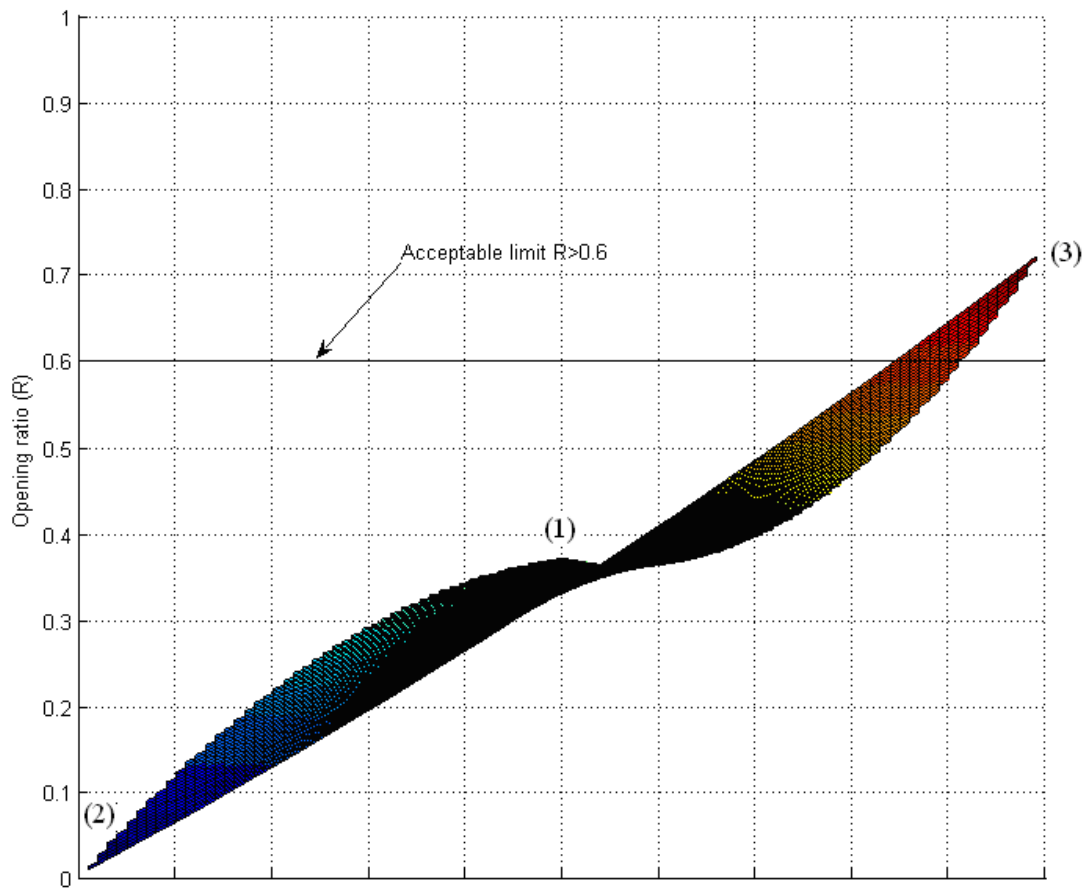


Figure 6-18 Side view of the surface ( $P = 250$ )



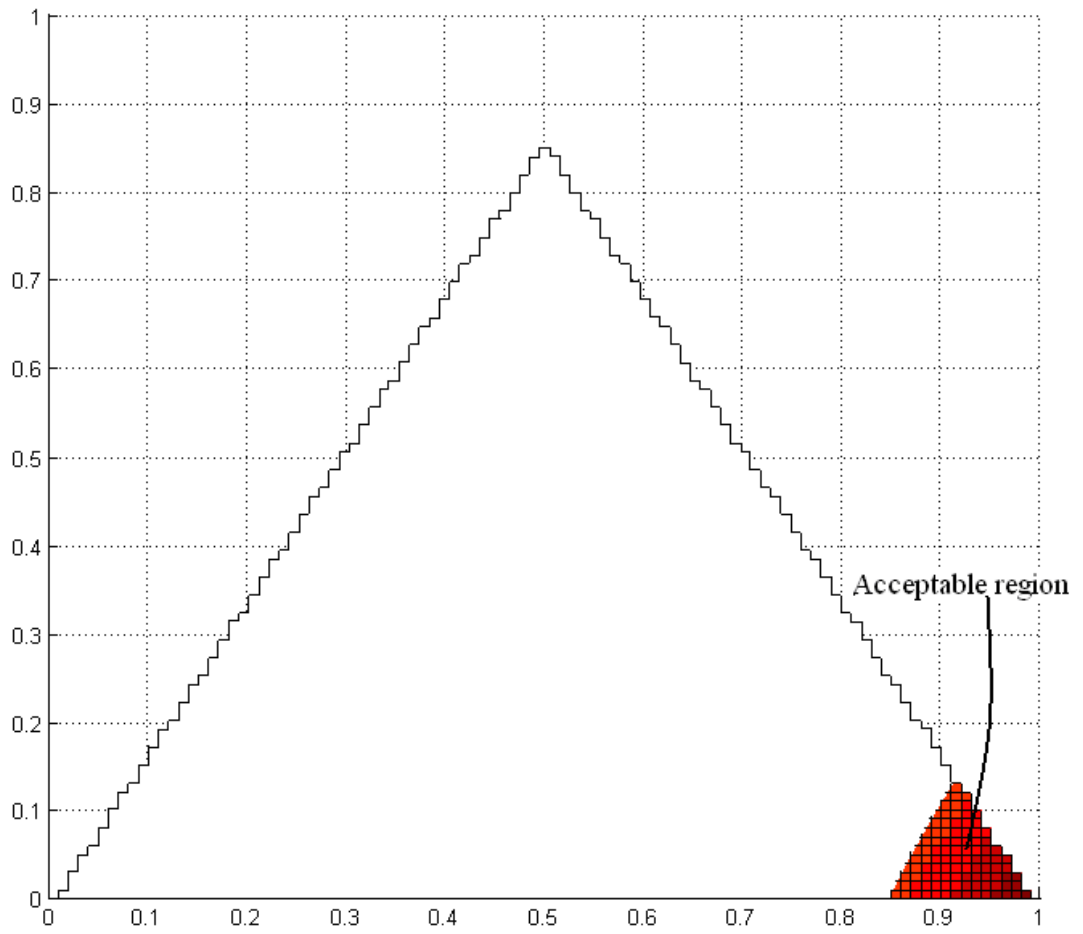


Figure 6-19 Acceptable region ( $P = 250$ )

## 6.4 Discussion

To sum up the results, all the surfaces produced so far can be plotted together as shown in figures 6-20 and 6-21. The figures show the solution space for the carton erector machine for its various configurations at different production speeds. It is clear from the figures that machine sensitivity to the setup parameters increases with an increase in the production speed. There were three setup configurations investigated. At lower speeds (<175 CPM) any configuration can produce desired results. However at higher speeds the configuration 2 is the most sensitive and skillet buckling is highly likely to occur with this setup.

Configuration 1 is more promising and can be used up to the production speeds of 200 CPM. Configuration 3, however, is the least sensitive to the production speeds. It produced acceptable results across the entire range of production speeds. Figure 6-19 shows that there is whole set of solutions that can produce desired results at higher speeds, though selecting configuration 3 would be the most sensible thing to do as it produces the highest opening ratio among all the results.

An important point here is to keep in mind that these results are based upon the model fitted by Singh *et al.*(2008b). It is not the ultimate aim of the thesis or this chapter to identify the best settings of the carton erection machine, instead to illustrate the applicability of the proposed approach in visualising the solution space and the sensitivity of a machine to its setup parameters.

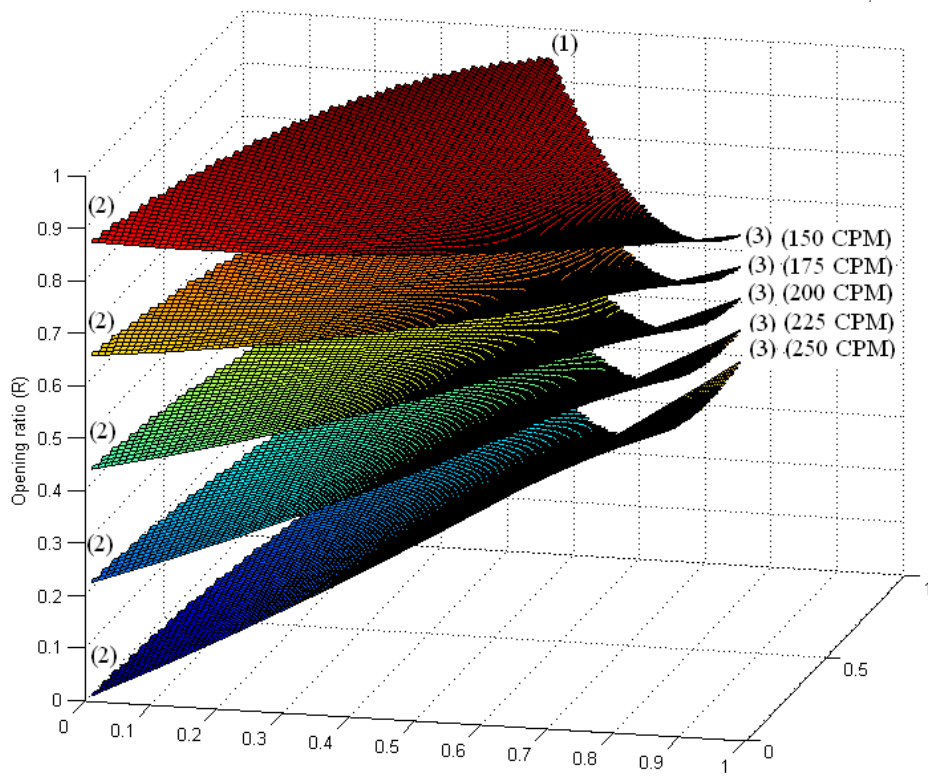


Figure 6-20 Opening ratios for various configurations at different speeds

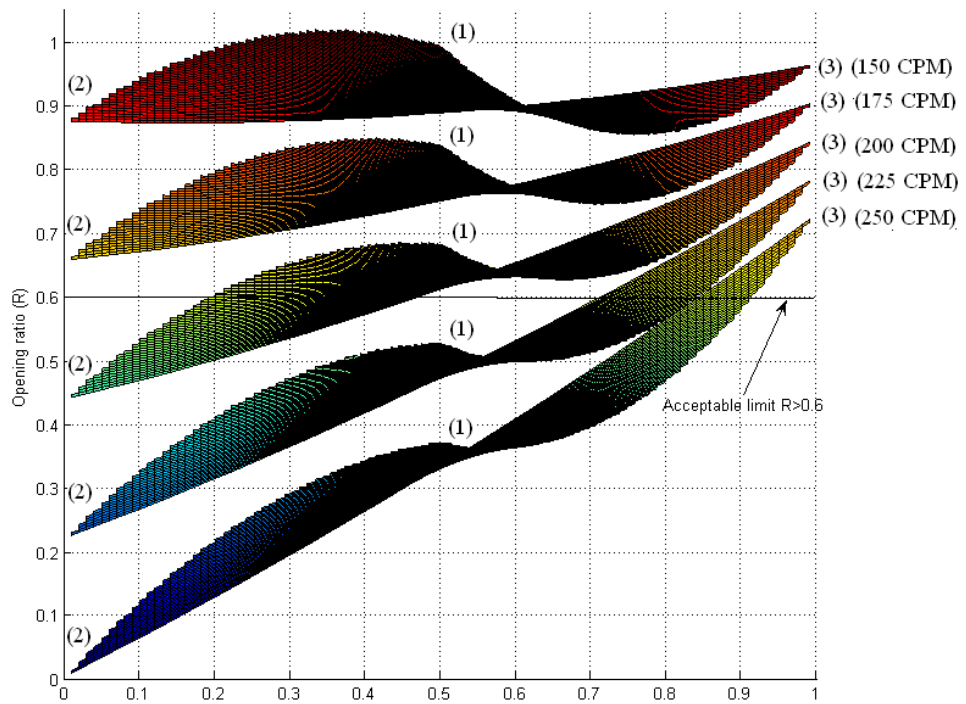


Figure 6-21 Side view of the surfaces

This case study shows an application of the multi-instance modelling approach when the computer based models are absent. The proposed approach in this case helped in refining the machine design by evaluating its sensitivity to setup parameters and determining the best machine settings for erecting cartons at high speeds. Earlier research work showed that the carton erecting machine was sensitive to its setup parameters and its ability to erect cartons was affected at higher production speeds. The approach helped in visualising machine's sensitivity at different production speeds and highlighted its performance capabilities. Thus the design knowledge regarding the current machine design is increased.

## **Chapter 7: Case study 3 – Computer based models are available**

Chapter 4 introduced an approach of multi-instance modelling in order to explore the design space that exists between various instances of a design. The aim is to investigate the product variants which essentially possess the same topology. There are also three distinct situations identified in chapter 4 for the applicability of the proposed approach.

This chapter describes a situation where the computer based models are available to the designer. The designer is interested in knowing the performance capabilities of the current design models and to investigate possibilities of finding better solutions. The advantage of computers based models is that the designer can run any number of experiments with ease. These models can accurately predict the performance characteristics of a machine/mechanism system. Any changes made to the parameter and the effect on the overall system performance can be studied. The models can be further analysed and optimised to serve the required (or changed) levels of the performance. However, due to black box optimisation methods one can end up with numerous feasible solutions. There can be further investigation required to see how optimal these solutions are and what is their sensitivity to small changes in the parameter values.

The following case study shows the applicability of the proposed approach to these kinds of situations.

## 7.1 Catalogue selection

This section discusses a particular case study example which is based around the use of a catalogue of mechanisms. These mechanisms such as four bar and five bars are widely used in applications such as pick and place operations, windscreen wipers and automobile hoods. A common design task is the selection of a mechanism to achieve a prescribed motion. Before the advent of computer aids, one starting point for the design of such mechanisms was an atlas of standard mechanisms and the output curves that they generate. Today such paper-based catalogues can be set up electronically (McGarva & Mullineux 1993). One way to do this is to create a parametric model of one or more standard mechanism types. Each is then run with a range of choices of the parameters. If the parameter choice is inappropriate, the mechanism does not cycle correctly and is not considered. When proper operation occurs, the mechanism is stored in a disc data file in terms of its type and parameters values, and its corresponding output path.

The path can be stored as a collection of points. However, an alternative is to treat the path as a closed planar curve and to form its (complex) Fourier coefficients (McGarva & Mullineux 1993; Singh *et al.* 2008a). These coefficients can then be stored instead of points on the path. When a new path is given and a mechanism is sought to create it, the first stage is to find its Fourier coefficients. These are then compared with those stored in the catalogue. Comparison is by taking the sum of the squares of differences of corresponding values (Euclidean distance). Mechanisms with low sum values are good. These provide candidate mechanism which can achieve the path required.

In some cases, the “best” mechanism found in this way is good enough to be carried forward into the next stages of the design process. In other cases, there may be other limitations on what can be done, and so the list of possible candidates needs to be inspected. If none is found to be suitable, then one strategy is to try adjusting the parameters of one such candidate mechanism in order to try to improve the selection. Such adjustment can be made manually (assuming a suitable parametric modeller is available). The problem with manual adjustment is that there may be a large number of degree of freedom: for instance a four bar linkage has nine independent parameters. This makes it a cumbersome process as each parameter can be varied independently

and in combination with others. It may also be hard to define clear boundaries (limits) on these parameters. Thus the number of iterations required in order to search for a suitable mechanism can be high.

The proposed multi-instance modelling approach can be helpful in this kind of investigation (Singh *et al.* 2008b). Its starting point is a number of successful instances of a design. Their parameters are varied within the limits placed by the initial parameter values of the base designs (starting instances). The fact that the instances are good designs suggests that some of the required relations between the parameters are already satisfied. The designs thus generated within the interpolated space can represent a successful assembly given the fact that base instances share same topology. This approach thus reduces the number of iterations (searches) that needs to be performed and also provides a visual feedback about the generated design spaces. The chance of finding a better solution is higher as the search is based upon the successful (working) instances of a design.

Another approach is to use some form of automatic optimisation scheme. If it is just a question of path matching, then the objective function for the optimisation is the comparison value between the Fourier coefficients and the variables are the parameters describing the mechanism. One drawback with the optimisation process is that as the search is automatic, the designer has little information about how well the search has performed or the sensitivity of the resulting solution to small changes in the mechanism parameters. Such feedback can be provided to the designer by giving some means to visualise the design space.

The following sections describe such a situation where a path is given and the designer need to select an appropriate mechanism from the catalogue. The solution instances thus generated closely follow the given path. However, the designer may be interested in knowing the solution space that exists between the selected design instances. There is also a possibility that a better design can be found by exploring this solution space using the multi-instance approach proposed earlier.

### 7.1.1 Case of three design instances: example 1

As an illustration, consider the three mechanisms shown in figure 7-1. These are all obtained from a catalogue as providing paths which match closely the prescribed path also shown in the figure. It is clear that these mechanisms are similar to each other with same topology. These mechanisms are now investigated with the proposed morphing approach in order to find a better solution, if one exists.

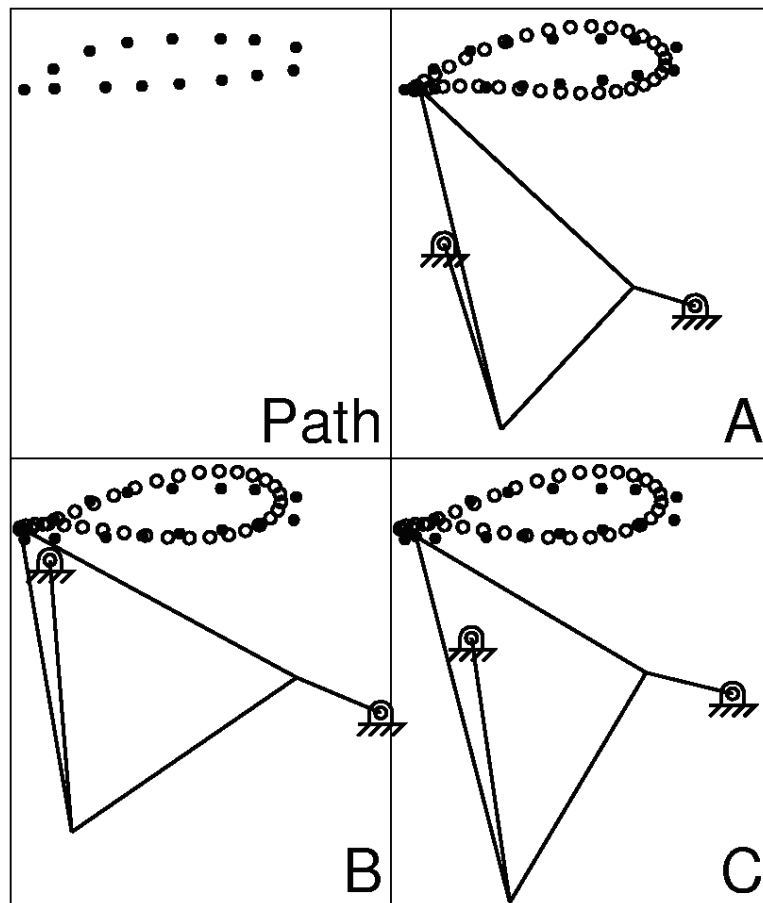


Figure 7-1 Given path and three base mechanisms

These three instances are taken as successful design instances and morphing between them is undertaken as previously described in chapter 4. However first two stages of the proposed approach (identification of the variants and initial modelling) are not applicable here as the parametric models of these instances are already available. The notation of a typical four bar mechanism is depicted in figure 7-2 and the key parameters that contribute to the functionality of the selected mechanisms are listed in table 7-1.



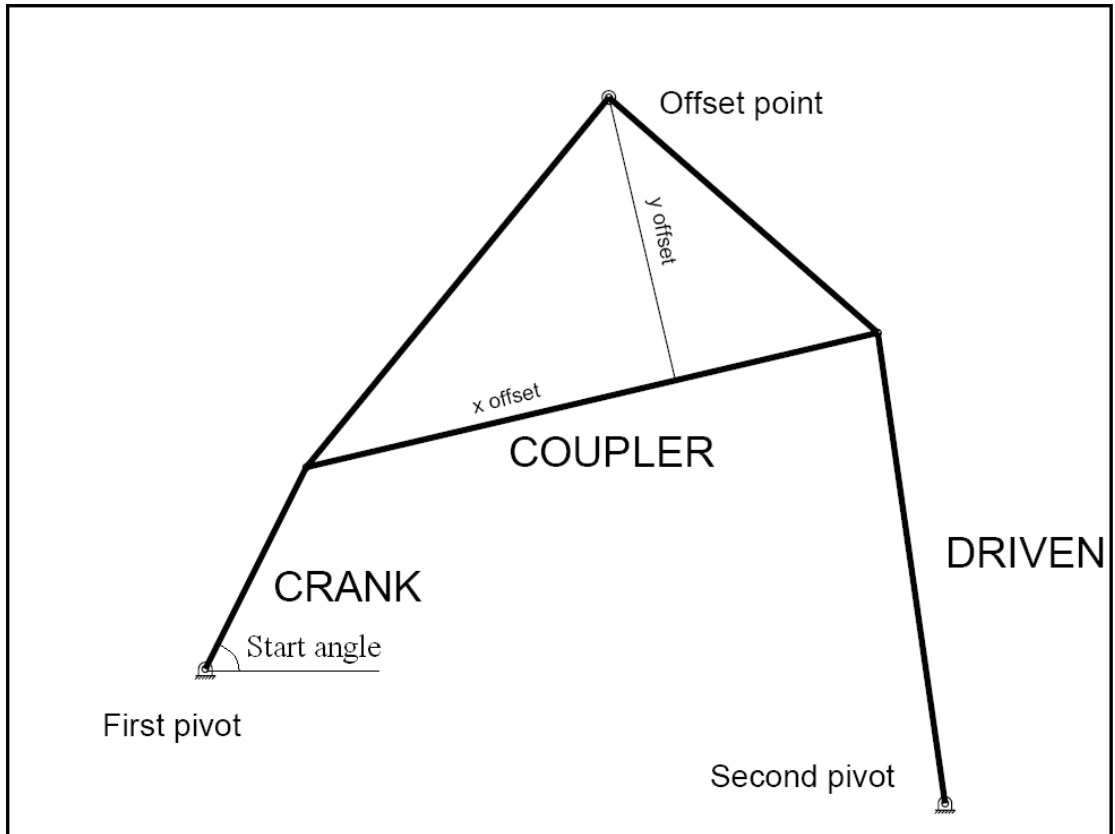


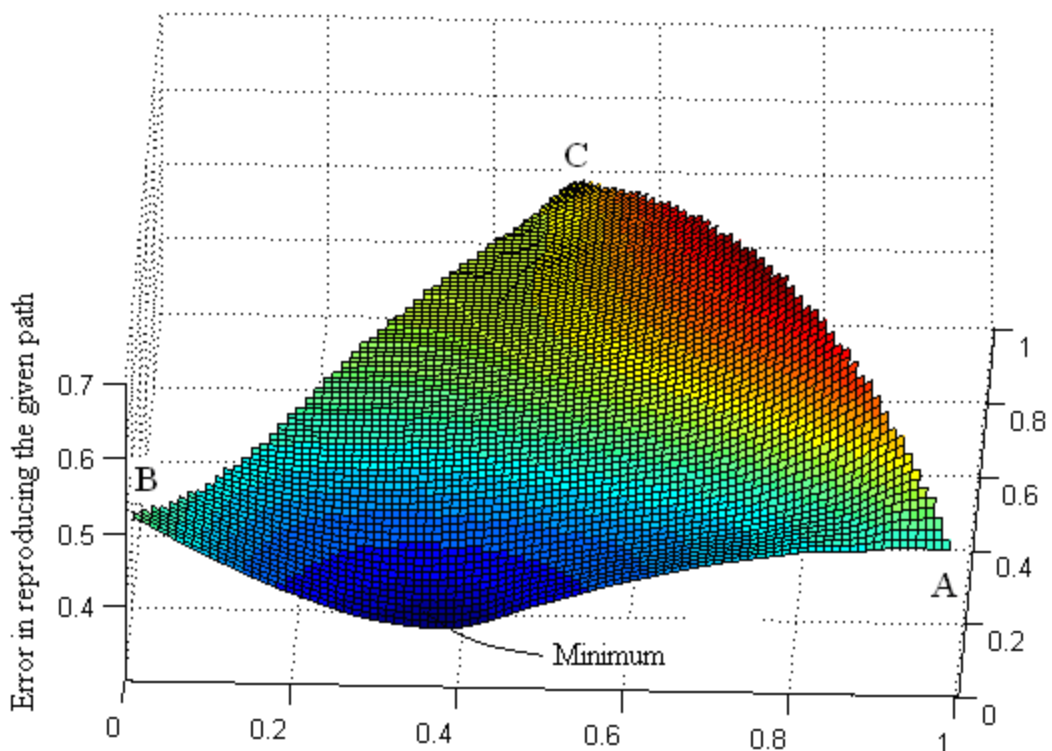
Figure 7-2 Four bar mechanism notation

Table 7-1 Key parameters of the instances selected from a catalogue

Parameters	Instance (A)	Instance (B)	Instance (C)
First pivot x coordinate	1.31	2.5	1.99
First pivot y coordinate	-4.19	-3.41	-3.06
Second pivot x coordinate	-3.26	-3.51	-2.76
Second pivot y coordinate	-3.06	-0.63	-2.05
Crank length	1.18	1.66	1.62
Coupler length	3.54	4.97	4.86
Driven length	3.54	4.97	4.86
Offset point X coordinate	0	2.6	0
Offset point Y coordinate	-5.3	-5.1	-4.86
Start angle	-197	-202.80	-198.252

Each newly created instance, as a result of parametric morphing, is cycled and its output compared with the given path. The performance value in this case is the ability of a mechanism to closely follow the prescribed path and thus inversely proportional to the error values generated in matching the given path. As explained earlier, this

error value is sum of the Euclidean distance between the Fourier coefficients of the required path and the generated path. A value of zero is ideal which means that the generated instance exactly follows the required path. The error value for each instance produced as the result of morphing is held and used to plot the surface shown in figure 7-3. These values for the base instances A, B and C are 0.50, 0.53 and 0.55 respectively. It is assumed that any instance providing a lesser value is better performing than the base instances.



**Figure 7-3 Result of morphing between the base mechanisms**

The surface is roughly flat. However there is a minimum value of the error value within the triangle and this represents a better mechanism providing a better path match than the original three. The flatness of the surface suggests that the three candidate mechanisms are similar and that any solution in the triangular region is likely to be insensitive to small changes. The minimum (best solution) in this case is found at a location that corresponds to weights values of 0.4, 0.6 and 0 placed at the instances A, B and C, respectively. The mechanism thus produced is depicted in figure 7-4. The error in reproducing the given path by the instance at this point is 0.38.

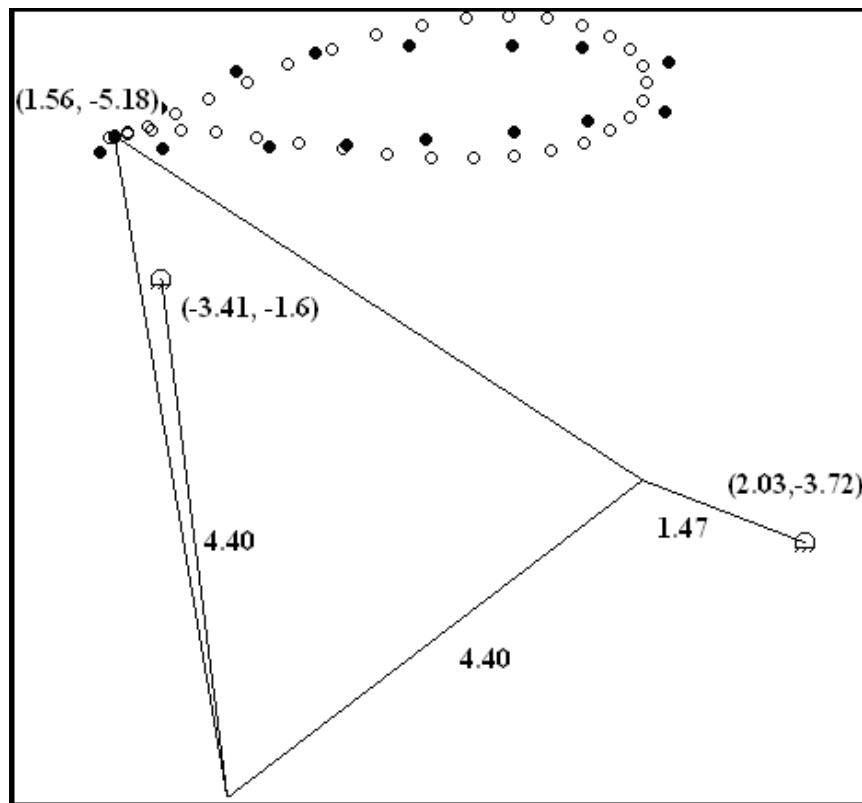


Figure 7-4 Improved mechanism

The proposed approach also helps to divide the design space in order to magnify the region of interest. In this case the triangular representation ABC is divided into two halves namely, ABC' and ACC' (figure 7-5). As the minimum lies in the triangular region ABC', this region can be further explored by performing the parametric morphing. The instances at points A, B and C' are taken as the base instances this time. The resulting surface is also shown in the figure. The location of the minimum in this region is found to be the same as the previous optimal solution (weights at, A=0.4, B=0.6 and C'=0, error = 0.38).

In the previous two iterations the step size for the parametric morphing was kept constant. It is, however, interesting to see how the error values change when the step size is further reduced (halved). Reducing step size essentially means conducting a finer search. In the next experiment the step size is reduced to half and the resulting surface generated is shown in figure 7-6.

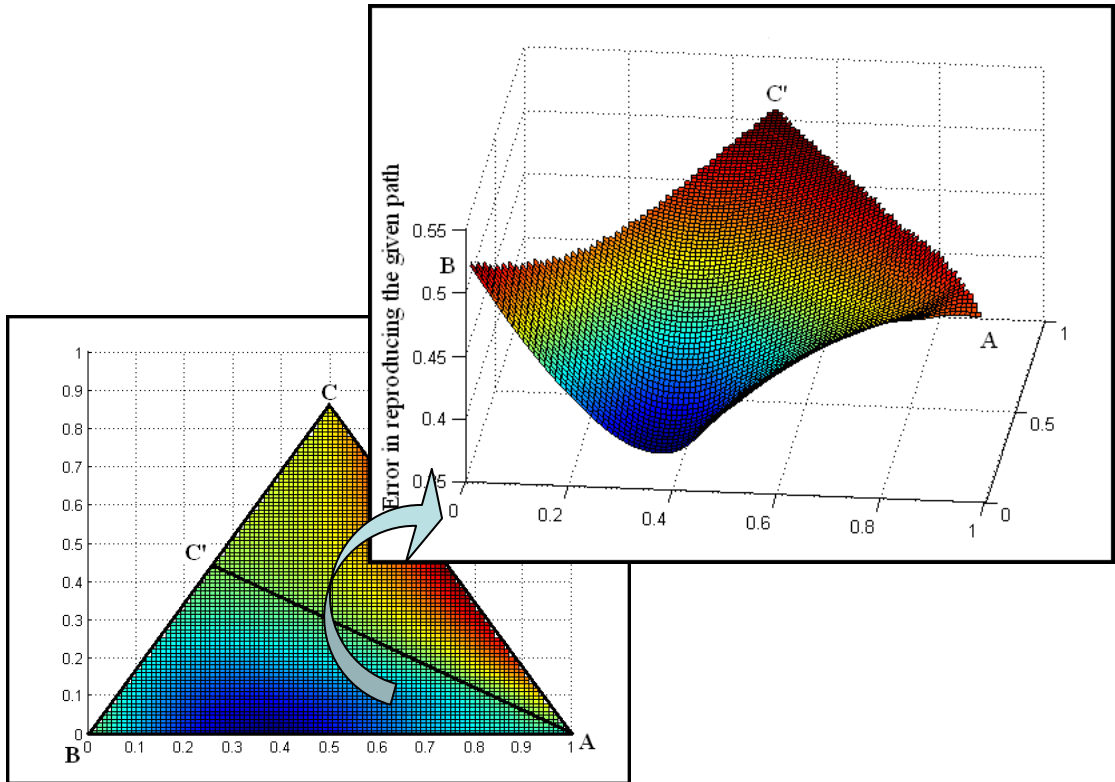


Figure 7-5 Division of the design space

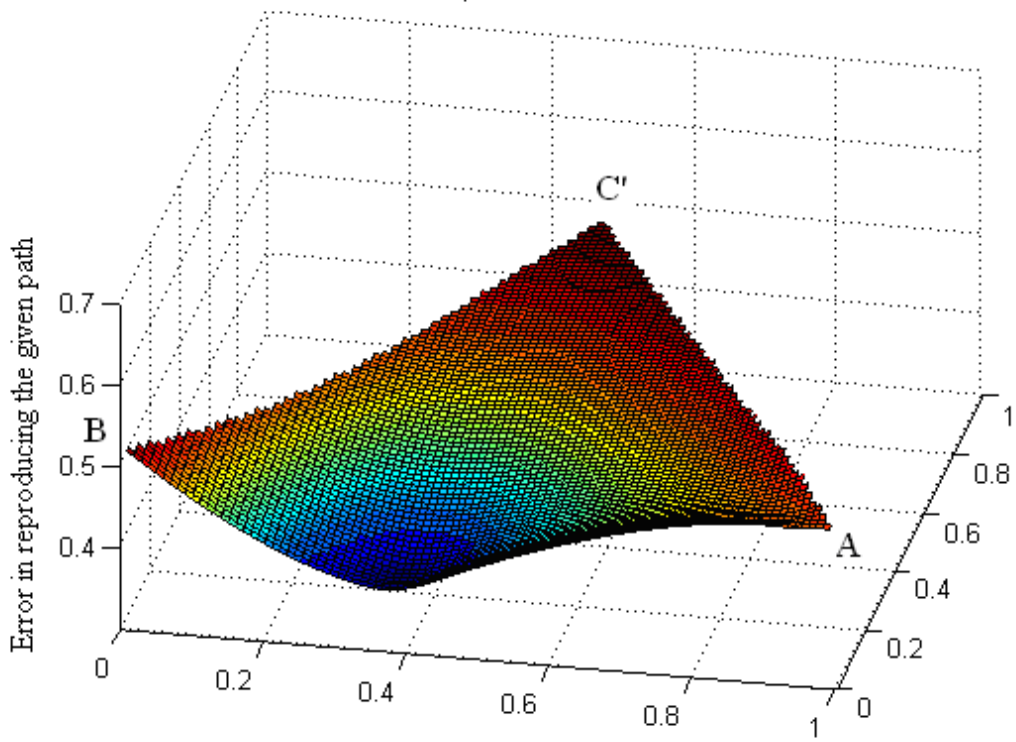


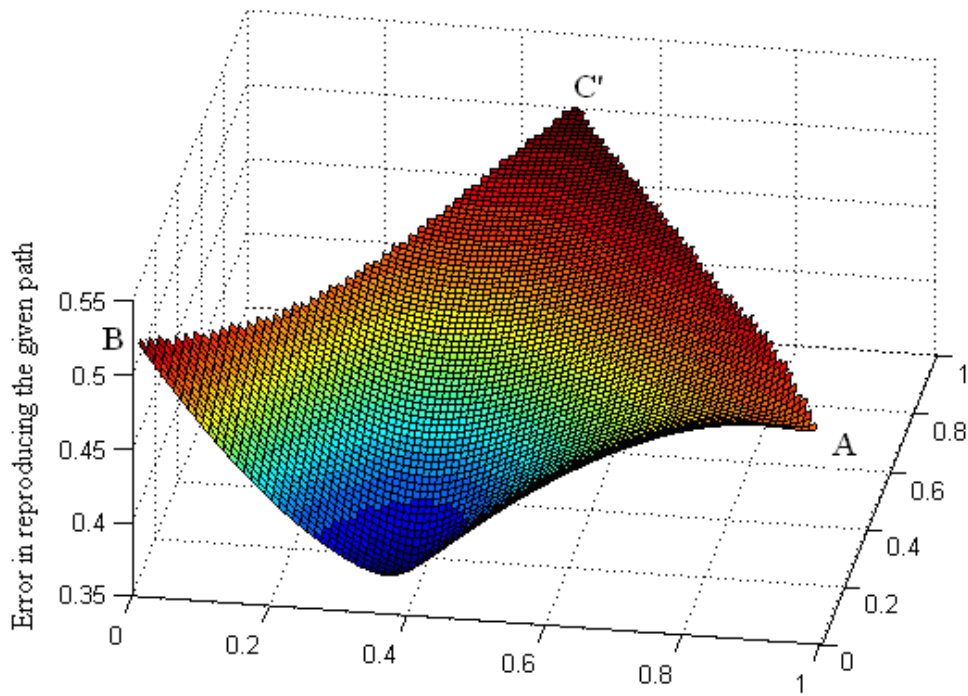
Figure 7-6 Resulting surface with step size = 0.5

A better minimum is found in this case with an error value of 0.3767. It is located at a point corresponding to the weights of 0.35, 0.6 and 0.05 placed at the instances A, B and C', respectively. The parametric description of the generated mechanism is given in table 7-2.

**Table 7-2 Key parameters of the generated instance**

Parameters	Instance producing minimum error
First pivot x coordinate	2.07
First pivot y coordinate	-3.68
Second pivot x coordinate	-3.40
Second pivot y coordinate	-1.52
Crank Length	1.49
Coupler Length	4.46
Driven Length	4.46
Offset point X coordinate	1.63
Offset point Y coordinate	-5.16
Start angle	-200.54

A further reduction of the step size (step = 0.1) is carried out in the next experiment. The resulting surface produced is shown in figure 7-7.



**Figure 7-7 Design space with step size = 0.1**

Another better minimum is found in this case with an error value of 0.373. It is located at a point corresponding to the weights of 0.37, 0.58 and 0.05 placed at the instances A, B and C', respectively. The parametric description of the generated mechanism is given in table 7-3.

**Table 7-3 Key parameters of the instance generated with step size = 0.1**

Parameters	Instance producing minimum error
First pivot x coordinate	2.05
First pivot y coordinate	-3.69
Second pivot x coordinate	-3.40
Second pivot y coordinate	-1.56
Crank Length	1.48
Coupler Length	4.44
Driven Length	4.44
Offset point X coordinate	1.57
Offset point Y coordinate	-5.17
Start angle	-200.43

Comparing table 7-2 and table 7-3, the values of the different parameters of the two mechanisms generated are not far off. The search can be further narrowed, however it may not be cost effective to manufacture a mechanism with such a dimensional accuracy. The mechanism resulting from the last iteration is shown in figure 7-8.

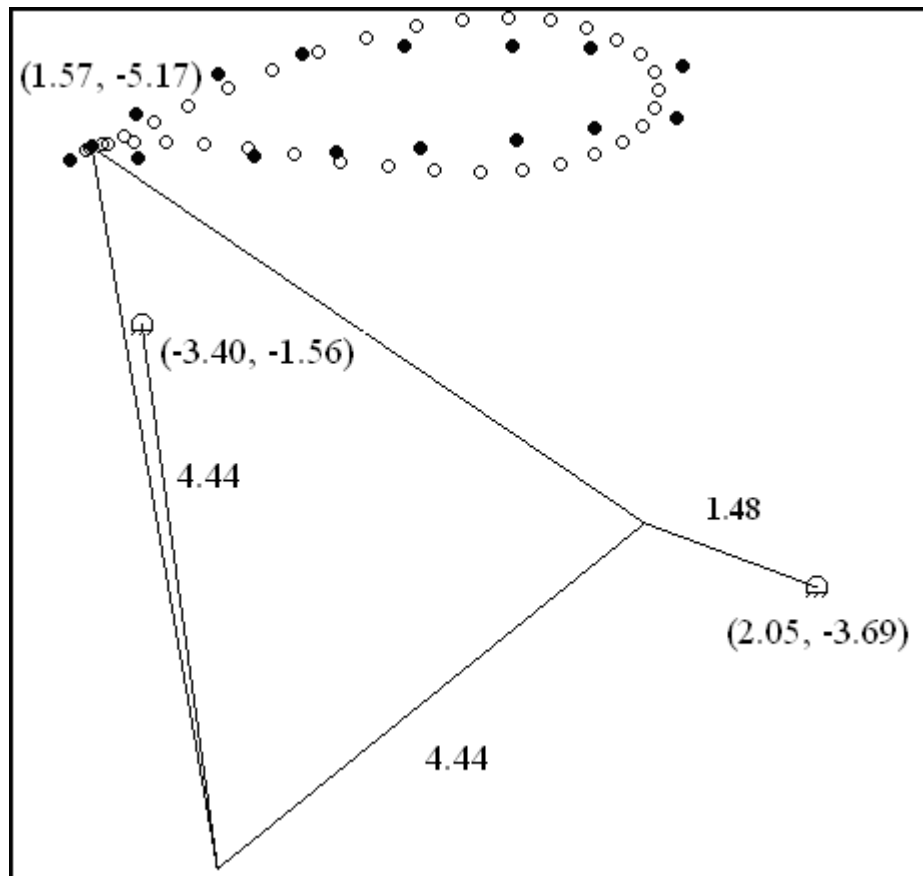


Figure 7-8 Resulting mechanism

### 7.1.2 Case of three design instances: example 2

Three other mechanisms producing good matches to a given path are shown in figure 7-9. These again come directly from a search of the catalogue. When these are morphed and the resultant mechanisms tested, the surface obtained is that shown in figure 7-10.

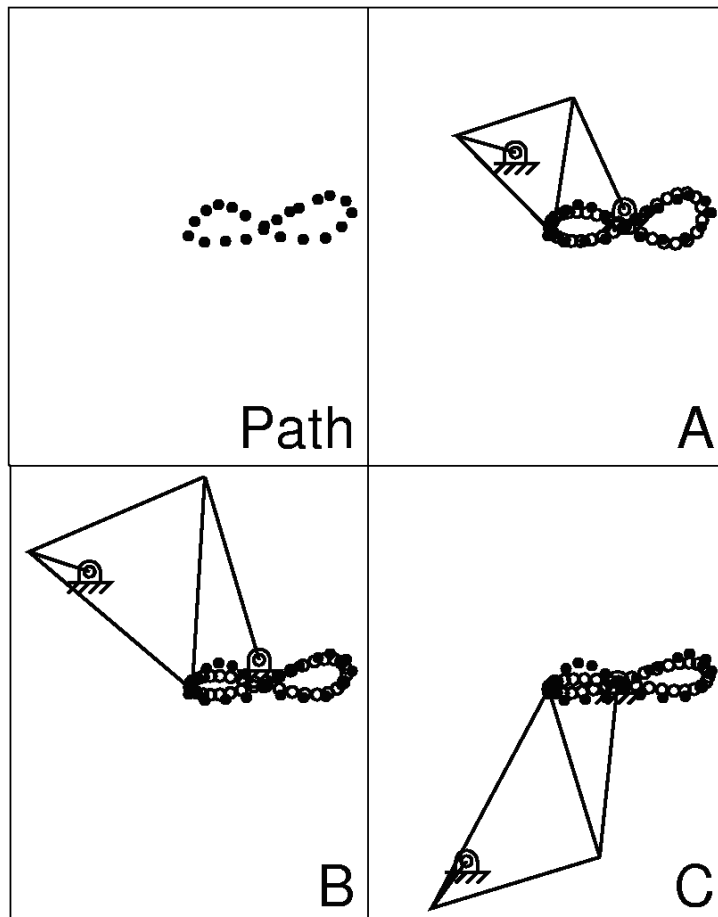


Figure 7-9 Given path and a set of three base mechanisms

What is now seen is that the surface is considerably less flat. There is a ridge separating one vertex from the other two. This suggests that the isolated vertex represents a mechanism which, in some sense, belongs to a different class. The other two can be thought of variations of each other. It is obvious in figure 7-9 that mechanism C is inverted in comparison to mechanisms A and B. The surface in figure 7-10 confirms this. A lowest point in the surface is still available and represents a better choice than any of the initial three.



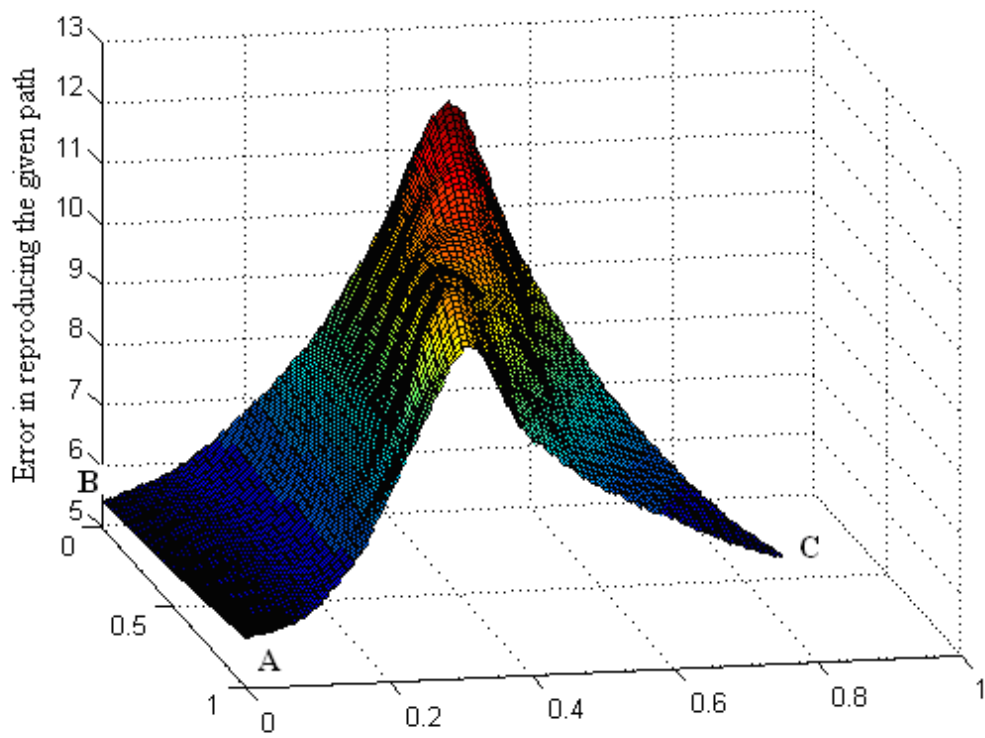


Figure 7-10 Surface resulting from morphing the base instances

### 7.1.3 Case of four design instances: example 1

Figure 7-11 shows four candidate mechanisms selected from the catalogue. Their parametric description is given in table 7-4. These can also be morphed and each new instance evaluated against the prescribed path. As mentioned in the previous chapter the order in which the original four are taken does now affect the resultant surface. One such is shown in figure 7-12.

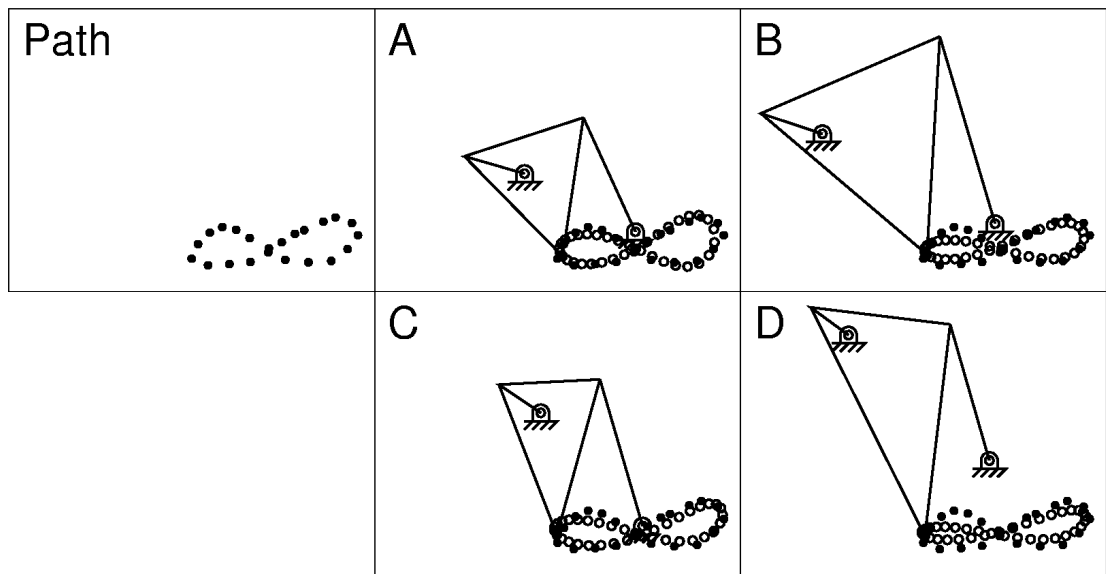
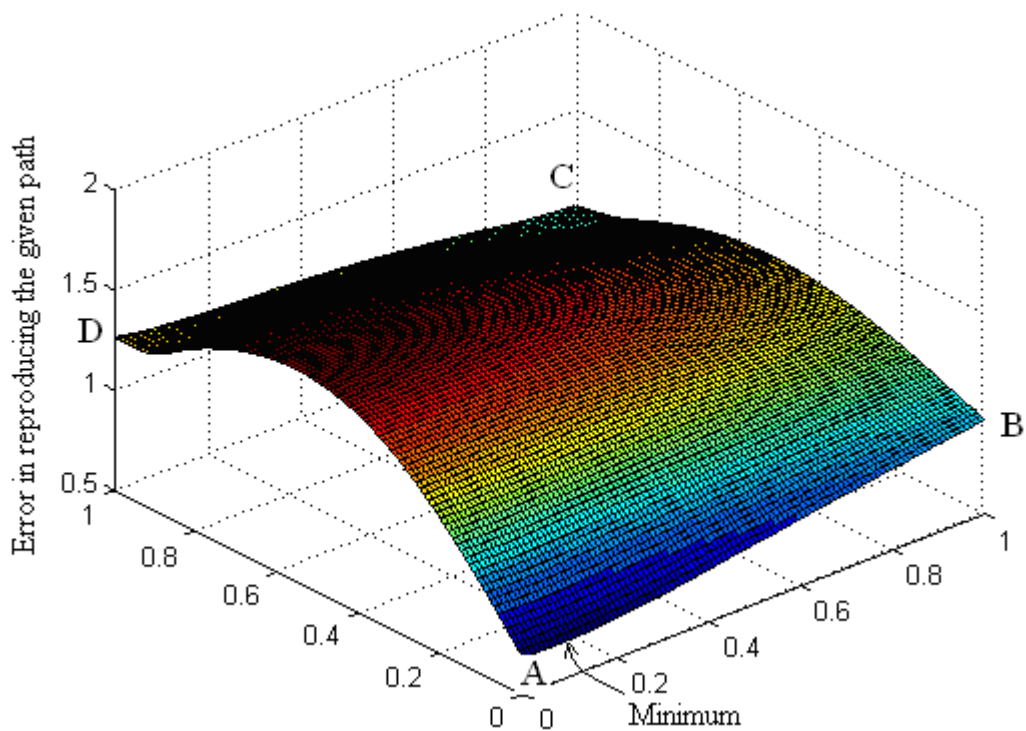


Figure 7-11 Given path and four base mechanisms

Table 7-4 key parameters of the instances selected

Parameters	Instance (A)	Instance (B)	Instance (C)	Instance (D)
First pivot x coordinate	-6.77	-10.98	-5.76	-9.37
First pivot y coordinate	5.01	7.47	7.73	12.50
Second pivot x coordinate	0.10	-0.28	0.55	-0.63
Second pivot y coordinate	1.42	1.91	0.77	4.80
Crank length	3.88	4.01	3.12	2.90
Coupler length	7.75	12.07	6.27	8.71
Driven length	7.75	12.07	9.40	8.71
Offset point X coordinate	3.88	6.02	3.12	8.71
Offset point Y coordinate	-7.75	-12.07	-9.40	-13.09
Start angle	-195.98	-198.28	-213.78	-216.08



**Figure 7-12 Four-sided surface**

The error values produced by the base instances A, B, C and D in reproducing the specified path are 0.684, 0.97, 1.02 and 1.26 respectively. It is seen that the surface is roughly flat with a minimum, corresponding to a better choice, lying on the interpolation between the instances A and B. The minimum is found at a point corresponding to weights 0.9, 0.1, 0 and 0 at the instances A, B, C and D, respectively with an error value of 0.683. The resulting mechanism is shown in figure 7-13.

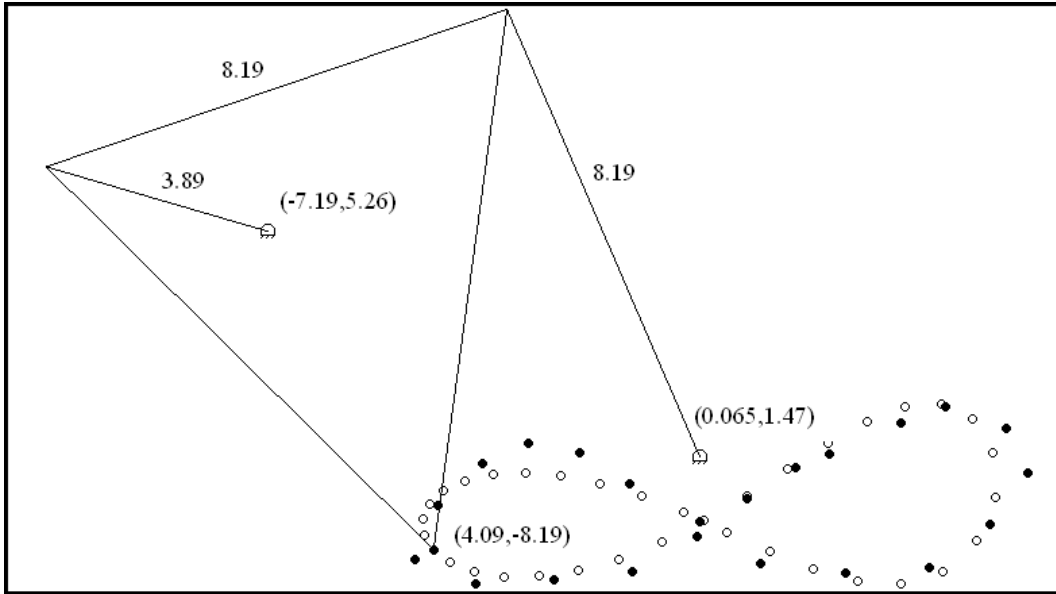


Figure 7-13 Produced instance

Now the search is narrowed by first dividing the surface to region of interest only ( $AB'C'D'$ , shown in figure 7-14).

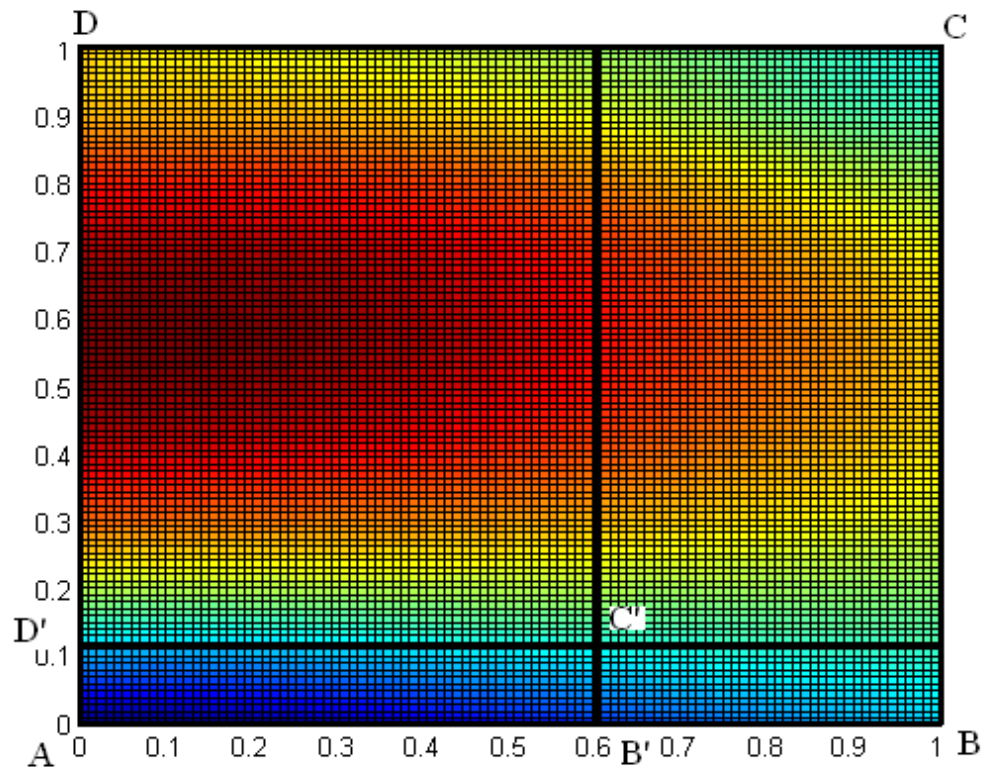


Figure 7-14 Division of the surface

A, B', C' and D' now serve as base instances. A further parametric morphing is carried out with the same step size. The resulting surface is shown in figure 7-15.

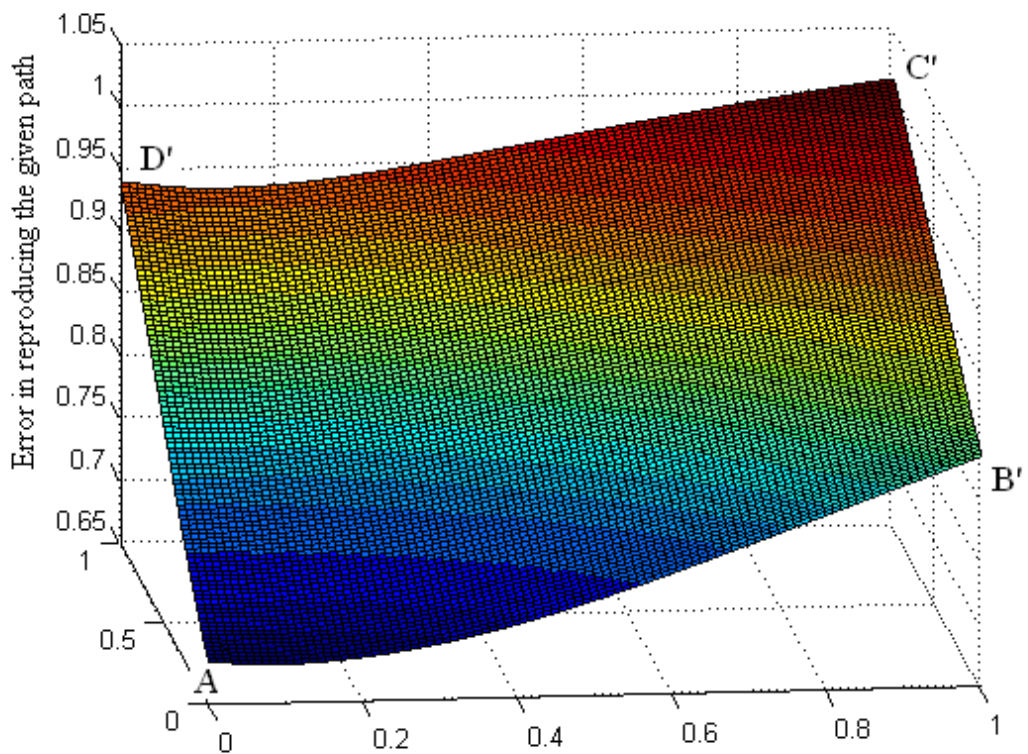


Figure 7-15 Divided surface

A better minimum, with an error value of 0.6809, is found at a point where weights are 0.9, 0.1, 0 and 0 corresponding to the instances A, B', C' and D', respectively. The parametric description of the instance produced at this point is given in table 7-5.

Table 7-5 Parametric description of the instance generated

Parameters	Instance producing minimum error
First pivot x coordinate	-7.02
First pivot y coordinate	5.16
Second pivot x coordinate	0.08
Second pivot y coordinate	1.45
Crank Length	3.88
Coupler Length	8.013
Driven Length	8.013
Offset point X coordinate	4.01
Offset point Y coordinate	-8.013
Start angle	-196.12

The minimum lies on the edge  $AB'$  of the surface. It is also interesting to know how the design space looks like on the other side of this edge of the surface. For this purpose, one can extrapolate away from the edge. Figure 7-16 below shows the same design space (figure 7-15) with edge  $AB'$  extrapolated further to  $A_1B_1'$ .

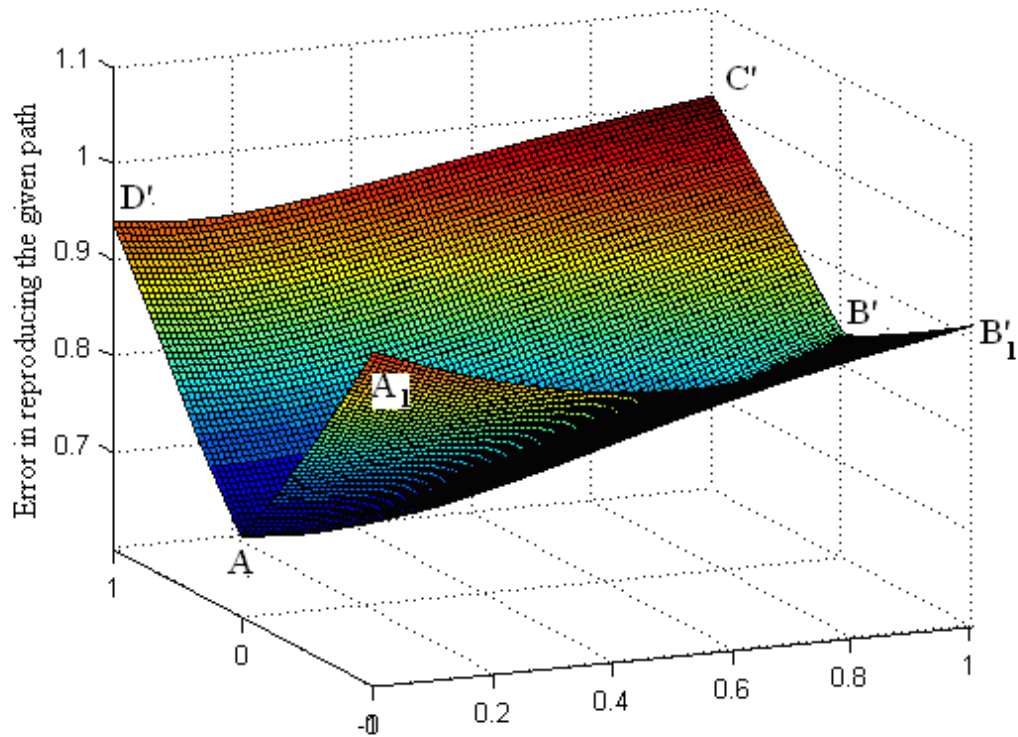
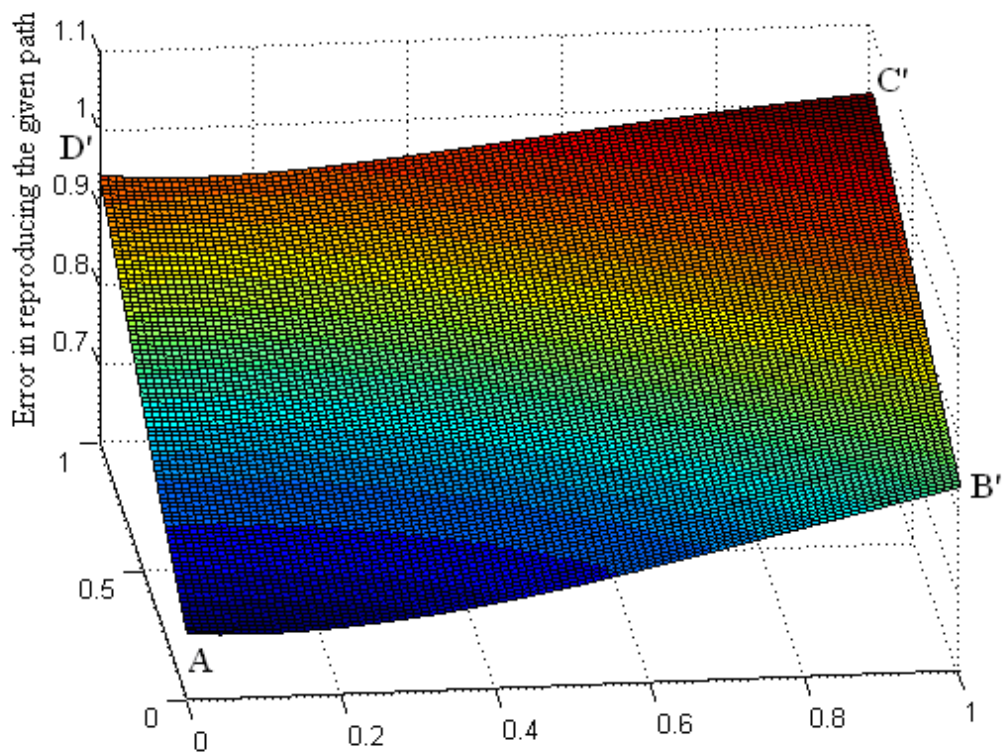


Figure 7-16 Extrapolated surface

Figure 7-16 highlights two main features of the design space in this case:

- Location of the minimum stays the same as of the previous step.
- The error values starts to rise again as one move away from the base instances (A & B').

As no better solutions are found during extrapolation, the design space generated in the previous step (figure 7-15) is further explored for better solutions in the following steps.



**Figure 7-17 Surface produced using step size = 0.5**

The search is further narrowed by reducing the step size ( $= 0.5$ , figure 7-17). The location and value of the minimum found in this case is still the same as of the previous step with step size of 1.

With further reduction in the step size (step = 0.1) a better minimum is found at a point, where weights at the instances A, B', C' and D' are respectively 0.9207, 0.0693, 0.0007 and 0.0093. The error value in reproducing the given path in this case is 0.680379. The search here is not carried out further as the error value is not reducing to a great extent. The mechanism found in this step is considered to be the best one and is shown in figure 7-18.

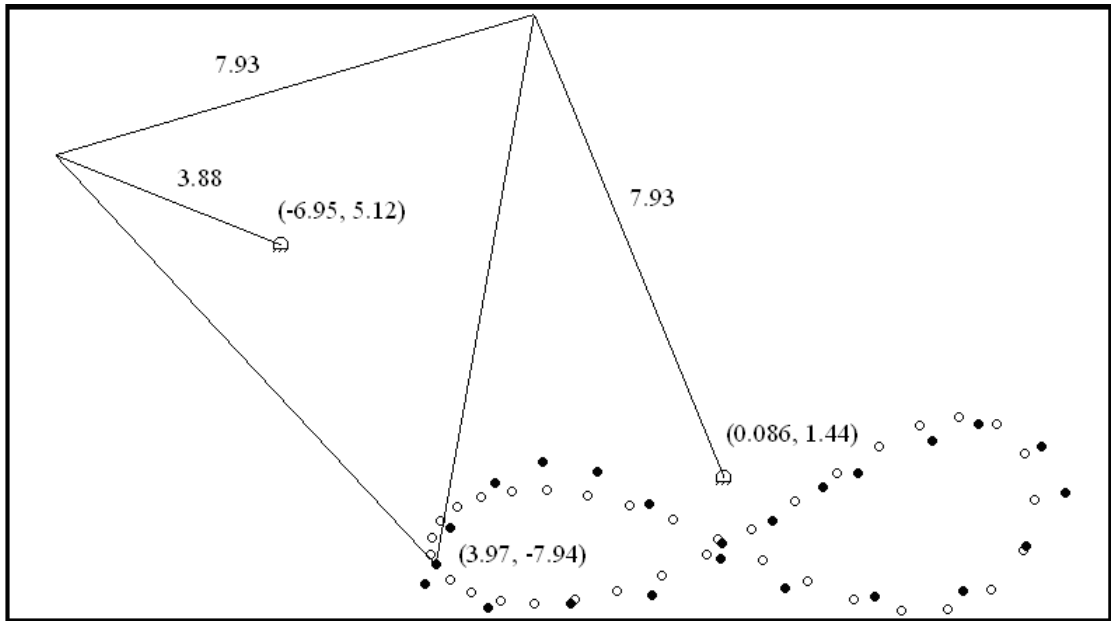


Figure 7-18 Mechanism generated



### 7.1.4 Case of four design instances: example 2

Figure 7-19 shows the same (earlier) example with the exception of mechanism D. Mechanism D has been intentionally replaced by one whose path is close to the given figure of eight but which is roughly elliptical. The resulting surface is shown in figure 7-20. It is clear by comparing figures 7-12 and 7-19 that the relationship between mechanism A, B and C holds the same as of the earlier case. A better choice is still lying on the interpolation between mechanisms A and B. However performance of the mechanism D is changed significantly; Point D on the surface is approximately raised by a factor of 3 (error = 3.64). There is a ridge separating mechanism D from others which indicates that this belongs to a different class. In this particular case, even though mechanisms (A, B, C & D) shown in figure 7-19 look similar, the ridge in resulting surface shows that mechanism D belongs to a different class. It also validates the objective function used which is based upon the comparison value between the Fourier coefficients of the prescribed path and the generated path.

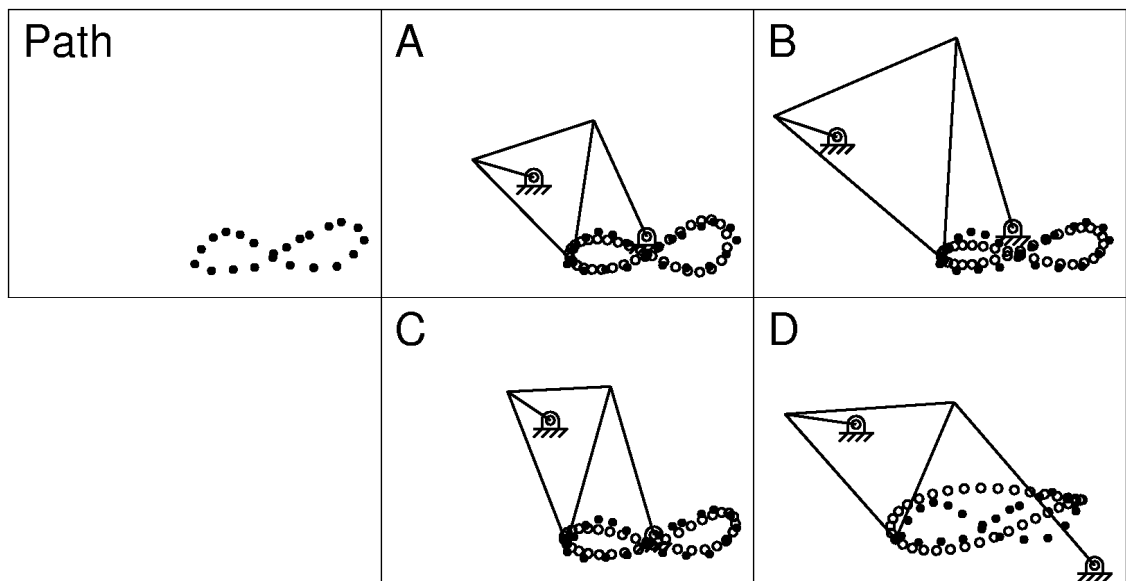


Figure 7-19 Four mechanisms with one following different path

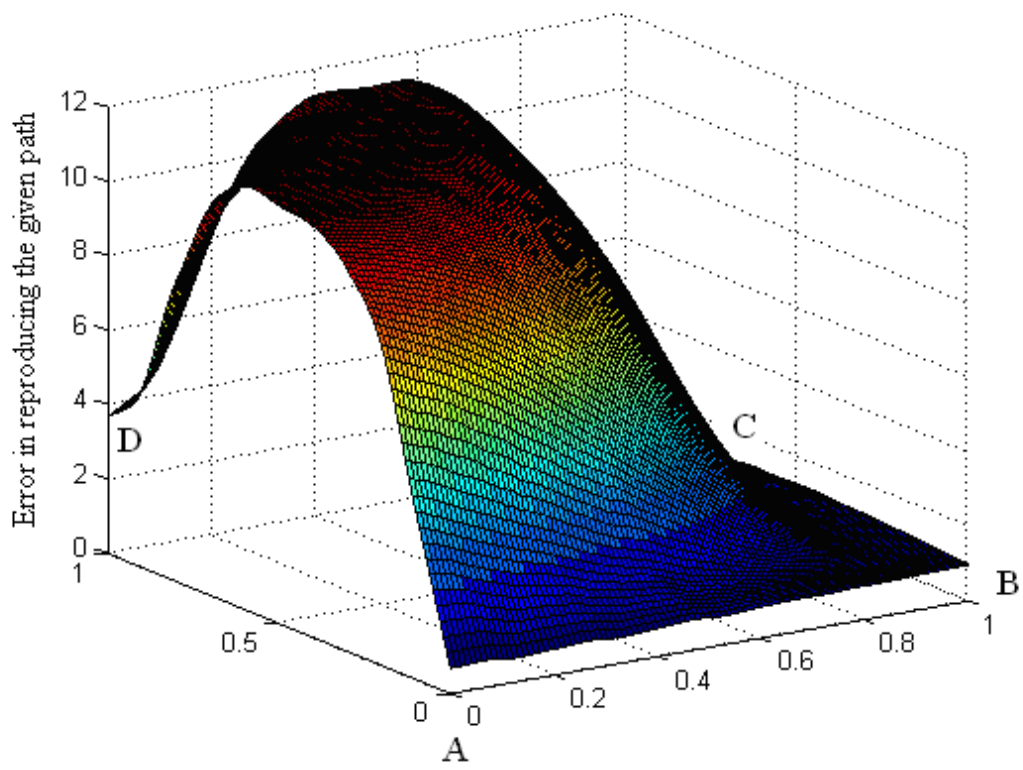


Figure 7-20 Resulting four sided surface

### 7.1.5 Case of optimisation

This example is a continuation of example 1 (figure 7-1) for the path matching where three mechanisms were selected from a catalogue to achieve a desired path. However the designer may further want to optimise these designs. This can be done by using any optimisation scheme where objective function is the comparison value between the Fourier coefficients and the variables are the parameters describing the mechanism.

In this case the mechanisms obtained from the catalogue are further optimised and an optimal solution generated for each one of them (shown in figure 7-21). The error in matching the path for these mechanism are 0.1734 (A), 0.1048 (B) and 0.1654 (C).

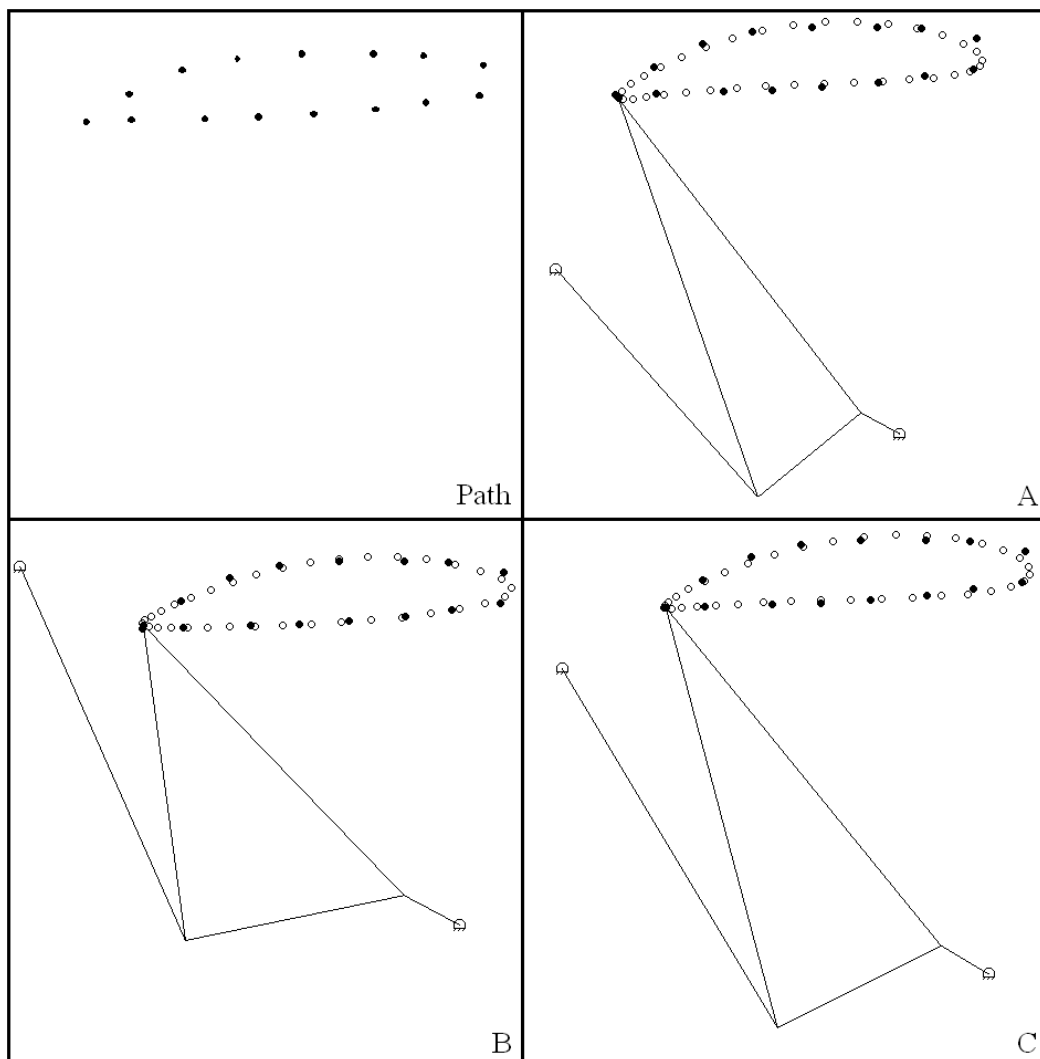
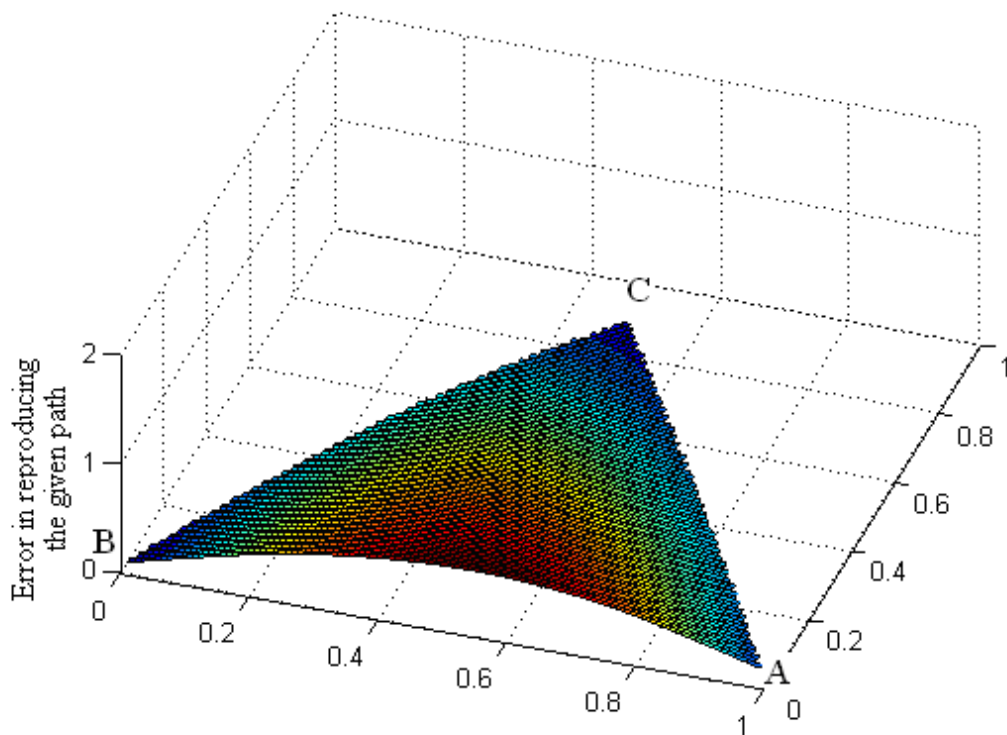


Figure 7-21 Given path and three optimised mechanisms

As discussed earlier that due to black box type optimisation one can end up with a solution which is a good solution to the problem, however no information is available about how sensitive is the design to small changes in the geometric parameters. The multi-instance modelling approach can help to explore such sensitivity by visually representing the design space that exists between the optimal solutions. Figure 7-22 shows the design space that is generated by parametric morphing of the above optimised mechanisms.



**Figure 7-22 Resultant surface**

The surface thus produced is roughly flat. This shows the solution space between these instances is fairly insensitive to changes the design parameters. The performance values for the designs lying within the morphed space vary but certainly there is little variation. One important point to be noted here is that this is not a full analysis for the design sensitivity. This is limited to the design space bounded with the limits imposed by the parameter values of the base instances.

## 7.2 Discussion

This chapter discusses a case study based upon the selection of mechanisms from a catalogue. The use of catalogues in one way promotes design reuse where already proven designs can be adapted for new requirements. In some case these designs can be directly used while in other cases some modifications are required to achieve the required levels of performance. These modifications can be done manually or computer based search strategies can be used to obtain an optimal solution.

The proposed multi-instance modelling approach can be helpful in both cases. In the former case, this approach can help in locating a better solution that may lie in the design space between the selected design instances from the catalogue. It helps in grouping/differentiating these instances into families based upon their performance levels. The sensitivity of these design instances to the small parameter changes can also be predicted. In the latter case of optimisation, the proposed approach can identify how optimal is the solution. It may find a better solution that is missed by the optimiser. Nevertheless this approach helps in identifying the sensitivity of the optimal solutions to small parameter changes.

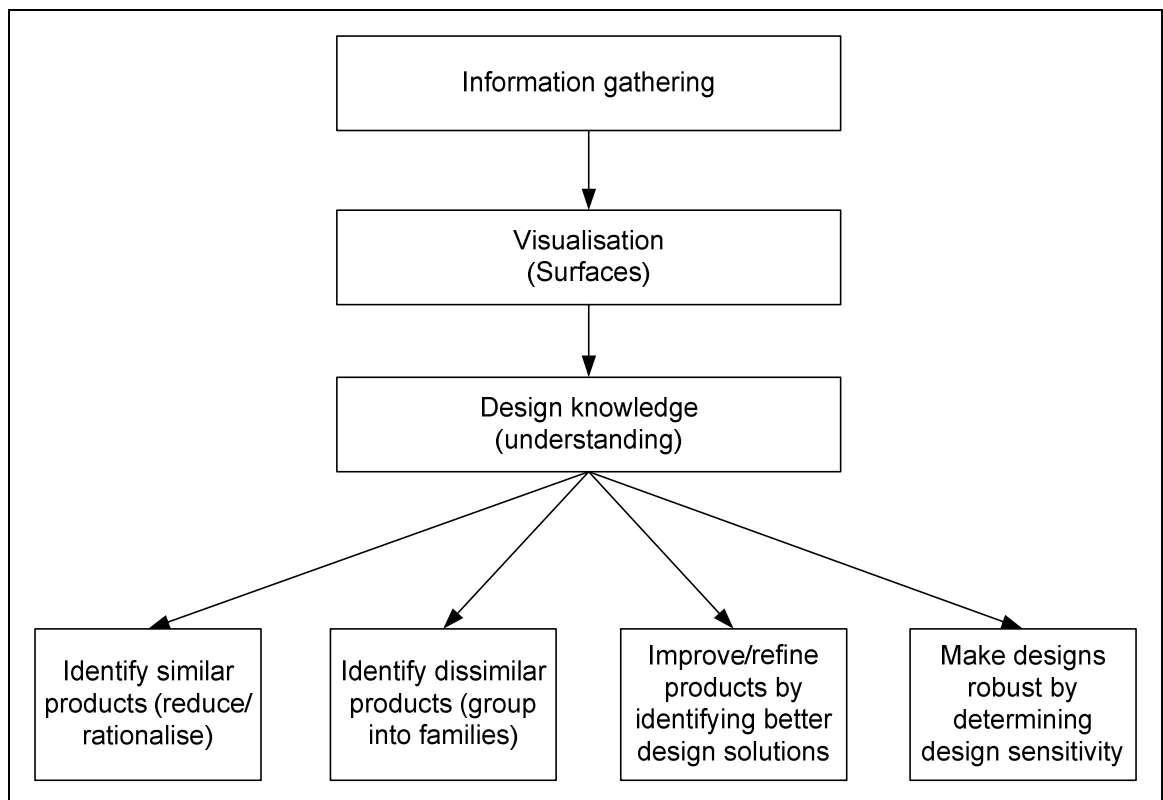
Thus the proposed approach is useful in visualising and understanding the design space that exists between the known instances of a design. This case study successfully demonstrates a situation where computer-based models are available to the designer. Using the current approach, these models can be used to investigate the design variants and establish their performance capabilities. This can further lead to identification of better solutions and even sensitivity of the designs to changes in their parameter values can be studied.

## **Chapter 8: Multi-Instance modelling approach revisited**

The case study examples in the previous chapters highlighted the application of the multi-instance modelling approach in the three situations identified in chapter 4 (section 4.4). It was shown that the proposed approach can be helpful in tackling various design problems when a number of design variants need to be investigated. Based upon the findings from the various case studies, this chapter provides an overview of the proposed approach.

## 8.1 Multi-instance modelling: an overview

The proposed approach is illustrated in figure 8-1. Considering the three case studies discussed so far it is seen that the approach initially involves gathering information about existing designs. It may either be a case of simply identifying what instances currently exist or further involve undertaking experimental work to establish how design performance varies with changes in (design) parameters. This investigation can then lead to some form of mathematical model relating these parameters to the performance. The experimental investigation and/or the model effectively allow a greater range of design instances to be considered.



**Figure 8-1 Proposed approach**

From the information about design instances, surfaces of performance can be created. These are naturally more detailed when more information (and more instances) is available. The surfaces are based on the idea of morphing between design instances. The assumption is made that morphing between successful instances preserves any underlying relation between the design parameters. This is an assumption, but it is the one that considerably eases the burden of developing a full model of design

performance, and it is partly this aspect which makes the approach suitable well suited to SMEs with limited resources.

The surface(s) produced represent aspects of the design space close to the known instances used. Visualisation of the surface(s) helps in focussing attention of particular regions of interest or concern. If necessary, the design space can be subdivided (section 4.3, chapter 4). Consideration of the form of the surface(s) allows a greater appreciation of the nature of that local design space and helps in increasing design knowledge regarding the design instances. In particular, insight can be gained in the following areas:

- Identifying similar products: if the surface is essentially flat it suggests that there is no a great deal of difference between the initial design instances and they fall into a single family (chapter 5). This might lead into an investigation of whether a product range can be rationalised.
- Identifying dissimilar products: if the surface is (highly) irregular it suggests that there are fundamental difference between the original design instances and there is more than one family of products present (chapter 7).
- Improving products: if the surface has a well defined (local) extremum then this suggests that this is a design configuration which performs better than those around it. If it is not one of the original instances, then the new one might be a better design alternative than existing ones (chapter 7).
- Identifying sensitivity issues: if a surface has steep gradient close to a design instance then this suggests that that design is likely to be sensitive to small changes in its parameters (chapter 6). This might be an indication that the design ought to be modified to one in a flatter region of the design space.

The following section recaps the application of the proposed approach in each of the three identified situations.



## **8.2 Application to the three identified scenarios**

This section describes how a number of design variants can be investigated depending upon the type of situation involved.

### **8.2.1 Isolated instances – no provision for experimentation**

In this type of situation, as highlighted in chapter 5, there is a minimal amount of design information available to the designer. Further, there may not be any provision for conducting any experimental work. In this case, only a simplified investigation can be performed. The designer can use the limited information available (as shown in chapters 5) to obtain a rough representation of the design space. Such a representation can still help in increasing the current design knowledge regarding products.

### **8.2.2 Experimental investigation is possible**

In this type of situation, a number of design variants are available to the designer and also there is provision for carrying out experimental work in order to establish performance characteristics of the design instances. The visualisation stage of the proposed approach can be applied to the experimental results in order to gain a better understanding of the system. An application of the proposed approach in this type of situation is given in chapter 6. In that particular case, it helps in determining optimal setup parameters for a carton erection machine.

### **8.2.3 Computer based models are available**

When a computer based model is available that can predict performance capabilities of current designs, it can be used to explore the instances between the base design variants. This allows more complete surfaces to be created to represent the design space. This can help the designer in a number of ways that include identifying better design solutions, identifying similar/dissimilar products and exploring sensitivity of designs to their design parameters. An application of the proposed approach in this type of situation is shown in chapter 7.

It is also interesting to note that these three situations are not distinct. They merge one into another. One can start with the limited information available about the designs and gain further insights by representing that information in visual form (surfaces).

This is the case of isolated machine instances. If some experimental investigation can be carried out for further analyses of the designs, there is a move towards the second situation. If using the experimental results obtained, one can fit some sort of mathematical or parametric model then this leads into the third situation where a model of the system is available. The next chapter presents such a case study in which all three situations are present.

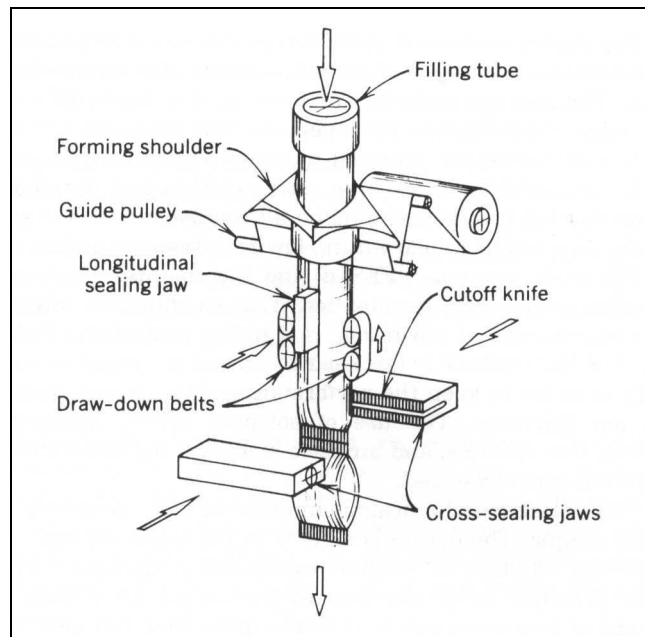
## **Chapter 9: Case study 4 – Investigation of forming shoulders using multi-instance modelling approach**

This chapter investigates a vertical form fill and seal (VFFS) machine for its performance capabilities using the proposed multi-instance modelling approach. A VFFS machine incorporates a forming shoulder for making bags/pouches of packaged products. Generally, a different shoulder is used for every product/material type due to limited understanding of the relationship between machine and material interface which dictates the performance capabilities of the machine. This makes forming shoulders a crucial component for these machines. The current design practice for these shoulders is to select them heuristically and then to test for a particular type of packaging material. This process is not only error-prone but also costly and time consuming. It presents a situation where machine manufacturers lack the full understanding of machine-material interactions.

This case study investigates a number of forming shoulders using the proposed approach with an aim to increase current design knowledge relating machine-material interactions that take place during packaging operations. All the three situations identified earlier in chapter 4, namely isolated machine instances, experimental investigation is possible and computer based models are present, are examined here.

## 9.1 Background

Vertical form, fill and seal machines are commonly used to package particulate products such as pasta, rice and snacks. The products are packed inside bags or pouches which are formed from a reel of flat packaging material film. Figure 9-1 shows a schematic of such a machine that uses a forming shoulder.



**Figure 9-1 Schematic of a packing system using a forming shoulder Source: (Brody & Marsh, 1997)**

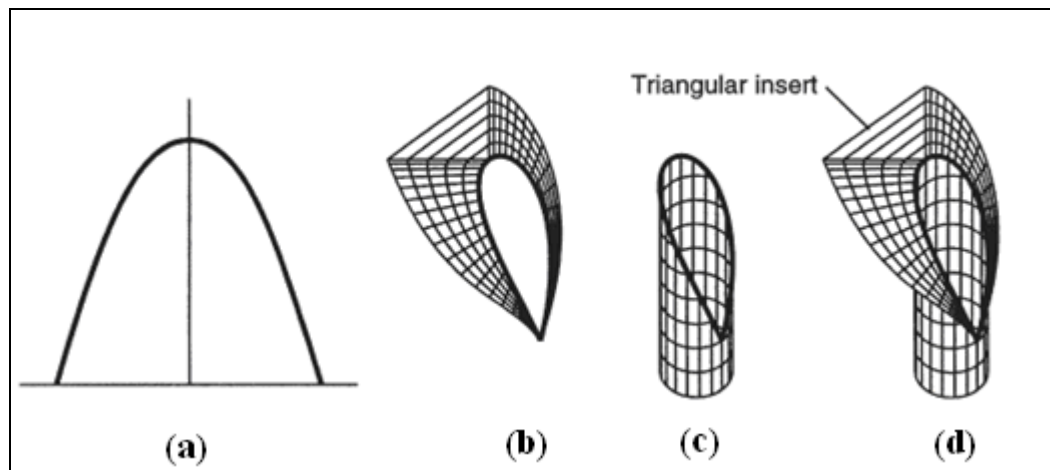
In this packing system, film is drawn from a roll and then fed to the shoulder. The film is normally supplied as flat, pre-printed sheet of uniform width and is stored on a roll. It is guided by the forming shoulder from a flat sheet to a tubular form. During this process, the edges of the film are brought together and then sealed by either heating or gluing. This forms a tube of the packaging material. It is then cross-sealed at the bottom. The product to be packed is inserted from the top using a product feed tube. The process is then completed by advancing the material and forming a final seal at the top of the bag.

The performance of the shoulder to successfully create a bag largely depends upon the surface geometry of its collar (McPherson *et al.* 2004), which is closely related to the type of packaging material and cross-section shape of the bag to be produced. As mentioned before, the current design practice for these shoulders is largely based upon

selecting and testing them for a particular type of packaging material and does not provide an optimal way for designing shoulders.

### 9.1.1 Current design practice for forming shoulders

Mullineux *et al.* (2007) describe the traditional process of making a forming shoulder. A typical shoulder is made up of two parts (namely collar and tube) assembled together along a curve (Figure 9-2).



**Figure 9-2 (a) Bending curve, (b) collar, (c) tube and (d) complete shoulder Source: McPherson *et al.* (2004)**

The curve, which is termed as bending curve, can be regarded as a planar curve of roughly parabolic shape (part a, figure 9-2). The collar surface (upper portion) is made by bending a metal sheet backward to form the shoulder surface. A triangular insert is also included in the collar at its highest point in order to have a smooth transition of the film from its flat form to tubular form. The tube is made by wrapping round the part below the curve into a circular cylinder. The bending curve ultimately forms the edge over which the film passes and the overall shape of the forming shoulder depend upon the bending curve and the radius of the tube.

This process of manufacturing forming shoulders relies on human experience and incorporates trial and error testing (Hicks *et al.* 2007). There is limited understanding about how the geometry of a particular shoulder affects the behaviour of different packaging films during the forming process. Ideally, the film should track smoothly across the shoulder and there should not be any permanent stretching or tearing of the

film. For this purpose, the shoulder has to be matched to a particular material that is to be run over it. It is accomplished manually by making slight adjustments to shoulder parameters. Normally, minor problems can be compensated by hand tuning. However, a complete new shoulder design can be required to tackle major problems. It can take up to four or five modifications before a suitable shoulder is manufactured. This process is both error prone and time consuming.

There has been some research work undertaken in order to understand the underlying theory of forming shoulders so that improved means of manufacturing shoulders can be obtained. McPherson *et al.* (2004 & 2005) proposed a theoretical model of the shoulder which helps in defining the bending curve in mathematical form. The model can also help in defining the collar surface including a planar triangular insert. They also highlighted the four basic design parameters that define the shape of the bending curve and thus geometry of the shoulder. These design parameters include (figure 9-3):

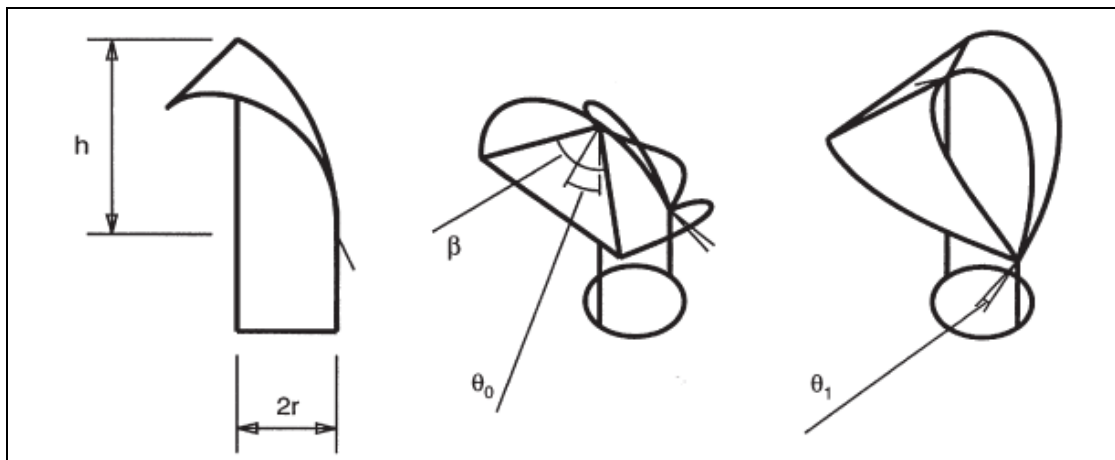


Figure 9-3 Basic design parameters Source: McPherson *et al.* (2004)

$h : r =$  ratio of the overall height  $h$  of the wrapped bending curve to the radius  $R$  of the cylindrical tube

$\theta_0 =$  back angle, i.e. the angle between the normal to the surface and the normal to the tube at the highest point of the bending curve, which is then also the angle between the triangular insert and the vertical generator of the cylinder

$\theta_1$  = front angle, i.e. the angle between the normal to the surface and the normal to the tube at the lowest point of the bending curve, which is also the angle between the tangent plane to the surface and the vertical tangent plane to the tube

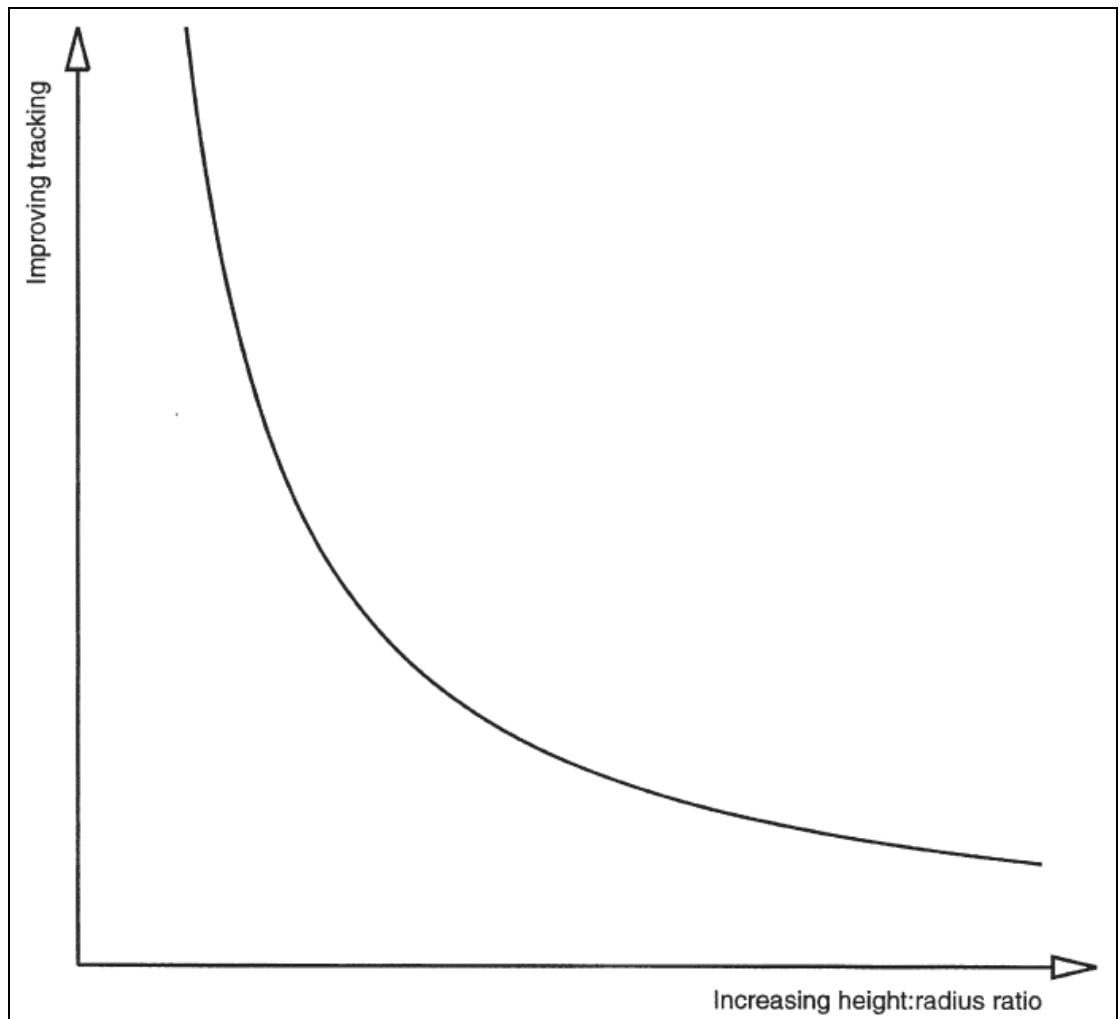
$\beta$  = opening angle, i.e. the angle at the apex of the triangular insert.

### **9.1.2 Machine-material interactions: the conventional wisdom and related research**

There is little known about how machine-material interactions define the performance of the forming shoulders. The aim is to reduce the stress produced in the packaging material in order to avoid permanent stretch or tearing. Research conducted by Berry *et al.* (2003), McPherson *et al.* (2004 & 2005), Hicks *et al.* (2007) and Mullineux *et al.* (2007) highlighted some interesting observations regarding effects of changing the main geometry parameters on the behaviour of a particular type of material. The main findings of their research work are listed below.

- $h:r$  ratio is the key design parameter among four design parameters identified. Once it is chosen, strict limitations are imposed upon the values of other three by the requirement of the geometry (Mullineux *et al.* 2007).
- Material stress, which is directly proportional to pulling force (force required to pull a particular material over a particular shoulder), reduces with increase in  $h:r$  ratio. Thus, there is little damage to material at large  $h:r$  ratios. However, the film's ability to track decreases as the ratio increases. It is also hard to manufacture shoulders with large  $h:r$  ratios and these shoulders are bulky (difficult to handle and setup). A heuristic relationship of material stress to  $h:r$  is shown in the figure 9-4.
- Material stress also reduces with increase in back angle. Also according to theoretical model given by McPherson *et al.* (2004), for the given values of  $h:R$ ,  $\theta_1$  and  $\beta$ , there is only small interval of allowable values for the back angle and broadly speaking, back angle increase with increase in  $h:r$  ratio.
- Material stress increases with increase in web tension (tension in the film due to load at the roller, which can be varied) in the film. The process of varying the web tension in the film is currently used to improve tracking on the forming shoulder. It is believed that tracking is improved by increasing the web tension.

- Tracking can be further improved by using exact shoulders, which are made by milling a solid metal block using machining instructions generated from the geometric model (Mullineux *et al.* 2007). Using exact shoulders requires considerably less web tension when compared to the shoulders made up of metal sheet using traditional methods. Thus when an exact shoulder is designed, there is almost no need to concentrate upon the tracking aspects.



**Figure 9-4 Heuristic relationship of material stress to the  $h:r$  ratio** Source: McPherson *et al.* (2004)

The following sections investigate a number of forming shoulders using the proposed multi-instance modelling approach. The aim is to increase current design knowledge regarding machine-material interactions that take place during packaging operations. There are three possible areas in vertical forming filling and sealing machines where machine and material interact. These areas are:

1. The feed system where the film leaves the roll.

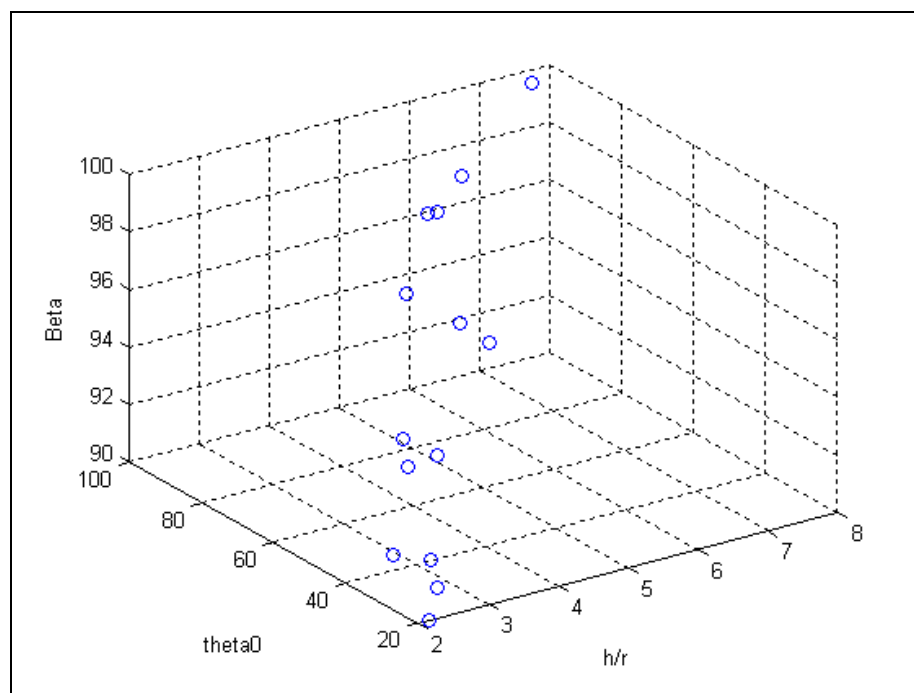


2. The shoulder surface over which film is dragged.
3. The traction system below shoulder which is used to pull film through.

Each of these tends to increase web tension in the material. According to Mullineux *et al.* (2007), the shoulder surface has the largest effect on web tension. Thus it is considered for further investigation.

## 9.2 Investigating forming shoulders - a case of isolated instances

For the purpose of this investigation, a number of typical shoulders were taken as examples of isolated design instances. These were measured for their main design parameters ( $h:r$ ,  $\theta_1$ ,  $\beta$  and  $\theta_0$ ). The variation in front angle ( $\theta_0$ ) for these shoulders was found to be small (2 degree approx). So, the front angle is assumed to be constant across all the available shoulders. Figure 9-5 shows a plot for the remaining design parameters. Figure 9-6 (part a) shows the plan view of the same plot and part b fits a rough surface by joining the neighbouring points.



**Figure 9-5 Design parameters for various shoulders**

It is clear from the figure that there is a relationship between back angle ( $\theta_0$ ) and the ratio  $h:r$ . The back angle increases with increase in  $h:r$  ratio. Also, there is a range of values for the back angle for every value of the  $h:r$  ratio. This suggests that there is some permissible variation in the back angle. This observation is in agreement with the theoretical model given by McPherson *et al.* (2004).

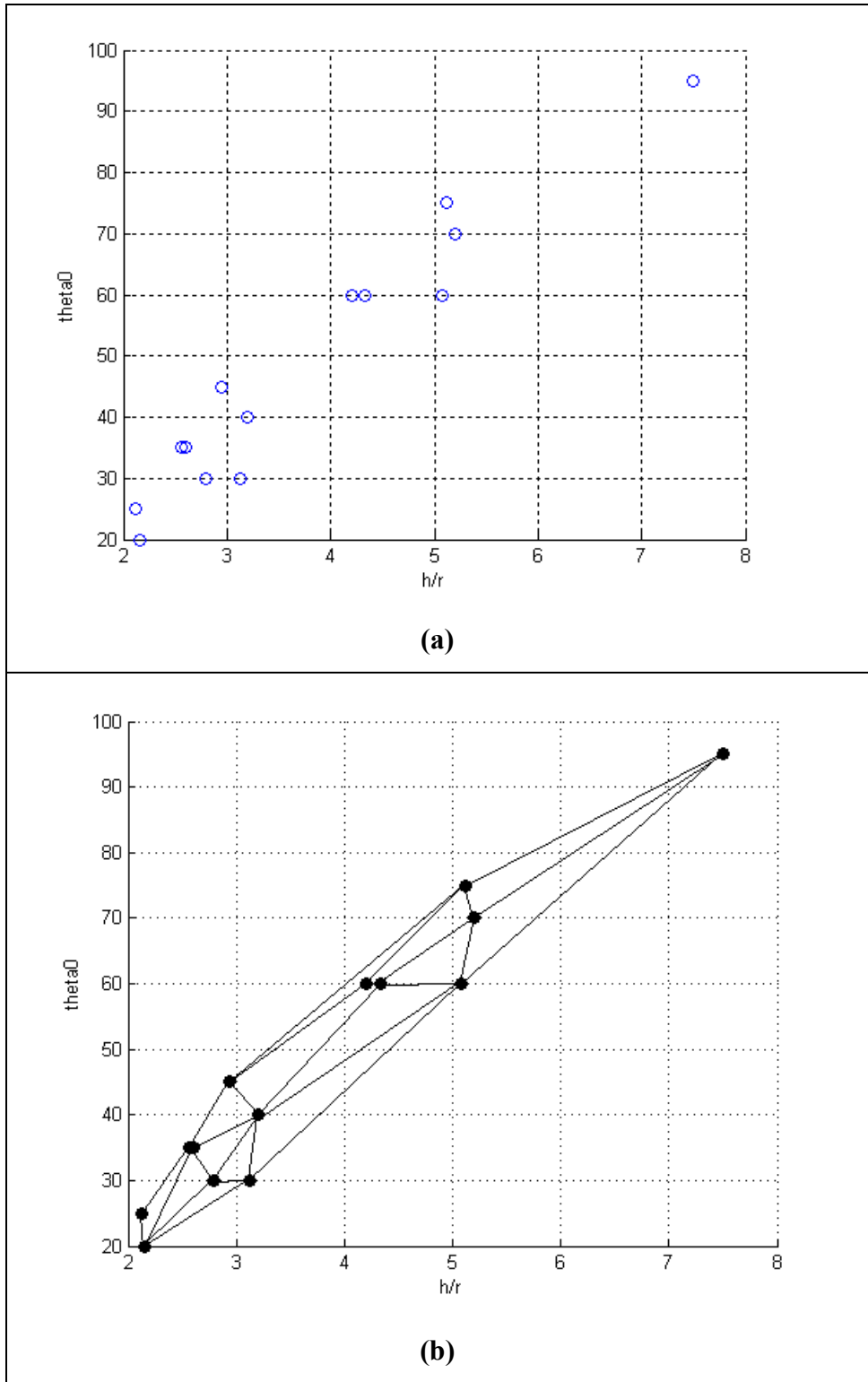


Figure 9-6 Design parameters for various shoulders

### 9.3 Investigating forming shoulders – an experimental investigation

The situation of experimental investigation is also possible in this case. For investigating shoulders with the multi-instance modelling approach three shoulders with same radius were selected. This helps in investigating the suitability of different shoulders for packing same sized bags. The selected shoulders are shown in figure 9-7 and their description of geometries is given in table 9-1.



Figure 9-7 Shoulders A, B, and C (from right to left) source: Royce (2008)

Table 9-1 Shoulder geometries

	Radius (mm)	$h:r$	$\theta_0$
Shoulder A	25	2.2	20
Shoulder B	25	3.2	41
Shoulder C	25	4.6	65

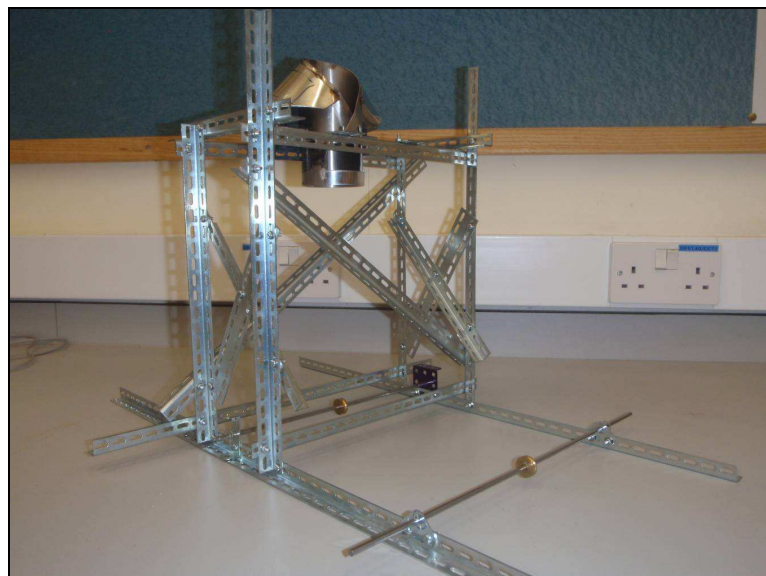
The main purpose of this investigation is to understand machine-material interactions. Previous studies (Berry *et al.* 2003, Mullineux *et al.* 2007) have looked at changing geometries of the various shoulders with different materials. However, no study has investigated the effects of change in material thickness. To understand how the thickness of a particular material affects the performance of a shoulder, this study mainly uses the same material with varying thickness. The material used (MonoSol L330) for experimentation was supplied by MonoSol LLC (MonoSol LLC 2008). Table 9-2 shows the thicknesses of the material used for experimentation. MonoSol L330 is a polyvinyl alcohol based thermoplastic film, which is soluble in cold water and completely biodegradable. This property makes it suitable for a range of

packaging applications that include dishwasher detergents, liquid and powder laundry detergents, agrochemicals and fertilizers.

**Table 9-2 Thicknesses of test materials**

Material	Thickness ( $\mu\text{m}$ )
MonoSol L330 (30)	30
MonoSol L330 (50)	50
MonoSol L330 (80)	80

The experimental values used in this study were obtained (Royce 2008) using the test rig shown in figure 9-8. The rig was built to accommodate the three shoulders.



**Figure 9-8 Test rig for experimentation source: Royce (2008)**

During testing the film was loaded uniformly at both ends. The roller end of the film was evenly loaded using weights (50g, 250g, 450g and 650g) to test films at different web tensions. An Instron 3365 tensile tester with a 5KN load cell was used to drag the film over the selected shoulders and to calculate the pulling forces required. Each test was repeated three times for each film on every shoulder. The tests were carried out at  $23^{\circ} \pm 1^{\circ}\text{C}$  room temperature and  $50 \pm 2\%$  relative humidity.

### 9.3.1 Multi-instance modelling

A triangular surface is plotted whose vertices are represented by shoulders A, B and C. The height of the surface represents the pulling force that was required to pull a certain film over a particular shoulder. Another important feature used in this representation is the use of the natural ordering while representing these shoulders. The vertices are plotted by mapping  $h:r$  and back angle along  $x$ - and  $y$ - axis respectively. This kind of natural ordering of base instances can overcome the problem of multiple choices of weights that can specify any given point within the polygon esp. in the case of four or more base instances (discussed in section 4.2, chapter 4).

The first experiment was carried out using MonoSol 80 film (thickness =  $80\mu\text{m}$ ). Figure 9-9 shows the triangular surface representation of three shoulders A, B and C for this experiment. There are four surfaces representing the pulling forces required for the given shoulders at various web tensions. Figure 9-10 shows the side view of the same plot. It is clear from the figures that with increase in web tension the average pulling force required for each shoulder increases. It is also observed in this case that for all shoulders, irrespective of increasing web tensions, the required pulling force decreases with increase in  $h:r$  ratio as suggested by McPherson *et al.* (2004).

The second experiment involved the investigation of MonoSol 50 (thickness =  $50\mu\text{m}$ ) film. Figures 9-11 and 9-12 show the average pulling force required for three shoulders at various web tensions. At low web tensions (50g), shoulders in this case also follow a similar trend as of the previous case. However, as the web tension is increased, shoulder B starts performing better by requiring the least amount of pulling force in every case. This phenomenon is amplified with further increases in web tension.

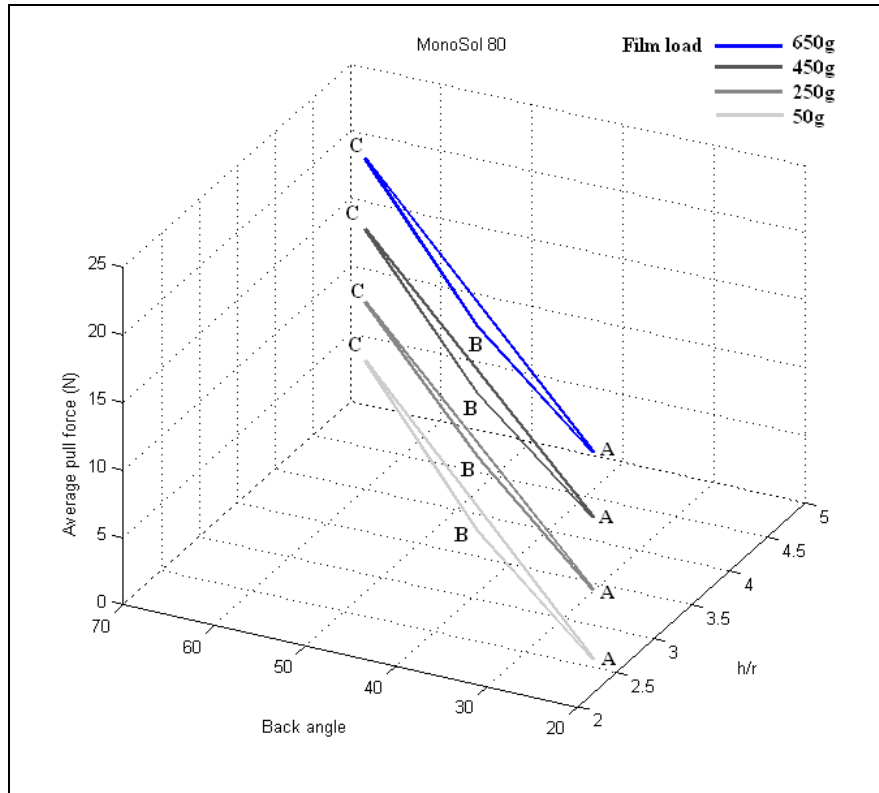


Figure 9-9 A surface plot of the shoulders for average force required to pull MonoSol 80 film

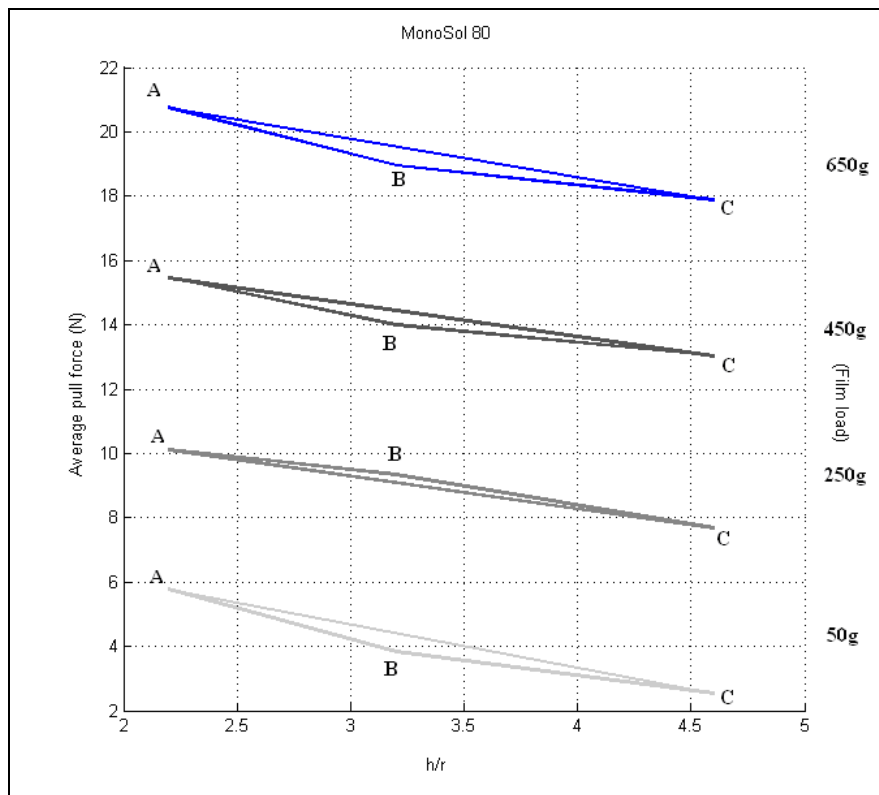


Figure 9-10 Side view of the plot

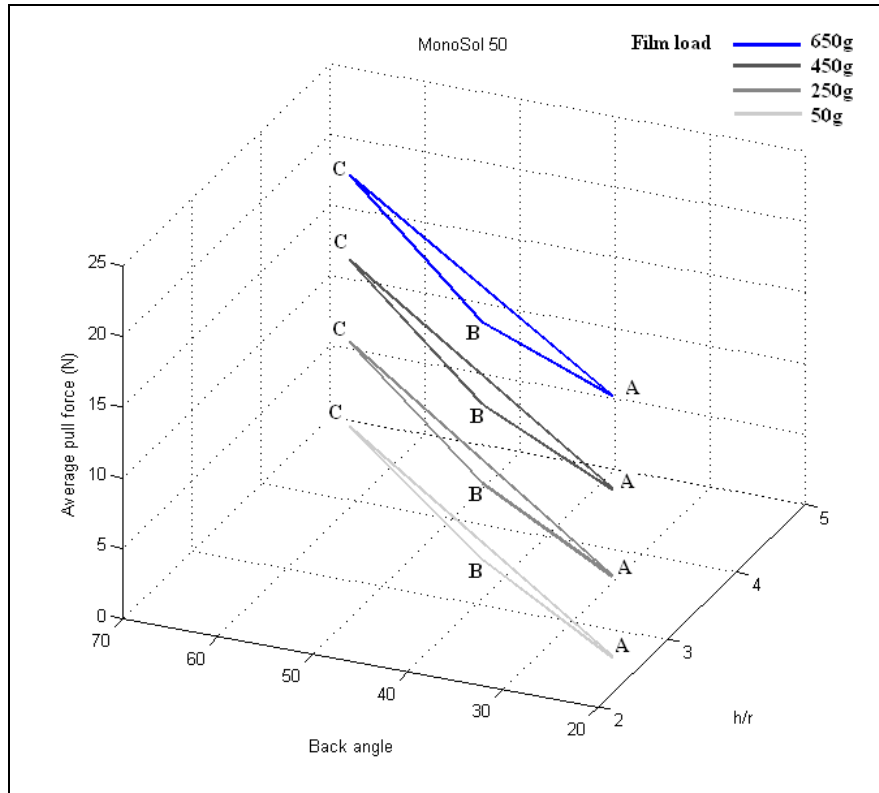


Figure 9-11 A surface plot of the shoulders for average force required to pull MonoSol 50 film

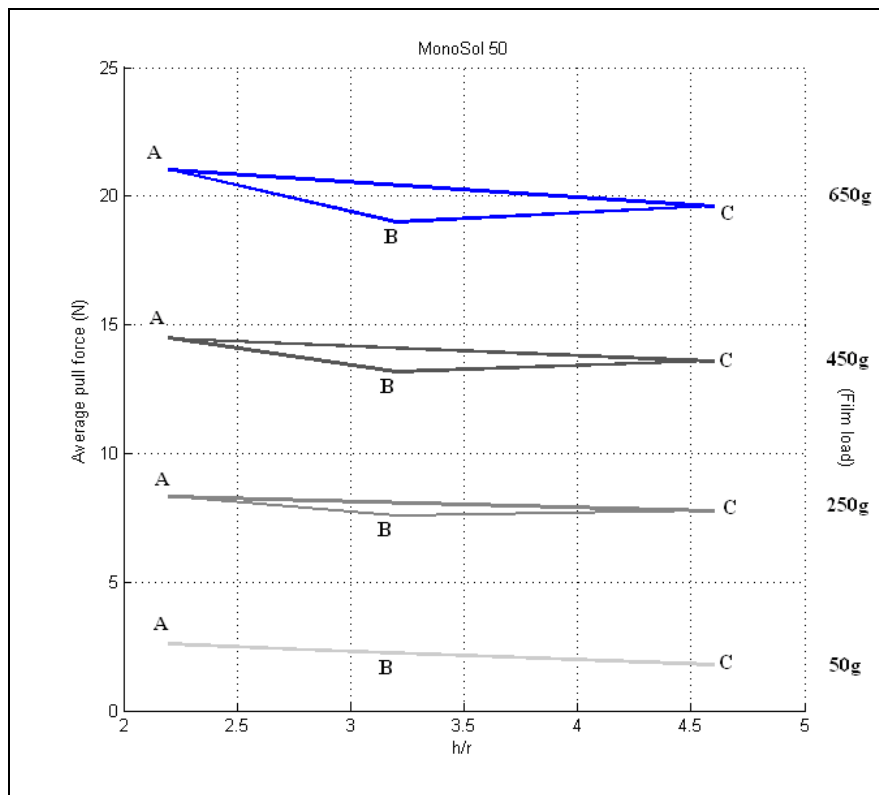


Figure 9-12 Side view of the plot



Similarly, the third experiment was conducted using MonoSol 30 (thickness = 30 $\mu$ m). Figures 9-13 and 9-14 show the average pulling force required for three shoulders at various web tensions. As noted before, at low web tensions (50g) the pulling force required by each shoulder decreases with increase in  $h:r$  ratio. As the web tension is further increased, shoulder B again starts performing better by requiring the least amount of pulling force in each case. The only difference in this case, when compared to the previous experiment with MonoSol 50, is that at higher web tensions shoulder A outperforms shoulder C.

It is interesting to note from the above experiments that materials with high thickness follow the conventional wisdom i.e. the required pulling force decreases with increase in  $h:r$  ratio. However, a different pattern emerges as the thickness of material is reduced and web tension is increased. At this stage, shoulders with moderate  $h:r$  ratio seems to perform well when compared to shoulders with high  $h:r$  ratios. This observation is very useful especially as the tracking of the material improves with reduction in  $h:r$  ratio (discussed in section 9.1.2). Thus for thinner materials by selecting shoulders with moderate  $h:r$  ratios, the material stress reduces considerably. Comparing figures 9-10, 9-12 and 9-14 also shows that the pulling force, in general, increases with increase in material thickness.

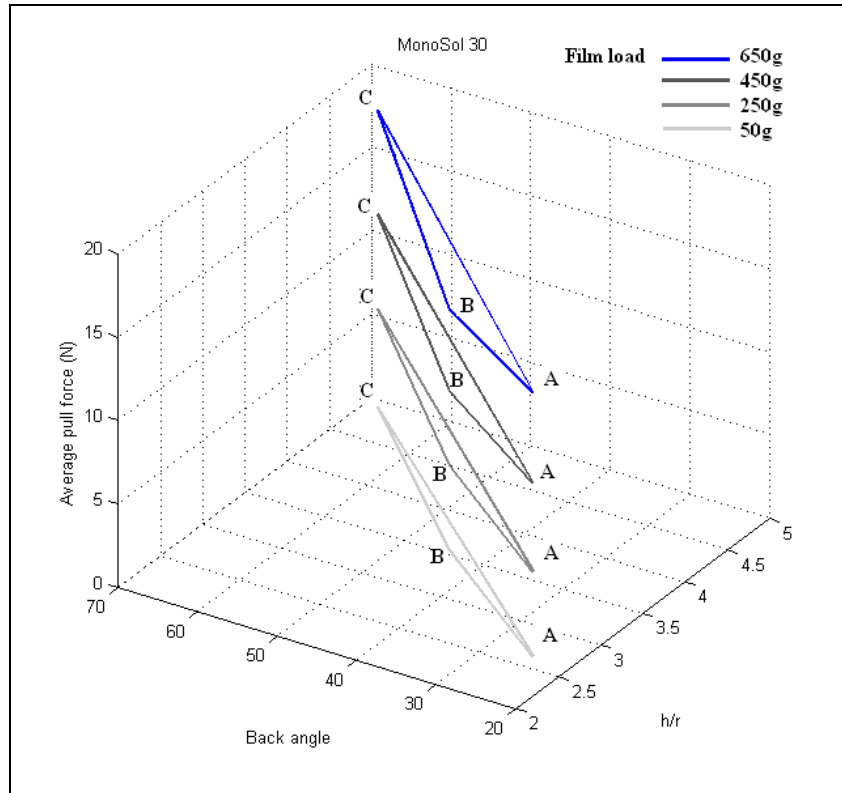


Figure 9-13 A surface plot of the shoulders for average force required to pull MonoSol 30 film

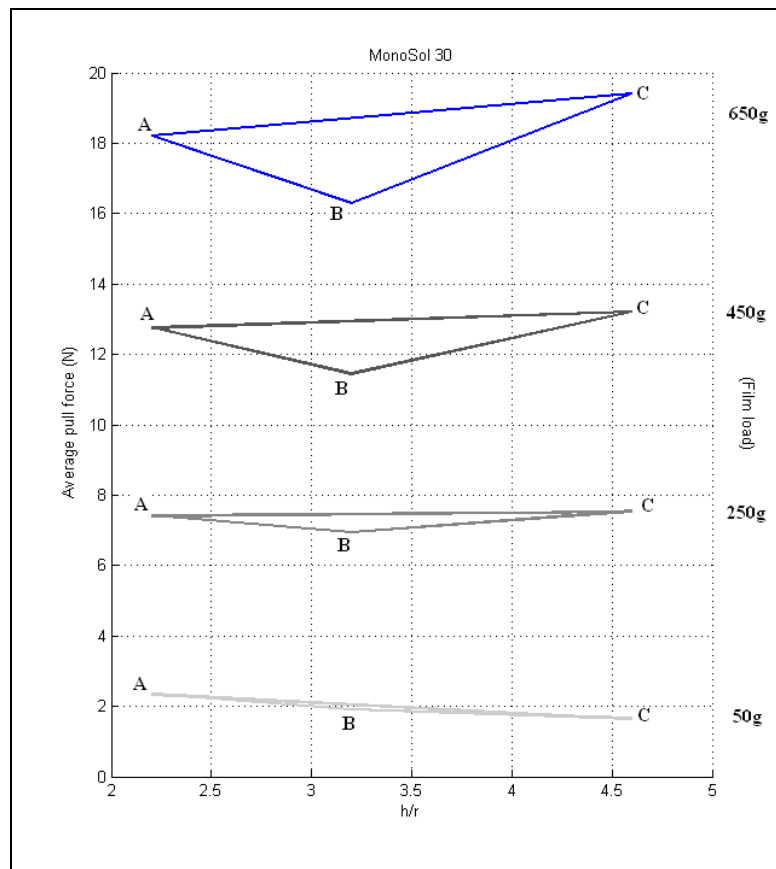
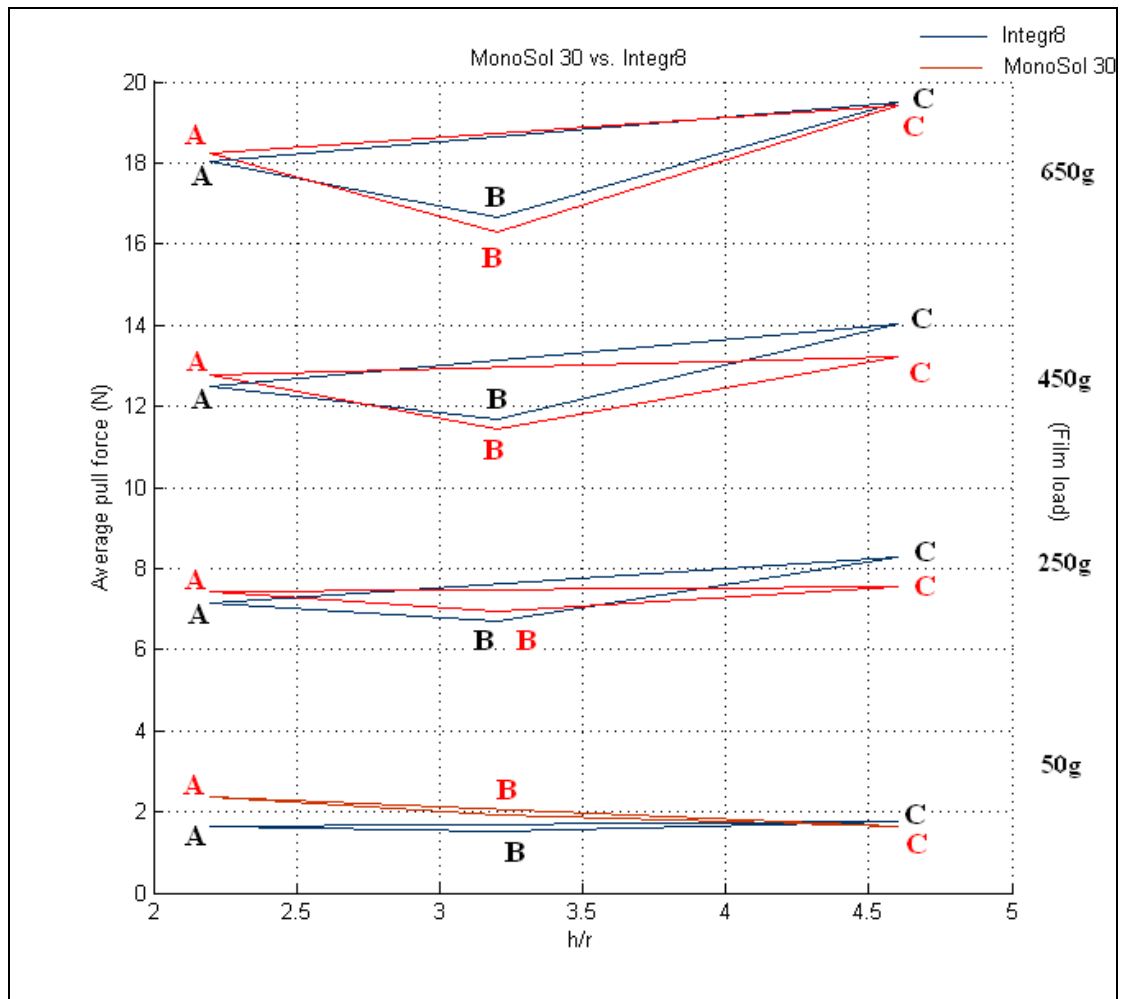


Figure 9-14 Side view of the plot

The above three experiments were conducted using the same material. Another experiment was conducted using a different material. For this purpose, Integr8 film with 32  $\mu\text{m}$  thickness was used. This film is supplied by BPI films (BPI films 2008) and is normally used for industrial composting facilities as it breaks down easily leaving no harmful residuals.



**Figure 9-15 Comparison of the shoulder performances with different materials (MonoSol 30 and Integr8)**

The experiments were again conducted using the selected shoulders at various web tensions. Figure 9-15 shows the performance of three shoulders using Integr8 film along with MonSol 30 film. Both of these films have almost same thicknesses (Integr8 film with 32  $\mu\text{m}$  thickness and MonoSol 30 with 30  $\mu\text{m}$  thickness). It is clear from the figure that both materials exhibit very similar behaviour. Again, in both cases, the conventional wisdom is only followed at lower web tensions

### 9.3.2 Fitting a mathematical relationship

The data obtained from the experimentation with MonoSol films can be used to fit a mathematical relationship between pulling force ( $F$ ), thickness of the film ( $T$ ), height:radius ratio (here termed as  $R$ ) and web tension/film load ( $W_T$ ) using regression. This can further help in selecting appropriate shoulder that requires minimum amount of pulling force required for a particular material thickness. For the purpose of fitting the given data, a nonlinear least square method available with MATLAB<sup>TM</sup> was used to fit a cubic model. The cubic model had the following form.

$$\begin{aligned} F = & b_0 + b_1R + b_2W_T + b_3T + b_4RW_T + b_5RT + b_6W_TT + b_7R^2 + b_8W_T^2 + b_9T^2 \\ & + b_{10}RW_TT + b_{11}R^2W_T + b_{12}R^2T + b_{13}RW_T^2 + b_{14}RT^2 + b_{15}W_T^2T + b_{16}W_TT^2 \\ & + b_{17}R^3 + b_{18}W_T^3 + b_{19}T^3 \end{aligned}$$

Where  $b_0, b_1, \dots, b_{19}$  are unknown parameters. These parameters were estimated using the “nlinfit” function provided by the statistics toolbox of Matlab (The Math Works Inc. 2002). It returns the least square parameter estimates of the coefficients of a nonlinear regression function. The fitted model is given below:

$$\begin{aligned} F = & 9.22759 - 4.38618 R + 0.01911 W_T - 0.18235 T - 0.00780 RW_T \\ & + 0.00068 RT - 0.06629 W_TT + 0.67980 R^2 + 9.244 \times 10^{-06} W_T^2 - 0.00139 T^2 \\ & - 0.00002 RW_TT + 0.01535 R^2W_T - 0.01233 R^2T - 1.711 \times 10^{-06} RW_T^2 \\ & - 4.128 \times 10^{-06} RT^2 - 3.66 \times 10^{-08} W_T^2T - 5.576 \times 10^{-06} W_TT^2 \end{aligned}$$

This model was validated by comparing it to original experimental results. The results obtained from the fitted model show a close match with the experimental results.

## 9.4 Investigating forming shoulders – a mathematical relationship is available

Once a mathematical model is available, it is possible to perform a greater level of investigation. The design space between shoulders A, B and C is explored and then represented using the proposed approach. It is observed that if natural ordering (discussed above in section 9.3.1) is applied in this case the resulting surfaces are very narrow and difficult to visualise. So here equilateral triangular surfaces are used to represent the design space between these shoulders.

### 9.4.1 Multi-instance modelling

Consider the case for MonoSol 80 (80  $\mu\text{m}$  thickness). The three shoulders are morphed and average pulling forces required for various interpolants are calculated using the fitted model. It is then recorded and plotted according to the proposed visualisation strategy. The process is then repeated at different web tensions. The resultant surfaces are shown in figure 9-16.

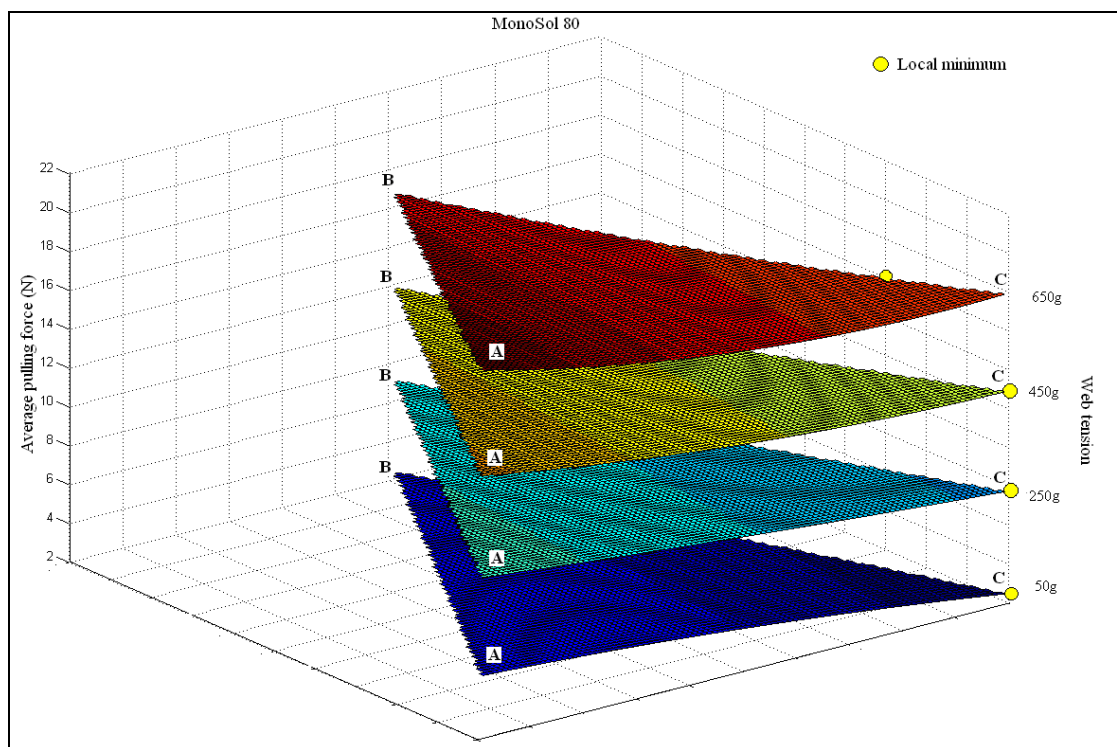
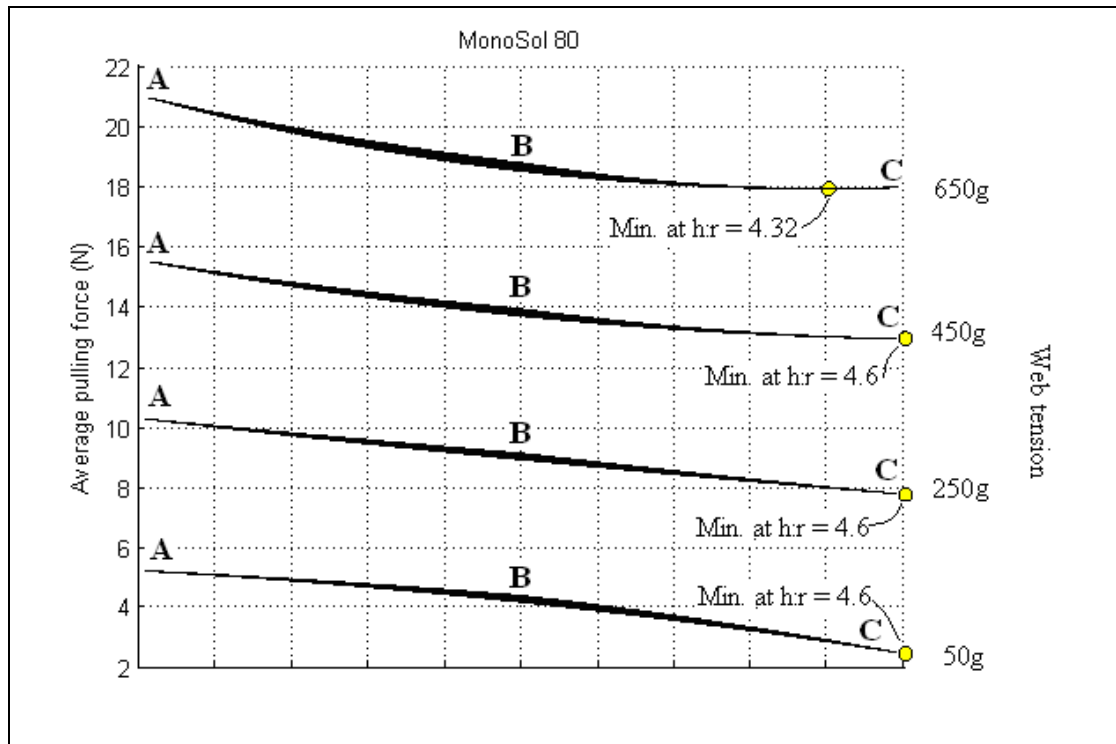


Figure 9-16 Resultant surfaces for MonoSol 80

Figure 9-17 shows a side view of the same surfaces. Various local minima are found within the triangle and are highlighted in the figures. It is clear that shoulder C is best

suites here as requires least amount of pulling force in almost every case (except at 650g web tension where minimum pulling force is required when  $h:r$  ratio is 4.32). It is also important to note that as the minimum lies at the edge of the surfaces in each case, there may be a global minimum lying outside of the explored design space. It can be located with the help of extrapolation.



**Figure 9-17 Side view of the resultant surfaces for MonoSol 80**

Now consider the case for MonoSol 50 (50  $\mu\text{m}$  thickness). Figures 9-18 and 9-19 show the resulting surfaces. Again, various local minima found are highlighted. It is clear from the figures that at low web tensions (50g) shoulder C with highest  $h:r$  ratio (4.6) requires the least amount of pulling force. However as the web tension is increased this value of  $h:r$  ratio (requiring least pulling force) starts decreasing and minimum starts shifting away from shoulder C. Similarly, for MonoSol 30 (30  $\mu\text{m}$  thickness) figures 9-20 and 9-21 show the resulting surfaces. A similar trend is noted in this case as well. At 50g web tension the minimum pulling force is required by a shoulder with  $h:r$  ratio equals to 3.66. As the web tension is increased the minimum starts shifting towards shoulder B. Based upon these results, it can be said that shoulder B is best suited of the three shoulders for the case of MonoSol 30 material at high web tensions.

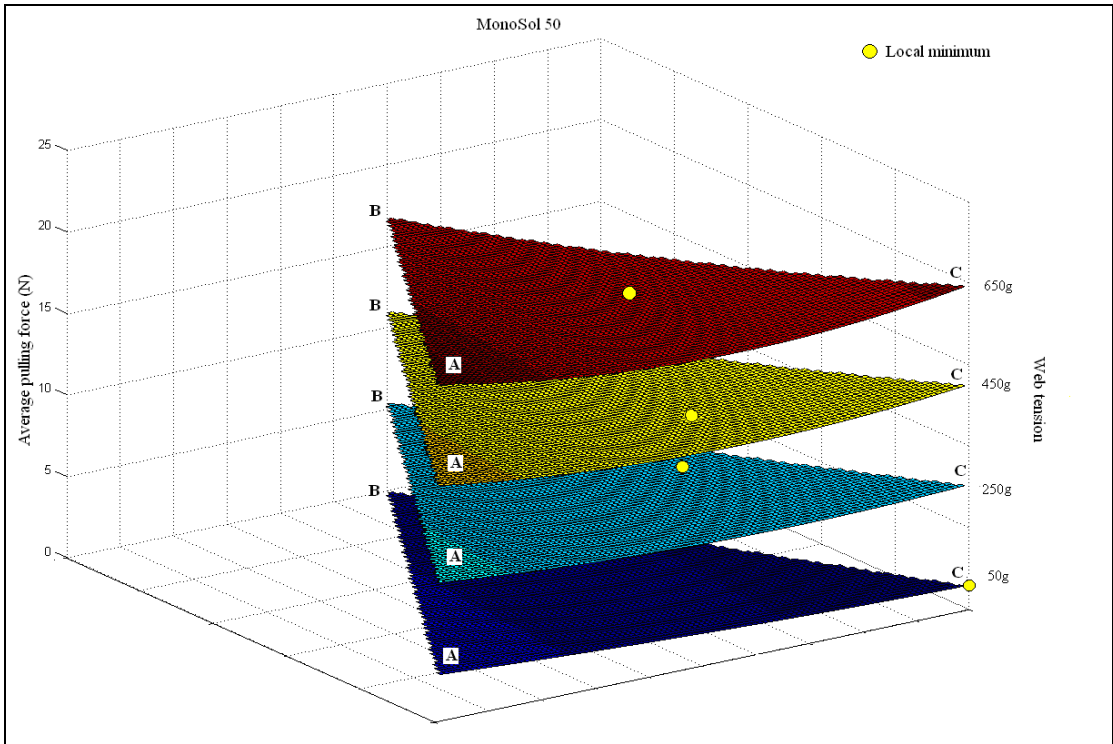


Figure 9-18 Resultant surfaces for MonoSol 50

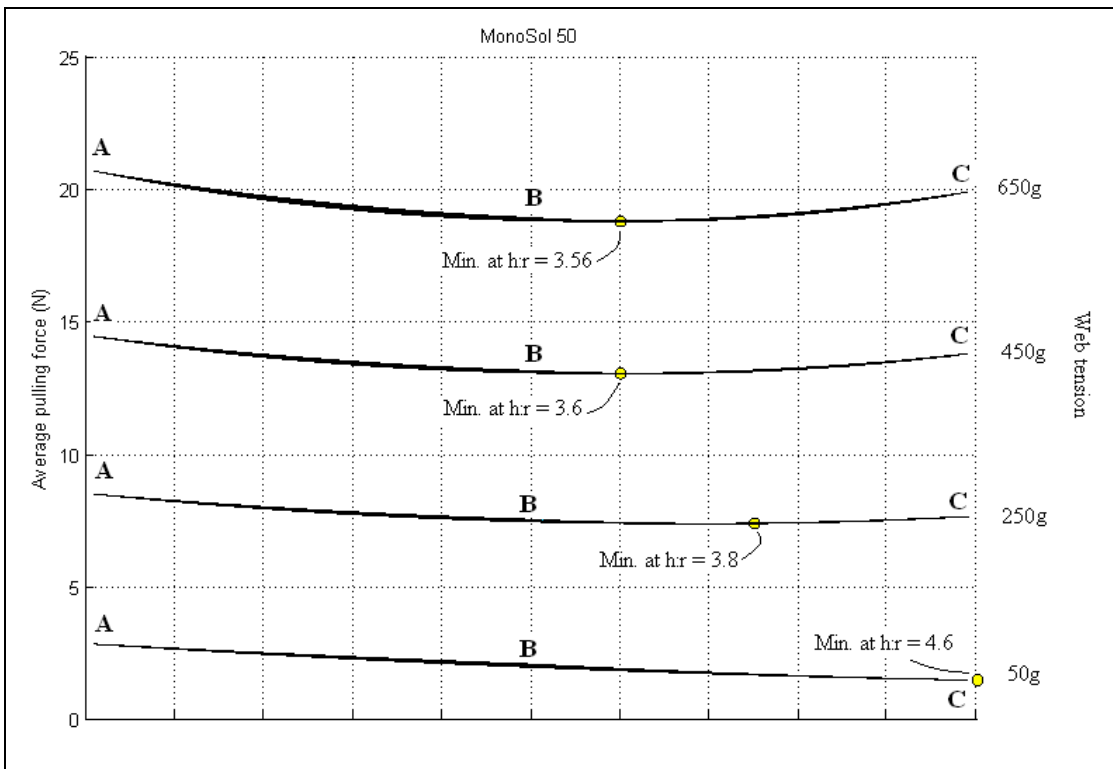


Figure 9-19 Side view of the resultant surfaces for MonoSol 50

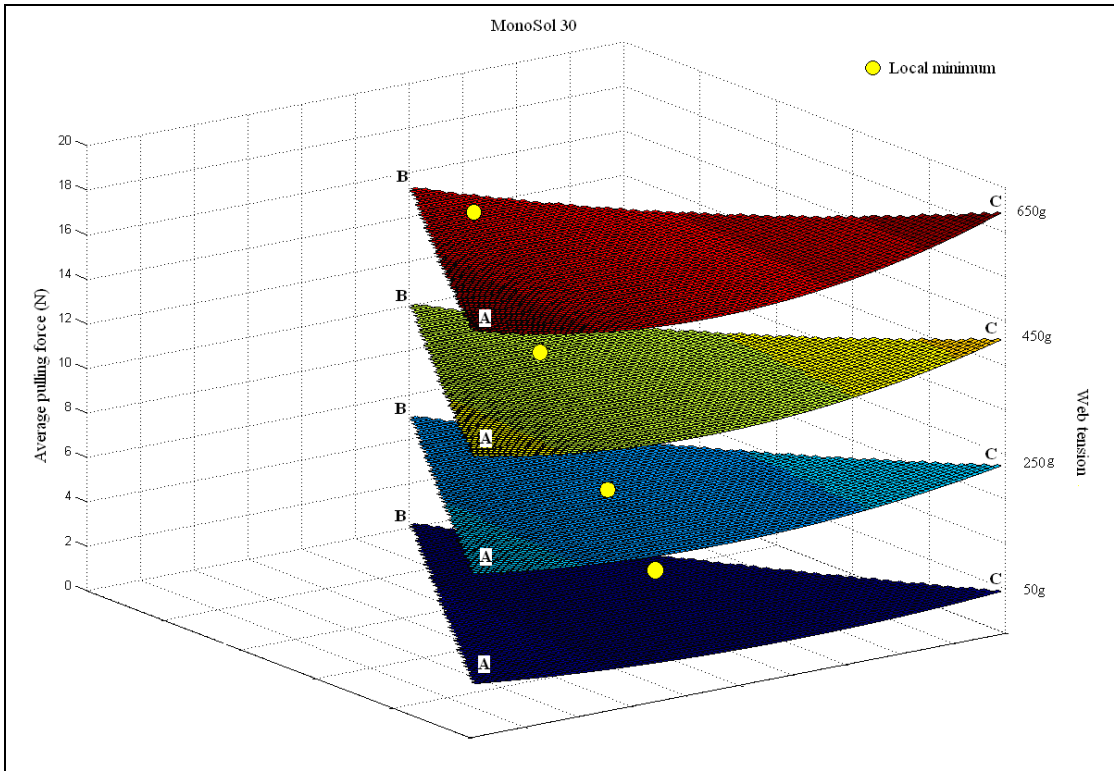


Figure 9-20 Resultant surfaces for MonoSol 30

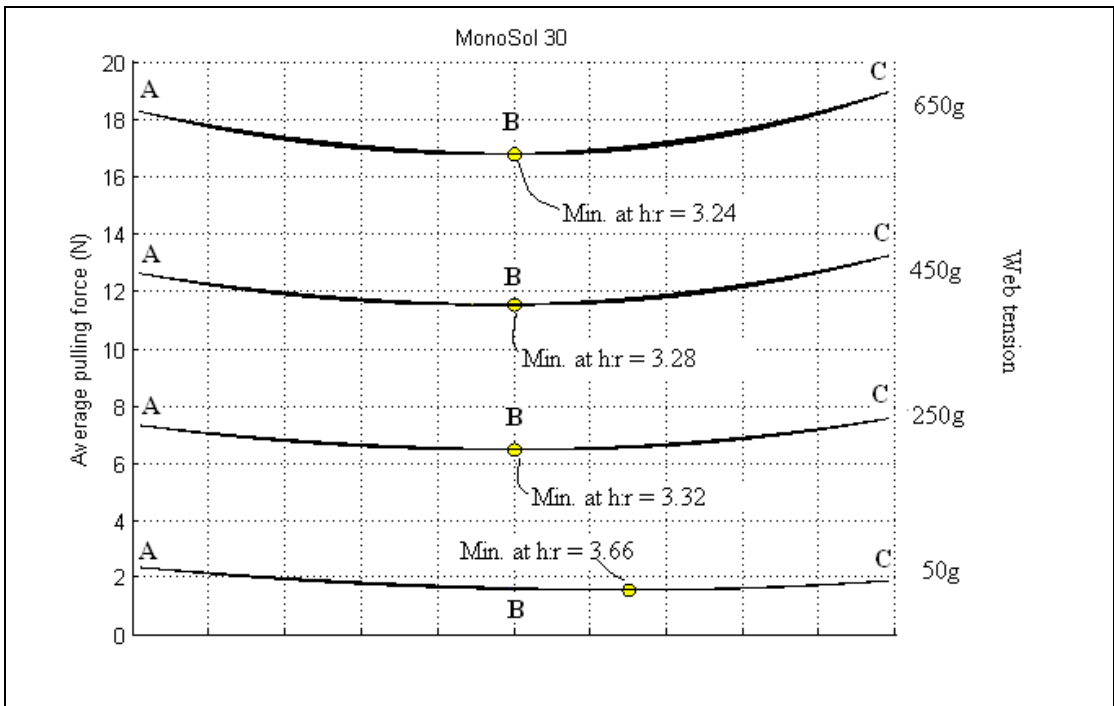


Figure 9-21 Side view of the resultant surfaces for MonoSol 30



Thus, the surfaces obtained give information about how the performance of the shoulders change for various films. The surfaces produced are reasonably flat. It suggests that the shoulders are similar in performance and can be said to lie within a single family. This family also includes performance with respect to Integr8 film, as the results are similar for this film as well (figure 9-15). The flatness also suggests that performance is reasonably insensitive to variation in the shoulder geometry. The fact that the surfaces are not perfectly flat means that one of the three shoulders is better in each case. For a given material (and thickness) the surfaces allow one to identify the parameters for an optimal shoulder for that material.

## 9.5 Discussion

This case study presents an application of the proposed multi-instance modelling approach in all the three scenarios identified in chapter 4. A number of forming shoulders were investigated and information about their performance capabilities was obtained. The proposed approach helped in seeing how the material properties (particularly thickness) affected the performance of particular shoulders. It showed that there are implicit relationships between the design parameters and allowed optimal parameters to be identified. Important findings can be summarised as follows.

### Scenario 1: A case of isolated instances

- An investigation which was based upon isolated instances of forming shoulders revealed that there is an implicit relation between the  $h:r$  ratio and the back angle. The back angle increases with increase in the  $h:r$  ratio, and there is a small interval of allowable values for the back angle for every value of the  $h:r$  ratio. (This supports the theoretical model given by McPherson *et al.* (2004)).

### Scenario 2: When experimental investigation is performed

- The results of experimental investigation can be plotted as vertices of a triangle and these are roughly flat (for the MonoSol film considered) suggesting that the shoulders lie in a single family.
- The resulting surfaces are similar for a second film (Integr8) which suggests that the shoulders lie in the same family for this as well; thus any one of the three shoulders is likely to operate adequately with either of the two materials.
- The shoulder corresponding to the lowest vertex of the triangle varies suggesting that in certain cases shoulder B is the best of the three and in other cases, it is shoulder C.

### Scenario 3: When a mathematical model is available

- The results from the experimental work can be used to obtain a model relating the design parameters and the performance and this allows the design space to be explored more fully.

- It is seen that the surfaces are reasonably flat suggesting that the shoulders lie in the same family.
- A local minimum can be identified which is either within or on the boundary of the surface. When the minimum lies within the surface it allows identification of the parameters for an improved shoulder which has better performance than any of the initial instances.

## **Chapter 10: Conclusions and future work**

This thesis has presented a novel and easy to use technique that can help SMEs to investigate their current designs and related design space with the intention of increasing their current design knowledge. The main idea that has been explored in this research work is that the existence of examples of workable designs (variants) can be used to perform a simplified investigation of the design space (formed by base designs) involved. Associated with the aim of proposing and demonstrating an easy to use technique for SMEs in order to investigate their current designs and related design space, there are six objectives identified in chapter 1 (page 6). The following section describes how the objectives have been met and from this conclusions are drawn.

## **10.1 The objectives of this research work revisited**

The following sections discuss how the six objectives are addressed in the various chapters of this thesis.

### **10.1.1 Investigation of current product development practises of SMEs**

The first objective was to investigate current product development practices of SMEs with the purpose of capturing factors that are hindering their development processes and identifying their current needs. This was dealt with in chapter 2. It was discovered from the literature that there are several factors that are hindering effective product development in SMEs. These factors include lack of resources (in terms of cash flow, number of employees and adequately trained work force), their focus on individual customers instead on the market, lack of design knowledge regarding their products and lack of clearly defined product development processes. The basic needs of SMEs were also highlighted here. These include the need for simpler techniques to develop their products, improved product refinement methods, increased design knowledge of existing products and the need for promoting design reuse and controlling product proliferation.

### **10.1.2 Investigate and critically appraise previous research work**

Again, addressed in chapter 2, the second objective was to investigate and critically appraise previous research work that has been undertaken to improve product development in SMEs. Views of several researchers were presented in this chapter. It was shown that a great deal of research has been done to satisfy some of the basic needs of SMEs such as design reuse and control of product proliferation (based upon the concepts of modularisation). However, some of other essential needs of SMEs such as increasing design knowledge of existing products and improving methods for product refinement still remain unanswered.

### **10.1.3 Investigating different tools and techniques to model and analyse machinery**

The focus of the thesis is on machine manufacturing SMEs. So, the next objective was to investigate different tools and techniques which are available to model and

investigate machinery. This was dealt with in chapter 3. The identified tools were classified into two categories namely computer based tools and practical tools. The computer based tools are helpful in modelling and analysing machinery. For this purpose, CAD, design optimisation and constraint based modelling were investigated for their relevance to support product development activities in SMEs. The practical (experimental) tools on the other hand provide strategies to conduct experiments on actual machines and are further required to validate computer based models.

However, there is a limited use of these tools/techniques for meeting current needs of SMEs. Some of these techniques such as design optimisation and constraint based modelling require specialised knowledge (or expertise) to be able solve design problems which SMEs often lack. Also, most of the techniques are limited for investigating single designs only. There is a need to provide support to the designers when a number of design options need to be investigated/evaluated.

#### **10.1.4 Investigating the suitability of design space exploration and various visualisation techniques**

Chapter 3 also tackled the fourth objective of investigating the suitability of design space exploration and various visualisation techniques for assisting product development in SMEs. The aim was to understand various techniques available so that a visualisation tool can be proposed that can aid in the designer's decision making process when a number of variants are to be investigated. The process of design space exploration was first explained and then several visualisation techniques were investigated that are being used by the researchers in order to display and analyse multi-dimensional data.

However, none of the existing techniques discussed here provided a support to represent and explore design space around a number of design variants. It was argued that such a technique can aid a designer's decision making process when a number of design options are to be evaluated and thus provide invaluable support to SMEs by increasing their current design knowledge about existing products and further help to improve these products.

### **10.1.5 To propose a simple approach that can help SMEs**

Chapter 4 addressed the fifth objective by proposing a simple approach that can help SMEs to increase their current design knowledge and so provide a basis for improving/refining their product ranges. A multi-instance modelling approach was proposed which takes what information on current design instances is available and displays this in terms of surface plots to aid visualisation. Polygonal surfaces are used for this purpose whose vertices represent the base instances (design variants). The height of a particular point on this surface represents the performance value of a design instance at that point. Such a representation enables the designer to represent a number of design variants in a single plot so that current product designs and their relative merits can be investigated.

The proposed approach helps in increasing the design knowledge regarding current products as the performance capabilities of current product designs are made known to the designer. It further helps in identifying similar and dissimilar products, finding better design solutions and improving product designs by determining their sensitivity to design parameters.

### **10.1.6 To demonstrate applicability of the proposed approach to meet current needs of SMEs through case study examples**

The sixth objective was dealt with in chapters 5, 6 and 7. These chapters presented the application of the multi-instance modelling approach to the three scenarios that can be encountered by SMEs (identified in chapter 4, section 4.4). Based upon the case study examples presented in these chapters, chapter 8 presented an overview of the proposed approach. The application of the approach in the three identified scenarios was also discussed. Finally chapter 9 presented an application of the proposed approach where all the three identified situations were present.

Chapter 5 showed an application of the proposed approach in a case of isolated machine instances when the amount of design knowledge available to the designer is limited. The approach, in this case, helped to identify redundant design variants by finding similarities (similar products) in the way current designs perform (chapter 5).

Chapters 6 discussed a case when experimental investigation was possible in order to gather the required design knowledge. A single complex system (carton erector machine) was analysed. The various machine settings were used as different instances and the design space between these instances was explored. The approach helped to determine the sensitivity of the machine to its setup parameters and to identify best machine settings to use.

Chapter 7 described a case when computer based models were already available. The usefulness of the approach was demonstrated by presenting its application to a case of selecting mechanisms from a catalogue. The proposed approach not only helped to locate better designs by optimising the mechanisms to the given requirement but also identified similar and dissimilar designs. It further helped in determining the sensitivity of the designs to changes in their parameter values.

Chapter 9 presented a case where all the three scenarios were present. A vertical form fill and seal machine was investigated for its machine-material interactions. The approach helped in increasing the current design knowledge about the machine-material interactions. It further helped in identifying a better shoulder for a given material (and thickness) at a certain web tension. Also, it was shown that the given shoulders belonged to the same family and their performance was fairly insensitive to variation in the shoulder geometry.



## 10.2 Conclusions

The research work presented in this thesis is concerned with supporting various design/redesign activities in SMEs. The thesis has successfully achieved the overall aim of proposing and demonstrating a technique which can help these enterprises to investigate their designs and the related design space with the intention of increasing their current design knowledge. The technique is specifically tailored to meet current needs of SMEs. It provides means to obtain design knowledge in various situations encountered by SMEs. The proposed approach has following characteristics:

- It is simple to understand and implement as the design space between various variants of a design can be represented, visualised and understood with the help of surfaces.
- The design knowledge regarding current products is increased using this approach as performance capabilities of current product designs are made known to the designer.
- It helps to identify similar and dissimilar products in case there is a fundamental similarity or difference in the way designs perform. In some cases, it can also help in reducing/rationalising products if there is an overlap of performances of various variants of a design.
- It helps in determining the sensitivity of a design to small changes in its parameter values. The design is more robust when it is less sensitive to its setup parameters
- It further helps in refining/improving product designs by identifying better (more optimal) design solutions, which may lie within the design space investigated. If found, these designs can replace the current designs and perform better.

The approach has been applied to a number of case study examples and has worked successfully.

### **10.3 Limitations**

The following are limitations associated with the current research work:

- The method of morphing is currently only applicable to designs that share the same topology.
- The sensitivity analysis is limited to the effects of combinations of the key parameters. Their individual effects on the design sensitivity are not dealt with.
- The design space exploration process is only based upon the interpolation between the base design instances.
- With four or more design instances the plot of the surface depends upon the ordering of the instances and can change with different orders.

## 10.4 Future work

Some of the limitations given in the previous section can be addressed in the future. Following is the list of areas that could be further explored.

- As essentially interpolation between the design variants has been explored so far, the next step can be to explore the extrapolation of the design space. Although this is discussed briefly in chapter 7, further work can be done in this area.
- Secondly, in case of four or more design instances, one can rely on some sort of natural ordering for the purpose of achieving consistency while plotting the surfaces. This ordering is possible in a number of ways such as ordering based upon foot print and physical location. This is also briefly discussed in chapter 8 and can be further explored.

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## Appendix

### Publications arising from this research

Following is the list of publications produced as a result of this research work and related areas:

Singh, B., Matthews, J., Mullineux, G., & Medland, A. J. 2006, "Embedding general constraint resolution into a CAD system", in *Design 2006*, May 2006, Dubrovnik, pp. 625-631.

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