Applications of Formal Design Matrices

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Declaration

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Abstract

Products today must satisfy all customer requirements, particularly relating to Quality, performance and cost, if they are to survive in their respective markets. Against such a background of global competitiveness, it is universally accepted that the design process has the greatest influence on overall product success. In this thesis design has been explored from within an industrial environment, developing a methodology simultaneously with that of commercially successful products.

Systematic design approaches have been proven to produce superior products, particularly where team working in large organisations is involved. In support of this activity, matrices offer a mechanism by which multi-variant problems can be evaluated. As part of the Quality Function Deployment (QFD) approach, the 'House of Quality' matrix has been established as a viable means of translating customer needs into Quality products.

Built upon the requirement to further develop a process known as *self-pierce* riveting, elements of performance, energy usage and statistical data have been effectively combined into a single measure of *objective function*. This has led to the development of a new form of correlation matrix, permitting the selection of factor combinations, through the introduction of Quantitative and Qualitative measures into the matrix 'roof'.

Understanding and dealing with cost issues is one of the most demanding challenges facing manufacturing industry today. Established as the activity most influential on final product cost, the design process must be structured to take account of financial considerations. By expanding the scope of matrices, cost data has been integrated in a quantitative manner into the product selection procedure.

List of Symbols Used

y	Quality characteristic reading or response
M	Target value
L(y)	Loss in monetary terms
k	Quality loss coefficient
Δ_0	Customer tolerance
A_0	Customer loss
C_{PR}	Process capability index
β	Characteristic slope
S	Signal factor
η	Signal to noise ratio
K	Yield shear stress
P	Applied pressure
F	Applied force
1	Unit velocity
V	Clench volume
v	Rivet shank volume
f	Anvil profile diameter
G	Anvil profile depth
H	Rivet shank diameter
s^2	Variance
$Z(\Theta)$	Normal distribution transform
CF	Correction factor
V	Variance of factor

Chapter One

Introduction

Matrices provide a tool by which opposing and complementary functions can be visibly compared and numerically evaluated. With the growing complexity of many products and an ever-expanding range of quality criterion to be met, matrices offer a mechanism, which can potentially address all such issues, within the design process.

Along with the research objectives, this chapter aims to introduce the many aspects of the design environment of today, as they relate to manufactured products.

1.1 The Process of Design

1.1.1 Definitions of Design

Several authors have defined the activity of design. Asimow (1962) gives his definition in terms of Engineering Design as.

> "A purposeful activity directed towards the goal of fulfilling human needs",

Alternatively Pahl & Beitz (1996) define designing as:

> "The intellectual attempt to meet certain demands in the best possible way. It is an engineering activity that impinges on nearly every sphere of human life, relies on the discoveries and laws of science, and creates the conditions for applying these laws in the manufacture of useful products."

Pugh (1990) draws the distinction between "partial design", as a limited perspective segmented approach, and what he calls "total design", which describes the entire process of full product design. Total design can be defined as:

> "The systematic activity necessary from the identification of the market/user need, to the selling of the successful product to satisfy that need – an activity that encompasses product, process, people and organisation".

As part of a survey of design methodologies, Finkelstein (1983) makes a clear and succinct definition of design:

> "Design is the creative process which starts from a requirement and defines a contrivance or system and the methods of its realisation or implementation, so as to satisfy the requirements. It is a primary human activity and is central to engineering and the applied arts".

The key points raised by all these definitions are that a need is identified, which through a sequence of primarily human activities, that need can be satisfied. Design is a direct function of human ability a point raised by Cross (1994).

> " ..there is something mysterious about the human ability to propose a design for a new-or even just- modified artefact.....This ability to design depends partially on being able to visualise something internally, in 'the minds eye', but perhaps it depends even more on being able to make external visualisations."

The way designers 'think' can be understood more clearly when they are compared against other intellectual disciplines. Pahl and Beitz (1996), refer to the work of Dixon (1966), who places design as a central activity between two intersecting cultural and technical streams (Fig 1.1). Research by Lawson (1984) compares the way designers and scientists approached the same problem. Scientists first systematically explored the problem to discover any underlying rules, which could be used to find an optimum solution. By comparison designers would make initial explorations to find possible solutions, from which a selection would be made. The conclusion of this work was that scientists use 'problem-focused' strategies and designers use 'solution-focused' strategies.

Another good example of a 'problem-focused' strategy is that of the medical profession. Initial effort is always aimed at diagnosing the condition (problem), before initiating any form of treatment (solution). In this case the consequences of not fully understanding the problem could be fatal.

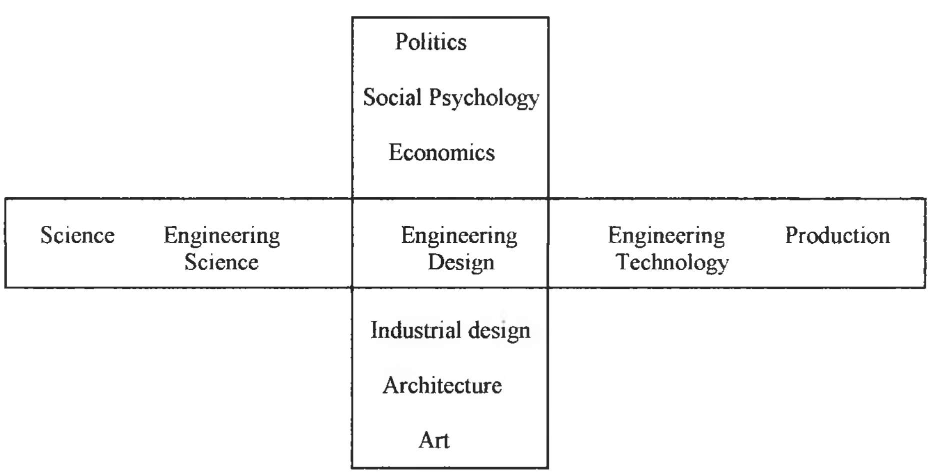


Fig 1.1 The Central Activity of Engineering Design (Pahl & Beitz 1996)

1.1.2 Praxiology in Engineering Design

The human perspective of design is best understood through a study of human behaviour. Praxiology is the study of human action in terms of its effectiveness and efficiency.

The development of what is termed 'classical praxiology' is accredited to the Polish philosopher, Tadeusz Kortabinski who evolved an explicit programme for the discipline. Kortabinski (1965) & (1966) gives a general methodology, which covers three points.

1. Analysis of concepts concerning all purposeful activity.
2. Criticism of the methods of activity in actual practice with respect to their efficiency, effectiveness, purposefulness and practical value.
3. Normative, advisory part containing instructions which would endow all work with the quality of greater technical resourcefulness.

Wojciech Gasparski continued the work of Kortabinski, developing what is known as modern praxiology, this being a more focused approach, particularly in relation to Engineering design. The praxiology of design is described as a general theory by Gasparski (1990), in the form of three conceptual contexts. The first two concepts relate to activities of design and the design process, whereas the third is concerned directly with the designer. This division broadly corresponds with the general division of theories of science into the logic of science and the philosophy of science. Since Design can be considered to form an interface between science and practice, studies of design should also be based on studies on practice and studies on science. Gasparski goes on to apply this viewpoint to a method of 'idealisation', i.e. from a fabricated situation of ideal product, process, designer and methodology, a praxeological design theory can be constructed. Transformation from this idealised state, is proposed to be achieved by the introduction of a 'practical situation', which incorporates requirement and constraints demanded for the design. These 'practical situations', are further segmented by Gasparski (1980), in the following format.

1. A standard situation which can be solved by the designer's current knowledge.
2. A non-standard situation which cannot be solved on the basis of the designers current knowledge.
3. A relative situation, which is a standard situation to some and a none-standard situation for others.

All none-standard 'practical situations' can be transformed into standard 'practical situations', by supplementing into the process the knowledge of an expert.

The object of design (according to Gasparski) therefore becomes a means of dealing with practical situations.

Other work by Gasparski (1987) and Moriarty et al (1990) discuss this same approach further, but very little emerges in terms of any tangible or usable methodologies. In private discussions with Gasparski (1994), the main thrust of his arguments were towards fully understanding problems and our conditioning, by education, to immediately answer the question rather than 'question the question'. Within the majority of design environments the designer is hardly ever presented with a correctly defined problem, this necessitates the need for the designer to define the problem first through the continued questioning of the problem. This situation can occur when dealing with 'customers' who often lack the skills to define their own requirements correctly, and in some cases may change their requirements part way through a project. Design methodologies such as DFD **(2.1.1)** are intended to provide a framework to assist in the problem definition process, however a designer may still be forced to start a project with incomplete information.

1.1.3 Problem Definition

The most fundamental aspect of the design process is that of problem solving. All problems emanate from an identified need, whether it be for an entirely new system, or some minor modification to an existing piece of equipment, that need will decompose into problems. As discussed in section **1.1.2**, achieving a correctly defined problem is the first (and most essential) stage of any design activity. According to Cross (1994), problems have three common aspects, that is they set a *Goal,* incorporate some *Constraints* within which the goal must be achieved and offer some *Criteria* against which the solution can be evaluated. Problems can be further categorised as either 'ill-defined', (into which design problems largely fall,) or 'Well-defined'. 'Ill-defined' problems have the following characteristics.

1. There is no definitive formulation of the problem.
2. Any problem formulation may embody inconsistencies.
3. Formulations of the problem are solution -dependent.

4. Proposing solutions is a means of understanding the problem.
5. There is no definitive solution to the problem.

By the very nature of design problems, it becomes easy to understand why designers have developed 'solution focused' strategies **(1.1.1).** In many instances it is only through exploring solutions (provoking the problem), that any progress can be made towards achieving the *goal.* The danger of this approach is that at an advanced stage of a project, some part or sub-solution may be found to de-validate all other solutions so far established. Cross (1994), describes this interconnection of sub-solutions as a 'pernicious' structure and quotes an example of such by Luckman (1984). Although an architectural problem, it highlights how the inter-relationship of roof span direction, bearing wall selection, first floor joists and first floor partitions all came full circle requiring the original design of the ground floor walls to be re-considered.

This cyclic, or iterative nature of the process is common place in engineering design and is symptomatic of 'solution focused approaches'.

Evbuomwan et al (1996) has concluded from literature surveys, that design problems fall into one of three categories. These being;

(i) Routine Designs – derived from common prototypes or originals.

(ii) Redesigns – where an existing design is either adapted or used as the basis for generating a new design.

(iii) Non-routine, original or new designs – These being innovative and radically new departures from existing solutions.

Understanding the type of design problem, is a vital first step in understanding the nature of that problem. Different categories of design problems will also necessitate different approaches to solution generation.

1.1.4 Problem Solving

Dieter (1982) describes problem solving, within an engineering environment, as the following logical sequence;

> "It begins with a decision maker, the engineer or manager, who identifies the problem, conducts an analysis to find the cause of the problem, and concludes with decision making to decide the course of events that must be followed".

A more detailed illustration of this statement is shown in fig 1.2.

A psychologist's description of the problem solving process is also given by Dieter (1982).

Preparation- The elements of the problem are examined and their inter-relationships are studied.
Incubation- You "sleep on the problem."
Inspiration – A solution or path toward the solution suddenly emerges.
Verification- The inspired solution is checked against the desired result.

In forming a problem solving strategy, understanding the human aspect of the process is essential. People of all kinds exhibit different aspects of strengths and weaknesses to varying degrees. The most commonly quoted of these is to think laterally, or 'lateral thinking'. This can appear as an almost magical ability, to take an apparently un-resolvable problem and to come up with a good (and now obvious) solution. Another description of this phenomenon is '3 dimensional thinking'. To view a problem from a multitude of directions gives a better insight into what is and is not achievable. Similarly Human weaknesses can inhibit problem solving. The most commonly encountered of these is a fixation on pre-conceived ideas, having seen what appears to be a good solution, there develops a reluctance to explore the problem further and a defensive stance is taken around the designers first idea.

Pahl and Beitz (1996), describe solution generation as a series of working and decision making steps, ensuring permanent links between objectives, planning, execution and control. Repeating of a working step as a result of a decision step, describes the essentially iterative nature of the design process.

A general process for finding solutions is described by Pahl and Bietz (1996), following Krick (1969). First the problem is confronted, maybe provocatively, to ensure the problem is correctly defined *(Gasparski)*. Information about the problem is next sought and from this the essential requirements are defined. Against these requirements solutions are created, which may be reduced and refined by the evaluation stage prior to a decision being made as to the best overall solution. If at any stage of the process the results found are unsatisfactory, then a re-iteration of the step must be carried out, (fig 1.3). Understanding of these generic approaches to problem solving, serves as an introduction to the more specific concept generation and methodologies within the design process.

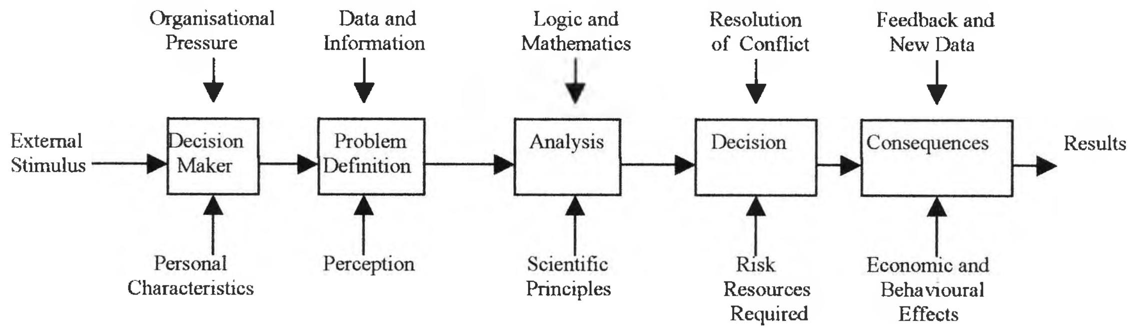


Fig 1.2 Problem Solving Process (Dieter 1982)

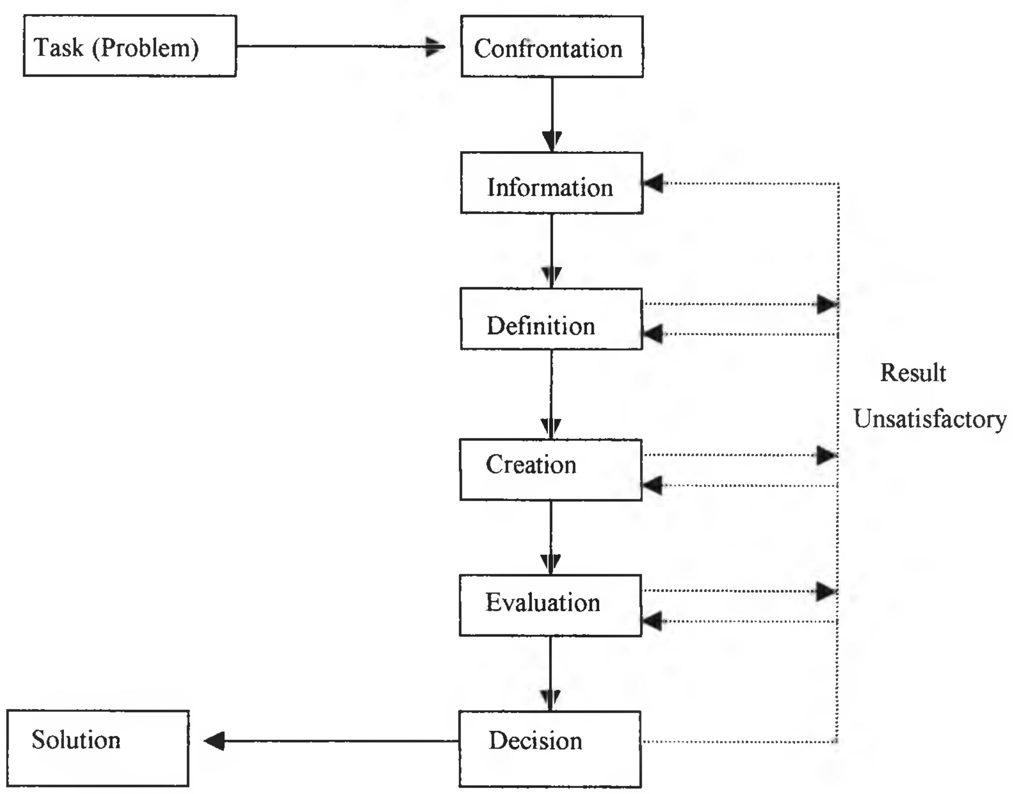


Fig 1.3 General Process for Finding Solutions (Pahl & Beitz 1996)

1.1.5 Concept Generation

The core of the design process is the generation of design concepts.

Finkelstien (1983), describes a design concept as:

> "A set of contrivances or systems, one of which could satisfy the design requirement".

The design concept is characterised by variable parameters, the nature and magnitude of which are chosen by the designer, finally resulting in the determination of specific design configurations. A *candidate* design is thus created.

New concepts can be generated from some form of adaptation of known systems (synthesis), or be an entirely new and innovative solution. Almost all-new design concepts are developments, or adaptations of existing design.

A good starting point, would be an exploration of current design solutions derived for satisfaction of a similar problem. For this, sources such as books, catalogues, patents, technical papers etc. may be consulted. By examining a wider and less obvious range of design solutions, more novel concepts may be derived by forming *analogous* representations of them. Throughout our lives we encounter a multitude of devices designed to fulfil various tasks. Designers often draw upon these past observations and apply them to design problems instinctively. A method known as 'function analysis' provides a basis for identifying common areas of existing designs. King & Sivaloganathan (1998) show the further development of such a method, allowing core designs to be produced as a basis for flexible design of other similar products.

The natural world provides many good examples of highly functional and refined solutions, which may be considered by the designer. Pahl and Bietz (1996) give several examples, which relate to structural design and the lightweight, yet strong structures, which can be found in nature.

Where there are no pre-existing ideas, some design strategies, attempt to generate new concepts by a logical sequential process. These can be termed *convergent* design approaches since they converge on a particular idea and proceed to build upon it. Most innovative solutions however, are normally the result of lateral creative jumps of the imagination. This represents a *divergent* approach. Designers tend to work predominantly in a *divergent* manner, particularly when presented with a new and unusual problem. *Convergent methods* apply more at a routine level where existing information/knowledge can be used to build and refine the chosen solution approach.

Kusiak et.al (1990) emphasises the fact that synthesis forms a critical aspect of the design process. In order to provide a framework of synthesis an activity-based conceptual design model is proposed by Kusiak et.al (1991). This framework is illustrated in fig 1.4. The end results of following such an approach should be as follows:

(i) An overall model (after the synthesis) that ensures inclusion of all requirements and functions.

(ii) A rough physical layout (after the transformation process) that suggests the physical representation of the designed object.

In support of the above activities, Kusiak et.al (1991) proposes an object orientated modelling framework for component synthesis at the conceptual design level.

Computer/software systems to simulate possible concept models have been developed over recent years. In the field of mechanism design, attempts have been made to apply artificial intelligence and neural networks for design synthesis and optimisation. Kenney et. al (1997) describes a software system under development called SWORDS. This allows repeated trials of possible mechanism designs, within set constraints, until an optimum solution is derived.

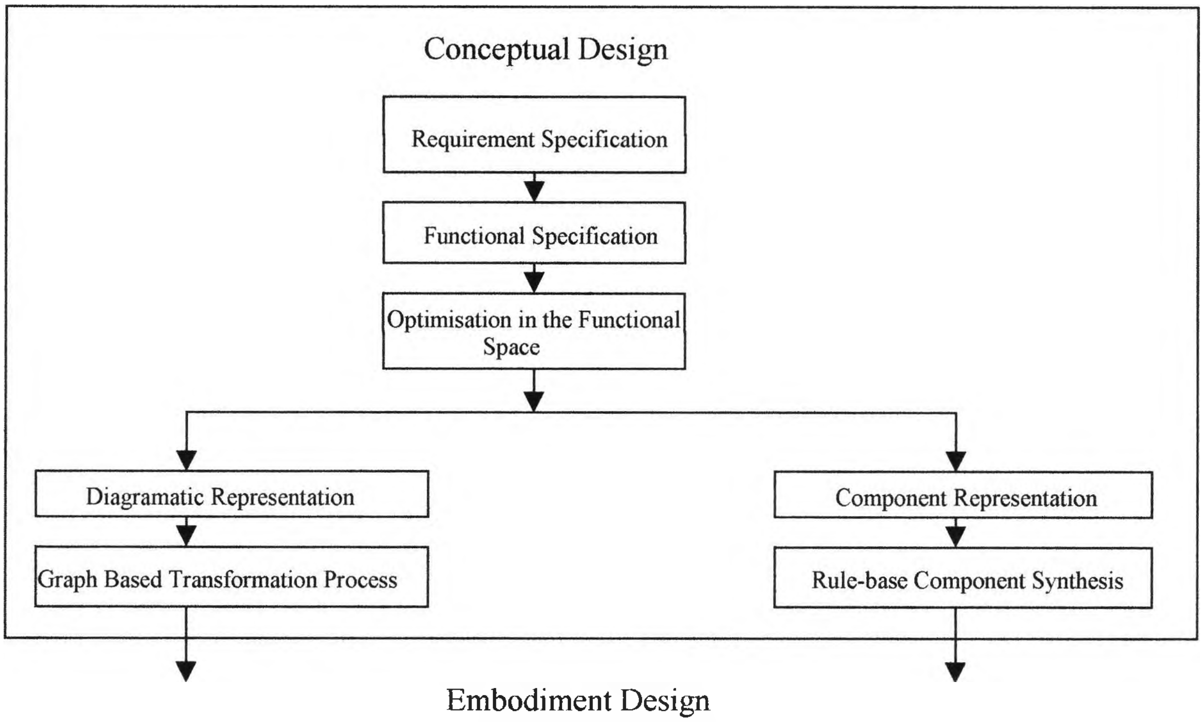


Fig 1.4 Activity-based Framework of Conceptual Design (Kusiak et. al 1991)

From an understanding of concept generation techniques, it becomes clear that any design strategy must accommodate a flexible framework, housing both *convergent* and *divergent* approaches.

1.1.6 Models and Methods

Design models are the philosophies or strategies to produce any required design. Some of these models *describe* a sequence of activities to be followed, whilst others *prescribe* a better route to follow. Based on a systems science approach, models are usually represented in flow diagram form, describing the various stages of activity with feedback loops for information flows.

According to Cross (1994), *descriptive* models are characterised by an early emphasis on solution concept generation, thus reflecting the 'solution-focused' nature of design. The initial solution would be analysed and refined to completion or, if the initial concept turns out to be inappropriate, the whole process would start again with a new concept. In its simplest form, the four stages; exploration, generation, evaluation and communication (fig 1.5) can represent the descriptive model. A more detailed model is given by French (1995), which is based on the following activities.

Analysis of concepts
Conceptual design
Embodiment of schemes
Detailing

Stating with a need and progressing through the stages to detail drawing, this represent a procedure which would be largely recognisable to most designers.

By comparison, *prescriptive* models do not attempt to simply describe a sequential series of operations, but provide a more algorithmic systematic framework. Such models are largely characterised by placing emphasis on the need to first fully understand and analyse the design problem. The basic structure of prescriptive models takes the form as defined by Jones (1981) ,which consists of only three phases.

(i) Analysis – Determining design requirements and creating a specification.

(ii) Synthesis – Finding possible solutions to satisfy the performance specification.

(iii) Evaluation – Evaluate solution alternatives against the specification to determine the final design to be selected.

More detailed models are proposed by authors such as Hubka (1982) and Pugh (1991) in fig 1.6. Other models are proposed by professional bodies such as the VDI (Verein Deutscher Ingenieure) in VDI 2221and the BSI (British standards Institution) in BS 7000. For many of these comprehensive models, there is a danger that the main issues can become lost in a diagrammatic maze, which in reality relates very poorly to the every day designer. A more recent, alternative model, and associated procedure, was proposed by Rodwell (1996). Although *descriptive* in nature, it does show a format, which relates closely to a recognisable Engineering environment, in this case, 'Special purpose', low volume manufacture. (fig 1.7).

Design methods are techniques, tools and support systems, which aid the process of designing. Jones (1981), describes 35 such methods, which address specific issues aimed at different parts of the design process. Typical of these are methods for solution generation, these include for example, Brainstorming, Synectics, Morphological charts etc. The effect of such methods is to add formal procedures into the design process, regardless of its structure.

The very abstract nature of the design process makes it a particularly difficult discipline to systemise with any laid down methodology (if this is indeed required). Any such methodology must, however, be structured to ensure the customer requirements and hence the specification has been satisfied. Furthermore the recording of information afforded by such an approach, should provide clear traceability, compatible with any future audit trials.

Any attempt at a formal design strategy must therefore offer the maximum flexibility of structure, exhibiting features of both a *prescriptive* and *descriptive* design model.

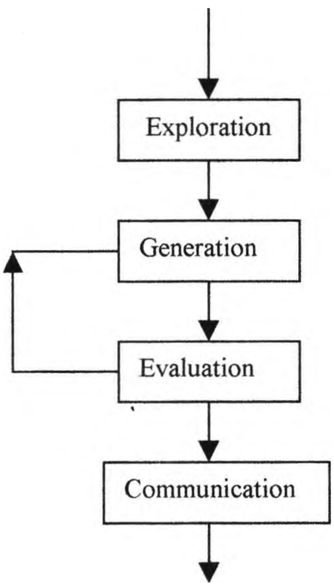


Fig 1.5 Four Stage Model of the Design Process

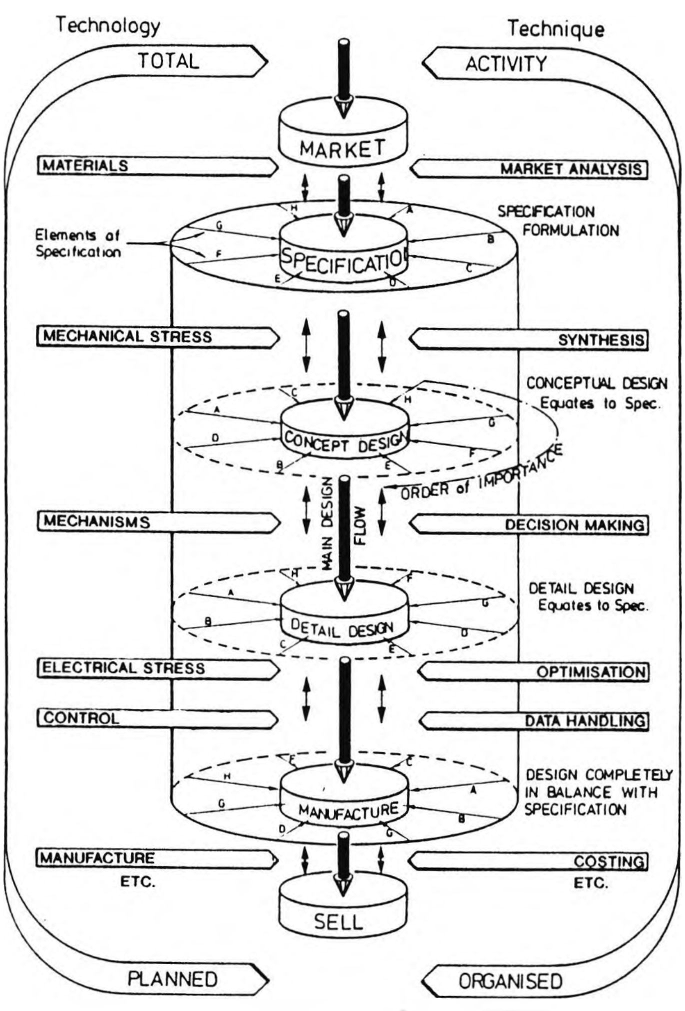


Fig 1.6 Design Model by Pugh (1991)

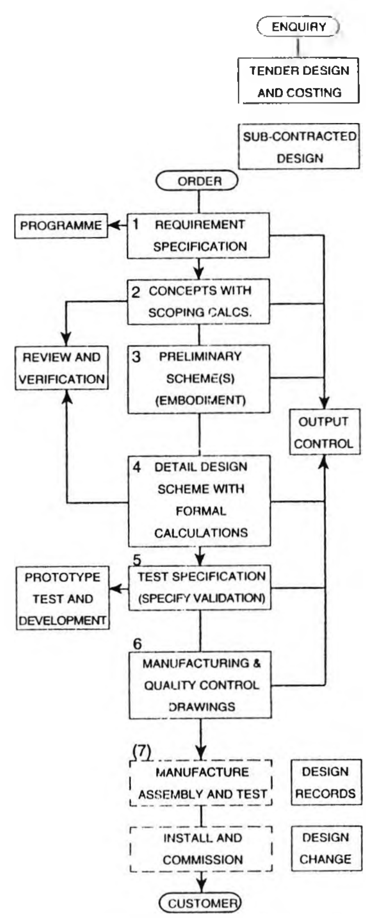


Fig 1.7 Design Model by Rodwell (1996)

1.1.7 Parts Proportion by 'Natural Phenomenon'

There exists in nature a relationship between large and small proportions, which conforms to the ratio of **1.618:1**. Known as the 'Golden Proportion', its existence has been known since the times of ancient Greece, although little reference has been made to it over the years. Many proportions within the human body conform to it. Levin (1978) details the use of the 'golden proportion' in relation to dental aesthetics, but also point to examples of its use in Engineering where the proportion exists, be it not by intentional design.

There are many instances, where applying such a proportion will result in both stable, and visibly pleasing structures. Recently in the design of a small control panel, the author spent some time laying out the relative positions of switches, to each other and the edge of the panel. When later checked, the positions conformed almost exactly to the 'golden proportion'. (fig 1.8)

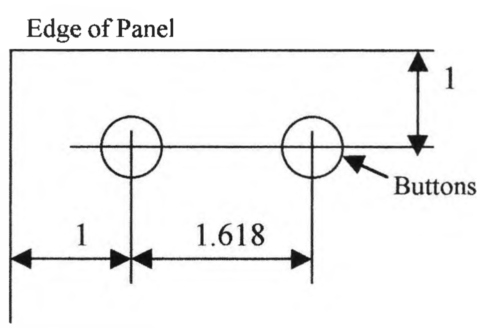


Fig 1.8 'The Golden Proportion'

1.2 Quality in Design

1.2.1 The Quality Culture

The formal European (including UK) definition of quality is.

'The totality of features which bear on a product's ability to satisfy the requirements'.

A more immediately identifiable definition is given by BS 4778.

'Fitness for purpose'

Both of these definitions reflect the modern, comprehensive approach to product quality. Traditionally, the quality function of a company was dedicated solely to a policing/inspection role, carrying out 'fire fighting' activities as problems occurred. This reflected the quality philosophy of the time, which was concerned only with conformance to specification rather than the more far-reaching issues of specification inputs. Typically, Ford Motor Company's definition of quality in the 1970's was.

> 'Quality is conformance to engineering requirements as defined in engineering drawings, specifications and related documents'.

The features and characteristics of a modern quality approach are summarised by Juran and Gryna (1980) as follows.

1. Factors associated with the physical properties of a product.
2. Subjective aspects of the appearance and feel of an item.
3. Factors associated with the on-going use of the item - durability, maintainability etc.
4. The buyer/seller relationship - a collection of commercial considerations.
5. Correctness of claims made for the product.
6. Satisfaction in ownership.

Many of the techniques, which constitute a modern quality system, were initially applied and evolved, with great success by the Japanese, a nation where product quality is a matter for government policy. Ideas from the west such as control charting and philosophy by Deming (1992), and orthogonal arrays by Fisher (1951), were adapted and used to great effect in the manufacturing world. Of particular importance is the work of Taguchi, who has been recognised for three major contributions to the field of quality.

1. The loss function.
2. The application of orthogonal arrays
3. Robustness in design

Overall Taguchi promotes a culture of continuous improvement, accelerated discovery, rapid problem solving and cost effectiveness while sustaining quality gains.

The most dramatic influence on product success, comes from the comprehensive integration of both a quality and reliability culture through out an organisation. As stated by O'Connor (1991).

> 'Quality and reliability awareness and direction must start at the top and must permeate all functions and levels where reliability can be affected'.

Many tools and techniques to help apply quality, in a 'total quality' environment, have become available to the designer. The following reviews the most powerful of these methods.

1.2.2 Quality Function Deployment (QFD)

Quality function deployment (QFD) was developed in Japan in the 1970's,as a means of translating customer needs into quality products. Cohen (1995) gives a recent definition of QFD.

> ' a method for structured product planning and development that enables a development team to specify clearly the customers wants and needs, and then to evaluate each proposed product or service capability systematically in terms of its impact on meeting those needs'.

Quality function deployment therefore exhibits the features of a prescriptive design model, structured to bring the customer requirements upstream into the design process. Through the application of matrices, the parameters that contribute to customer satisfaction are identified and evaluated, allowing the concentration of effort where it will be the most effective.

Quality function deployment is typically broken down into four stages, reflecting the four major phases of product design; these are summarised as follows.

(i) Stage 1, Product planning: Customer requirements (what's), are translated into identifiable design requirements (how's). These *how's* subsequently form a quantified requirements specification, retained in a solution neutral format. Prior to the second stage design concepts are generated as a 'stand alone' activity.

(ii) Stage 2, Design deployment: Highlights the target values of the critical part characteristics that must be maintained in order to satisfy the priorities from stage 1. These critical part characteristics are the design parameters judged to have the most significant overall relationship with the design requirements.

(iii) Stage 3, Process planning: The target values of critical process characteristics associated with the critical part characteristics are identified.

(iv) Stage 4, Production planning: manufacturing operational issue are considered for the successful achievement of stage3.

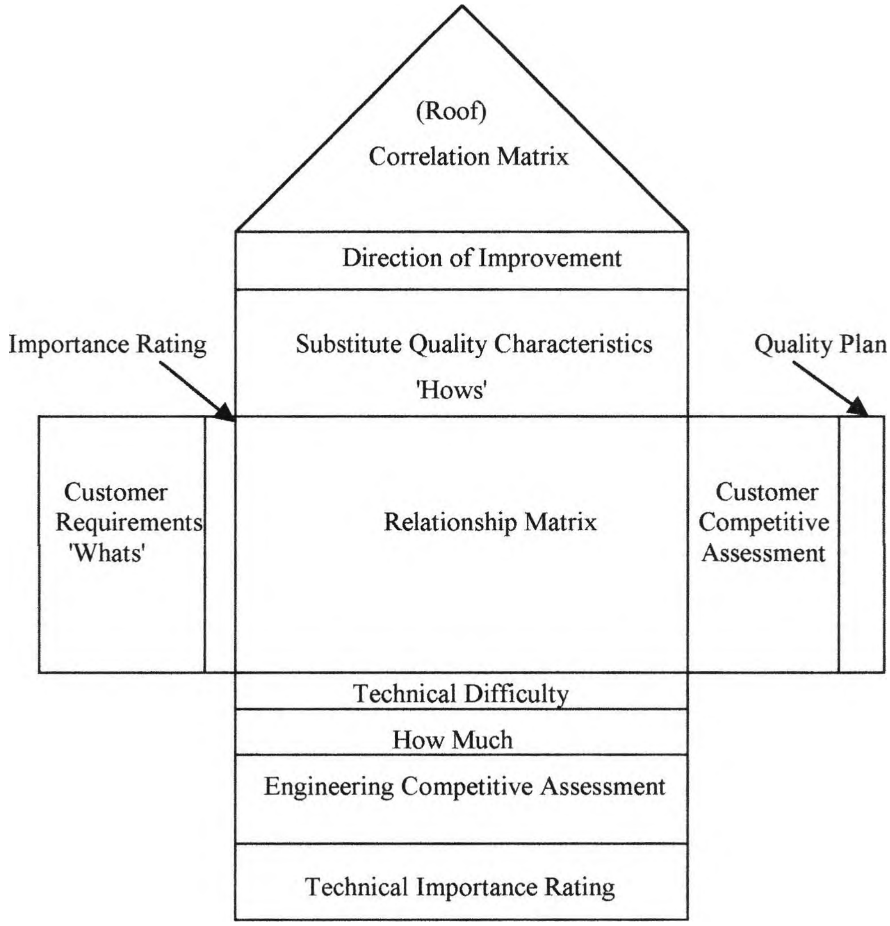


Fig 1.9 QFD Stage 1 Chart Layout

Fig 1.9 shows a typical way of presenting a stage 1 chart. Raw customer requirements (what's) are placed in the left column, against which design requirements (how's) are brainstormed and placed along the top row. Relationships between how's and what's can be evaluated and subsequently numerically rated in the relationship matrix of the chart. The correlation matrix at the top, (roof of the 'House of Quality') is used to record the identified interactions between design requirements, i.e. some may conflict and others support each other. Other features such as competitive assessment may be made, but the main out put from this stage of the process is the calculation of technical importance values at the bottom of the chart. Combined with relative numerical weightings and interaction observations, a fully informed specification for use in the next stage can be generated. Fig 1.10 shows an example of a completed stage 1 chart for an electric motor.

Sivaloganathan & Evbuomwan (1995), highlight the underlying design model within the QFD framework as follows.

1. Developing the quality plan and quality design.
2. Designing the parts and assemblies.
3. Designing the manufacturing process for the fabrication and assembly of parts to form the final product.
4. Establishing the production control plans.

Research by Ramsaway & Ulrich (1992), goes on to propose the combining of 'Engineering models' with the 'House of Quality' matrix. This they claim is preferable to using only customer and competitor information to set Engineering targets.

Quality function deployment can be summarised as a technique for understanding the problem, and applying a cohesive 'team' effort into a process which embraces all primary activities within a manufacturing organisation.

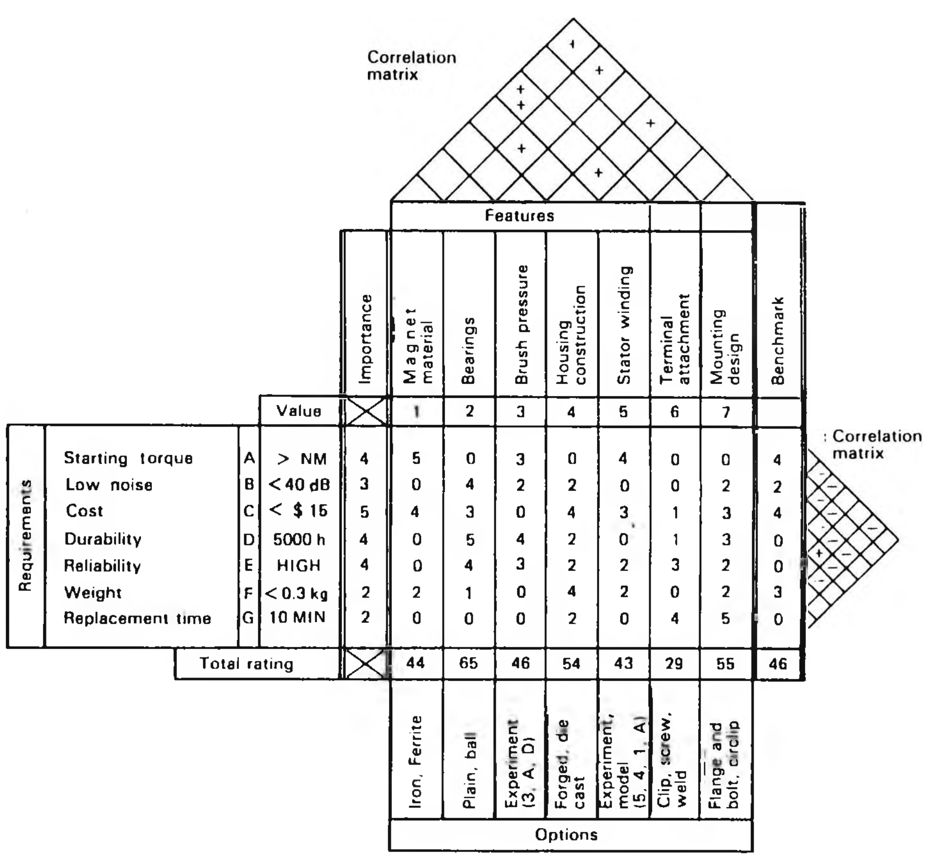


Fig 1.10 QFD Chart for an Electric Motor (O'Connor 1991)

1.2.3 Design Optimisation

The ultimate aim of all engineering design is to achieve as near as possible an optimum design solution to a particular problem, although this approach may be rationalised in view of product types, manufactured volumes and general economics. When considering the behaviour of a system, many engineering problems can be formulated to the point where the system behaviour can be expressed in terms of a mathematical equation. A simple example of this is the design of a liquid container, Hundal (1997).

Many design problems involve optimising for multi-variable criterion. The triangular 'roof' of the 'house of quality' Fig 1.10, can be used to identify trade-offs and conflicts between different design goals. Each design parameter in a multi-variable optimisation problem is given a target value and an improvement direction. The Triangular correlation matrix is then used to identify conflicting design requirements

1.2.4 Failure Mode and Effect Analysis

Failure mode and effect analysis (FMEA) is a means of predicting how a product is most likely to fail and thus how it can be improved to avoid such failure. It can be carried out at the part or product levels, and is usually applied at both the design stage and the process stage.

A full definition of FMEA is as follows.

> A team orientated technique aimed at ensuring that, potential failure modes are identified and their associated causes have been considered, recorded and addressed.

The first stage of the process, is to identify the failure modes which are inherent in the design, this requires a detailed understanding of every component and function within the product. The effects of failure on the final customer are then identified and evaluated along with the potential cause of such failure. Existing methods of design verification can be built into the process with an assessment of their detection effectiveness. As a product of all the above stages, a risk priority number (RPN) can be calculated. Having now arrived at a quantifiable level of risk, recommended actions to reduce or eliminate such risk, can be made as appropriate. Effectiveness of remedial action is determined by re-assessing the severity, occurrence and detection indexes and re-calculating the RPN. A typical example of a completed FMEA chart is shown in Fig 1.11.

FMEA's are most widely used in the automotive industry but are rapidly gaining ground throughout manufacturing. Although driven primarily by the need to integrate reliability into both product and process design, other none reliability issues, which further enhance the product, may well emerge as a result of such an in depth analysis. O'Connnor (1991) identifies some of these additional features, for example, preparation of preventative maintenance requirements, design of built-in test, preparation of diagnostic routines.

FMEA's provide a useful method for the improvement of an existing or proposed design, or processes, which can be applied in support of a comprehensive design approach.

1.2.5 Robust Engineering Design

A product or process, which is robust, will be consistent under a wide range of operating conditions through out its life cycle. Jebb & Wynn (1989), use a diagram to illustrate the variation of a *robust* designed product compared to an equivalent normal designed product over a full life-cycle, (fig 1.12).

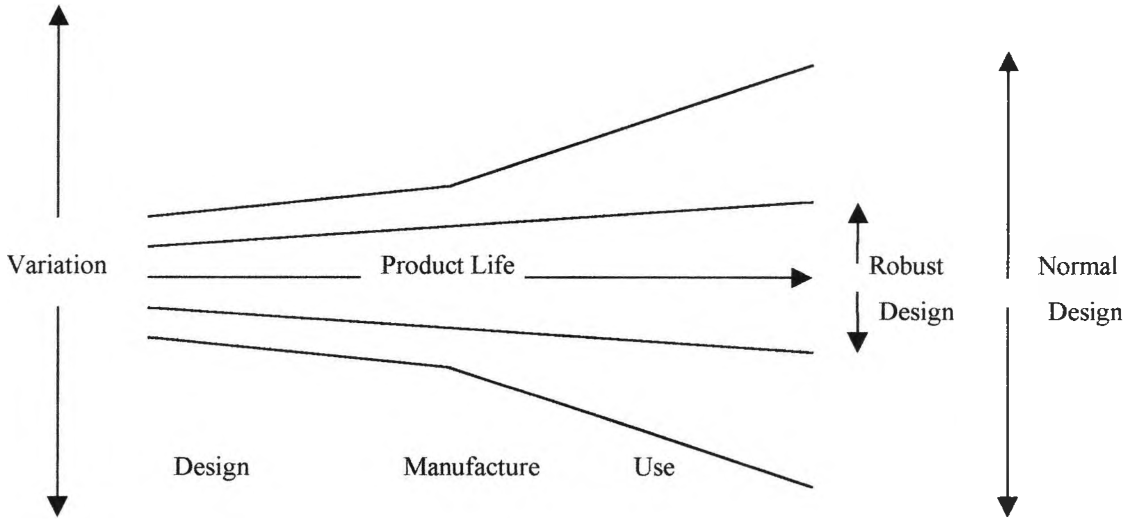


Fig 1.12 Illustration of *Robust* Design (Jebb & Wynn)

Potential Failure Mode and Effects Analysis (Design FMEA)

Name/Model Drive Unit / 250 **Other Areas Involved** Production Control **Prepared By** JCPS

Design Resposibility Design Office **Suppliers Affected** Foundry. M/C Sub con **FMEA date** 21-3-98 **Rev** 1

Part Name & Number Part Function	Potential Failure Mode	Potential Effect of Failure	Severity	Potential Cause of Failure	Occurrence	Design Verification	Detection	RPN	Recommended Actions	Responsibility & Completion Date	Action Results: Action Taken	Action Results: Severity	Action Results: Occurrence	Action Results: Detection	Action Results: RPN
Top Casting 290330 & 290331 * Location & support for bowl * Anchorage for springs and armature * Acts as top cover to prevent access	Fatigue fracture of spring anchorage and armature mounting	Renders feeder inoperable	7	* Material not to specification	2	* Certification of material used from foundry	1	14	None						
				* Bowl tooling too heavy	2	* Weight limitation	1	14	None						
				* Bowl & tooling out of balance	2	* Limit by balancing	1	14	None						

Fig 1.11 FMEA Chart

Controlling the potential *robustness* of a product through the design and development process is one of the primary purposes of 'Taguchi methods'. Taguchi's philosophy of robust design, is summarised by Hundal (1997):

- Design quality into a product, do not use inspection to weed out poor quality products.
- Set a target. The cost of quality is the deviation from the target value.
- Make the product insensitive to uncontrollable external factors.

Unlike the design models as reviewed in **1.1.6**, where great effort is directed at the early stages of specification and conceptualisation, Taguchi emphasises the later stages of design, particularly parameter design. Taguchi's overall approach to design can be grouped into three main stages:

1. System design - corresponds with conceptual design and aims to find the best technological means to provide the required function.
2. Parameter design - encompasses detail and embodiment design. The aim is to find values for the design parameters, which satisfy the requirements, at low cost and give the minimal performance variation over the product lifecycle.
3. Tolerance design - part of the detail design stage, where tight tolerancing is applied only to those parameters, which would most substantially improve performance.

It is at the parameter design stage where the most substantially improved robustness can be achieved at minimal cost. At an individual parts level, robustness can be illustrated as performance against parameter setting where the relationship between the two is known. Dunsmore et.al (1997), shows a simple example (fig 1.13), where parameter'A', although set at the optimum performance level, will give a worse overall performance compared with parameter 'B', which is nominally set at a lower performance level. Since variability will exist in all parameter settings, the effect of such variability must be considered. Only through understanding the relationship between parameters and performance can any such assessments be made, it is here through the application of statistical and experimental methods that Taguchi places the greatest emphasis.

As a central theme of Robust Engineering Design, searching for factor level combinations is achieved by the application of orthogonal arrays. Although not as rigorous as a full factorial experiment, orthogonal arrays allow economic experiments to be carried out, by ignoring many less significant interactions.

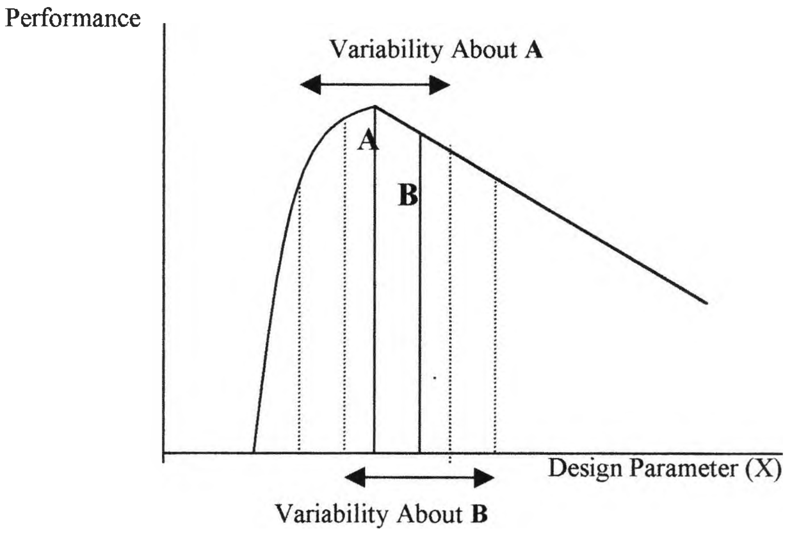


Fig 1.13 *Robust* Design Parameter Setting Comparison (Dunsmore et. al 1997)

Originally devised by R. A. Fisher (1951), an Orthogonal Array is a matrix showing a standard plan for combining design factor levels into experimental trials. Each design factor is assigned a column, within which its level setting is given for each experiment. Fig 1.14 shows a standard L_4 Orthogonal Array giving results for four experiments with two level settings. With most standard Orthogonal Arrays, for any pair of columns, all design factor combinations occur an equal number of times. Thus orthogonality means, that each design factor, has its effects considered in a balanced way against all other design factors, over the entire range of all design factor levels. Grove and Davis (1992), and Krottmaier (1993) give many examples showing the application of Orthogonal Arrays.

Factor	A	B	C
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

Fig 1.14 L_4 Orthogonal Array

The most significant addition to the work of Fisher made by Taguchi, is that of Linear Graphs. This makes it possible to assign even the most sophisticated problem to an orthogonal array without any major effort. Fig 1.15 shows two linear graphs drawn for an L_8 array. Graph 'A' means that the interaction between columns 1 and 2 can be read from column 3 and the interaction between columns 1 and 4 can be read from column 5. The same applies to columns 2, 4 and 6. Column 7 is represented as an independent point in this case. Graph 'B' would be used if the interactions between one particular factor (1 in this case) and other factors were considered significant. Standard arrays and linear graphs have been established by Taguchi and Konishi (1987), from which selections can be made to suit most experimental programmes.

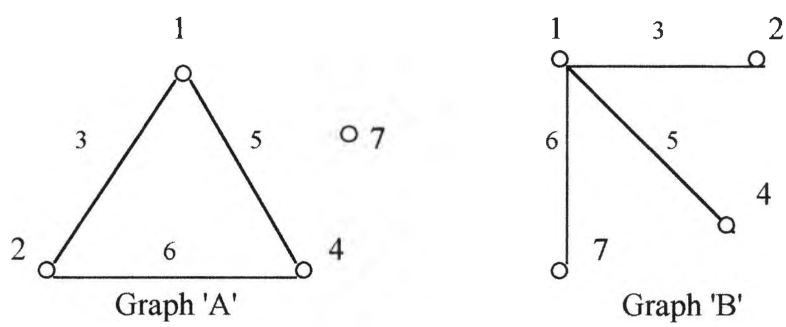


Fig 1.15 Linear Graphs for the L_4 Array

As an alternative to statistically designed experiments in the conducting of *robust* design, a lesser-known 'numerical optimisation' process may be used. Yang et. al (1994) describes a development of this approach, giving a formulation of parameter design with multiple quality characteristics as a 'non linear' optimisation problem.

1.2.6 Quality Loss Functions

Taguchi's proposal is that quality should be measured by determining the *loss* caused by a product to society after being shipped, other than losses associated with its intrinsic functions. The loss function indicates that the best quality component is one exactly on nominal, it causes the least loss because when all components are at nominal the system functions as intended.

For each quality characteristic there exists some function which uniquely defines the relationship between economic loss and the deviation of the quality characteristic from its target value. Taguchi advocates the quadratic representation of the loss function to be a valid approximation for assessing loss due to deviation of a quality characteristic from its target value. (Fig 1.16).

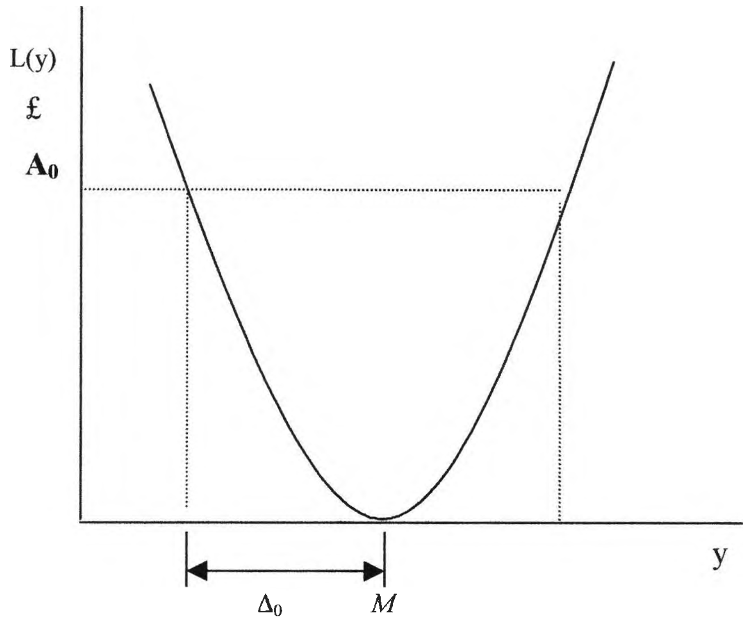


Fig 1.16 Quality Loss Function for Nominal is Best

If y is the quality characteristic reading and M is the target value, then the quality loss is given by:

$$L(y) = k(y - M)^2 \tag{1.1}$$

Where the quality loss coefficient, k, is a constant, and since A_0 = loss to customer (£).

$$k = \frac{A_0}{\Delta_0^2} \tag{1.2}$$

For some measurable characteristics, the objective may be to have the smallest possible value, in which case the ultimate target is zero. Therefore the quality loss function becomes:

$$L(y) = ky^2 \tag{1.3}$$

Similarly where the largest possible value for the quality characteristic is required, the ultimate target becomes infinity and the quality loss function becomes:

$$L(y) = k(1/y^2) \tag{1.4}$$

Tied closely to the loss function is the signal to noise ratio (S/N). As a statistical measure of performance, the S/N ratio is an evaluation of the stability of performance of an output characteristic, where the loss function allows an evaluation in monetary terms of the effect of that stability.

As with the loss function there are three standard forms of S/N ratio:

For nominal is best, use $10 \log_{10}(\bar{y}/s)$ **(1.5)**

For larger the better, use $-10 \log_{10}\left(\sum_{i=1}^{n} y_i^{-2}/n\right)$ **(1.6)**

For smaller the better, use $-10 \log_{10}\left(\sum_{i=1}^{n} y_i^{2}/n\right)$ **(1.7)**

The relationship between loss function and S/N ratio is illustrated in fig 1.17, where distinction is also made between three potential sources for operational Noise.

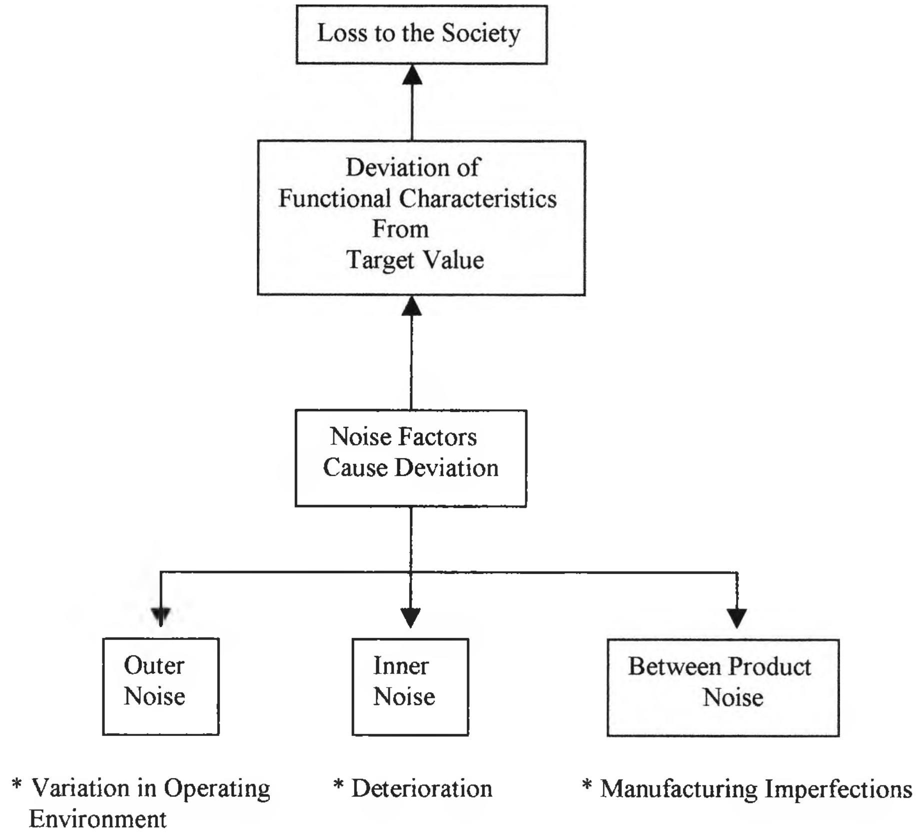


Fig 1.17 Relationship Between Loss and Noise Factors (ASI 1992)

1.2.7 Design Reuse

The reuse of existing design knowledge is an important approach to be applied in the generation of new designs. By integrating proven solutions into a new product, a large element of risk can be eliminated whilst reducing design costs.

One of the advantages of the QFD design matrices is to record previous design experiences and to document the design process. As well as providing an audit trial, this should also provide a starting point for the next generation of similar products. It should mean that much of the design effort for previous products can be carried forward to the next generation. **(2.1.3).**

1.3 The Design Environment

1.3.1 Engineering Product Types and Life Cycles

The type of product to be designed will greatly influence the method of approach to be taken throughout the design process. Influencing factors such as, value, sales volume, time scales etc. all play an important part. Different types of products will also be designed and built in different environments, which themselves will influence the way the design activity is carried out.

Products can be classified in many ways, both in terms of their production and consumption. Pugh (1991) makes the classic segregation of products in terms of manufacturing volume, these being: large one off manufacture, small/medium batch manufacture, and mass-produced. Hundal (1997) concentrates on *standard* or *generic* products for which a market need has been identified. Ulrich and Eppinger (1995) further classify these *standard* products into four groups:

1. Technology push product - A new technology product adapted to suit different possible uses.
2. Platform product - A well established new technology used as a basis for other products.
3. Process-driven product - A product whose existence depends on a very specialised process developed for its manufacture.
4. Customised product - A variation on an existing well established product.

Finkelstein & Finkelstein (1991), however makes a much more detailed segregation of products, classifying them under groupings of Genesis, origins, use and endurance. Further more, products are distinguished as being an item, model or family:

Genesis

- Special products - Designed by commission.
- General products - Designed and made for speculative sale.

Origins and use

- Primary products - Raw materials.
- Intermediate products - Incorporated into other products.
- Final products - direct satisfaction of need.

Endurance

- Consumable - used by satisfaction of need.
- Durable - Extensive functional life cycle.

Characteristics of usage

- Capital goods - Durables used in the production of other goods
- Consumer goods - Used to satisfy customer's individual needs.

Classification

- Item - Individual device, equipment or system.
- Model - Set of product items manufactured to a particular design
- Family - Set of product models the design and marketing of which are closely related.

By making such a detailed segregation, the life cycle of a product can be more clearly determined. For example Finkelstein & Finkelstein (1991), represent the life cycle of an, *intermediate product item*, using a block diagram (fig 1.18) which not only shows the major life phases of the product but also the potential points of sale.

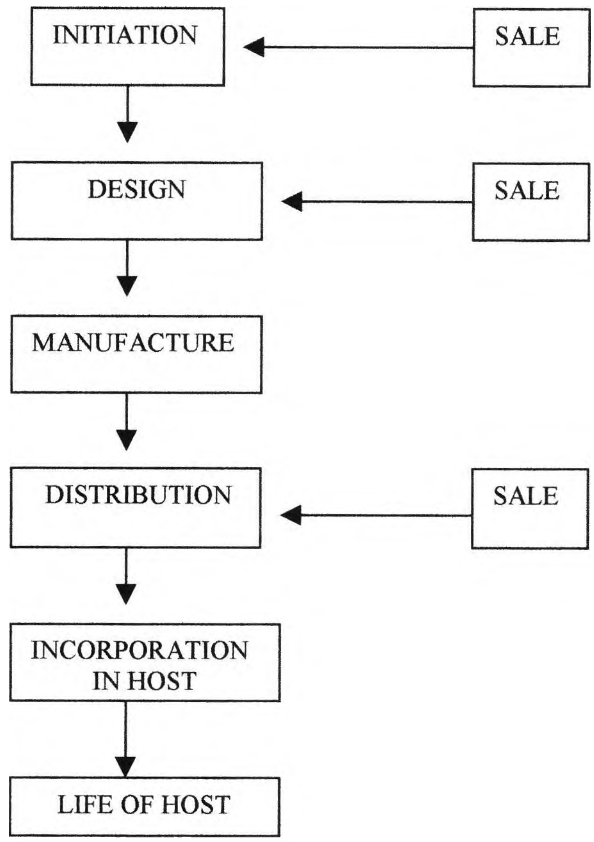


Fig 1.18 Life Cycle of an intermediate Product Item (Finkelstein 1991)

1.3.2 Product Cost in Design

For any product to be a commercial success, it must be sold at a price, which is acceptable to the customer. Such a price however must not be at the expense of product quality or functionality.

The manufacturing economics for many industries have become far more aggressive over recent years. The majority of suppliers previously lived in a world where they established their price levels simply as:

$$\text{Cost} + \text{Profit} = \text{Selling Price} \qquad \textbf{(1.8)}$$

For many industries today, the international market place in which they now compete sets the product price for them:

$$\text{Selling Price} - \text{Cost} = \text{Profit} \qquad \textbf{(1.9)}$$

The automotive supply industry is an example of this economic environment. The price, which the automotive manufacturer (i.e. Ford, G.M etc.) will pay for component parts, is presented to the supplier who must meet this price or risk loosing the business.

In order to survive in this aggressive market place, the manufacturer must be capable of producing products at the lowest cost possible whilst still satisfying all other customer requirements.

It is during the design stage that the greatest influence on product cost can be made. Hundal (1997) quotes the commonly stated figures of 70 to 80% of the costs being set at the design stage compared to the design process itself accounting for only 6% of the product cost. Such statements, although correct, must be made in the context of a particular product type. For example the proportioning of costs within a 'special product' as opposed to a 'general product' (see 1.3.1) would be totally different. Similarly the cost equations **(1.8)** and **(1.9)** would apply in the context of different product types. For example, **(1.8)** would apply when arriving at a price for a specialised 'one off' product, whereas **(1.9)** is the most likely situation when selling into a highly competitive mass-produced market. In any event, the requirement is that a price for a product must be known prior to the design process, a situation requiring cost estimation to be performed. Also during both design and manufacture stages of a product, cost information is required for management purposes.

Ehrlenspiel (1985) states that the most important cost influencing factors are as follows:

1. The concept - including physical effects, material types and number of active surfaces.
2. Size of the product - dimensions and amount of material
3. Number of parts - including standard, similar and same parts.

The entire above is a product of the various stages of the design process.

Hundal (1997) gives a breakdown of the cost influencing factors within the concept and embodiment design stages. From this it becomes clear, that the greatest design influence on final product cost is at the concept stage.

Understanding of costs both prior to, and during the design process is hence a vital ingredient in any systematic design approach.

1.3.3 Design Management

Whatever the type of organisation, management of the design process must be effective at both a corporate and personnel level. As stated in BS7000 (1990):

> "A company's most valuable resource is its staff, especially its design staff, whose output in terms of both quality and quantity largely depends on their skill, training and motivation".

The responsibility for ensuring such an environment exists, is that of management.

Wray (1991) makes a forceful assessment of how management has failed to recognise fully the importance of the design process and the key role that it plays in many organisations. He argues that design is a management tool, capable of increasing market share or creating new market opportunities. Many successful companies, are those which have realised the benefits which can result from integrating design, within the overall management structure.

At an operational level, the role of design management is primarily to plan, control and evaluate the design activity. If specific models and methods are to be applied in the design process then it becomes the management's responsibility to ensure they are correctly utilised. For many industries, safety legislation such as the *European Machinery Directive*, through the requirements of a 'technical file', will demand certain activities such as risk assessments etc, are carried out. Ensuring any such obligatory requirements are compiled with is also management's responsibility. A useful set of checklists, to aid in the management of the design process, is given by the Institution of Engineering Designers (1988). These cover marketing, resources and design procedures.

1.4 Research Products Background

1.4.1 Introduction to the *Self-Pierce* Riveting Process

The *self- pierce* riveting process is a primary product of the sponsoring organisation for this research, **Aylesbury Automation.** Marketed under the trade name of **Fastriv,** the product includes the consumable fastener, the mechanical equipment to place and set the fastener and the specialised knowledge required to apply the technology effectively.

Originating in the 1960's, the *self-pierce* rivet was a direct adaptation of a standard PT (punched tubular) form rivet, with only the component hardness being substantially different. Sharing the same terminology, (fig 1.19) both standard and *self-pierce* rivets have a cylindrical shank of circular cross section, with an integral enlarged head at one end, and a hole in the shank end (poke). Rivets are normally manufactured from wire material by a high-speed cold forging process.

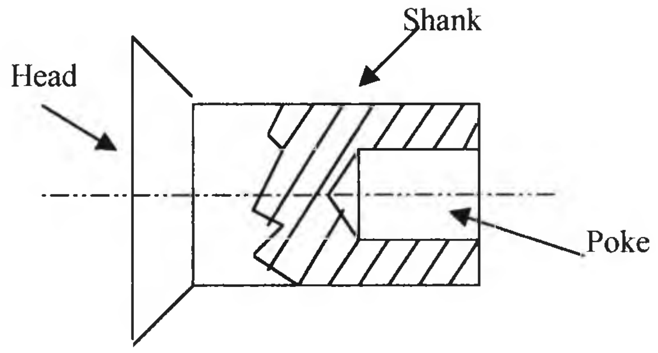


Fig 1.19 Rivet Terminology

Intended for forming joints in metallic materials with a maximum total thickness of 6mm, the great advantage of *self-pierce* over conventional riveting is that no pre-formed holes are required in the components. Unlike conventional mechanical fasteners, which pass through a hole and pull the joint materials together, the self-pierce rivet generates it's own hole, before deforming, to create a tight mechanical joint. The mechanics of the process are better understood by breaking down the joint formation into a number of stages. Researchers at Paderborn University, namely Budde et.al (1991), describe the process in four stages, fig 1.20.

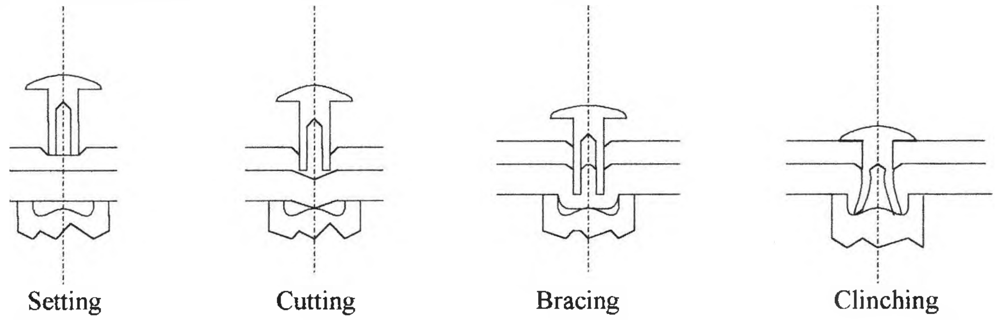


Fig 1.20 Stages of Joint Formation

The first stage is **Setting**, here the rivet is presented to the component surface and a load is applied to the rivet head, forcing the component parts into tight contact. As this load is increased, the process enters the **Cutting** stage where the rivet forces a path through the upper material layer. **Bracing** then takes place and the lower material layer becomes forced into the reacting die (anvil). The final stage is **Clinching,** where the rivet shank end is expanded outwards under the influence of the anvil locking itself into the lower material layer. Simultaneously the rivet head is brought into tight contact with the upper material layer. Forces required to carry out this process are typically up to 40kN, which must be reacted within the riveting machinery structure. During the *self-pierce* riveting process, force is applied to the rivet head by a plunger, which is reacted against by the anvil. The riveting equipment must therefore have access to both sides of the component, necessitating a 'C' frame structure configuration as shown in fig 1.21. Hill (1994b) gives a full review of the self-pierce riveting process and equipment.

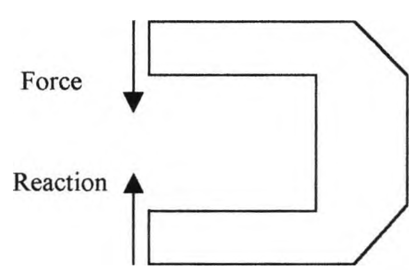


Fig 1.21 'C' Frame Structure

Prior to the late 1980's, this process had only found limited usage in such industries as; garage door manufacture, heating and ventilation ducting, white goods and road signs etc. Since then however, the process has become of great interest to the automotive industry. The major reason for this new interest in *self-pierce* riveting, is the impending need to fasten new combinations of materials, which are no longer compatible with the dominant resistance welding technique. Compared to mild steel, new materials such as aluminium alloys, magnesium alloys and high strength steels do not weld easily, giving joints of suspect strength and quality. Doo (1993) compares joint strengths achieved by both resistance welding and *self-pierce* riveting when fastening 5000 series aluminium alloy. Not only does the riveting process provide joints of superior strength, but with the added benefit of requiring no pre-treatment operations such as cleaning. Westgate et al (1994) and Westgate (1996) makes a more detailed comparison between *self-pierce* riveting, press-jointing, conventional riveting and resistance welding. Although results varied greatly between different material combinations, Westgate found the *self-pierced* joints showed greater overall static strength particularly in aluminium alloys. By comparison, much earlier work by Sunday (1983) showed *self-pierce* riveting in aluminium alloy joints to exhibit lower static strength than resistance welding but superior fatigue strength.

Automotive manufacturers world-wide are under pressure to reduce vehicle weights in order to meet government set fuel consumption targets. Osterman et al (1993) states that, by constructing the vehicle body entirely from aluminium, it is possible to save typically 150 kg in weight. Such a saving is highly significant, particularly where most other areas of weight reduction have been exhausted. The first manufacturer to successfully apply a total aluminium body construction, in a mass-produced main stream-manufacturing environment, has been Audi with their A8 vehicle. Other vehicle manufacturers are working on concept cars utilising aluminium alloys, magnesium alloys, high strength steels and composite materials but the final form of the vehicle of the future is still a matter of research and debate. One of the major issues to be faced when using these alternative materials is how are they going to be fastened, both to each other and in combinations. Amongst other possibilities, the *self-pierce* riveting process has emerged as a major contender. Pullin (1996) reviews the progress made by riveting in recent years, particularly in the light of 90% riveted joints on the Audi A8 and the introduction of riveting on two Ferrari models. Further success for the process has been achieved at a sub-assembly component level. All Ford Mondeo front seat assemblies, for example, are held together by 14 *self-pierce* rivets, a description of which is given in Hill (1994a). An overall, equipment focused appraisal, of mechanical fastening and resistance welding is made by Larsson et al (1995).

The process of *self-pierce* riveting therefore stands at a cross roads, if it is to continue to achieve its full potential, particularly in the automotive industry, then it needs rapid further development. Many issues of joint quality, equipment accessibility and performance must be improved. Both in Germany and the UK, research activities covering all aspects of self-pierce riveting are underway. Largely funded by BMW and

Rover, research is taking place at Paderborn and Warwick Universities. Under a recent Teaching Company scheme with the University of Hertfordshire, research has focused specifically on developing 'in process' quality monitoring, (see King (1995)). Whilst at City University London, 'design methodologies' have been successfully applied to develop a new model of riveting gun, (see Hill (1994)). These final two activities have made the sponsoring organisation, Aylesbury Automation, a market leader in the supply of riveting equipment, but not as yet the leaders in supplying of the overall process.

The most important components of the process are the rivet, and characteristics of the tooling (anvil) which influence joint formation. Joint material properties are the third component as required by the customer. In order to achieve the highest possible level of joint performance to satisfy customer requirements, with a product which is *Robust* to process fluctuations, extensive research into the design and combinations of process parameters is required.

1.4.2 The 'Made to Order' Machine Design Environment

In contrast to the medium size company structure of Aylesbury Automation, SPM is a small family run business of seven employees, which has achieved an elite status in the design and supply of special purpose machines, almost exclusively to blue chip companies. With no department structuring of any kind, the individual is responsible for all activities within their own particular project. This embraces sales, design, purchasing, assembly, documentation, cost accounting and commissioning.

Designing special purpose machines to customer order can be a particularly demanding environment for the design Engineer. A customer has a requirement, which must be satisfied, (in many cases within tight time deadlines), for which a bespoke piece of equipment must be designed and built. Often no prior knowledge of a similar system is available to help the designer, therefore working concepts must be developed before any cost estimates can be made. Once the project becomes live, the designer has to convert the proposed solution into a working system, within the combined constraints of time and cost.

The demands on the design process within a company like SPM, will be different to those within the more conventionally structured organisation like Aylesbury

Automation. In the formulation and use of structured design methodologies, such variations in the possible design environment must be accommodated.

1.5 Aims and Objectives

1.5.1 Aims

The overall aim of this research is to apply current design methodology theories to the industrial environment and to assess their relevance and effectiveness. Three working hypotheses will be tested against experiences gained in two different industrial design environments. Firstly a quality dominated mass production environment involving high volume, low variety, low added value products and processes. Secondly a bespoke machine/system design environment involving low volume (mainly one off's) high variety (every one unique) high added value products.

1.5.2 Working Hypothesis

1.5.2 (a) Hypothesis # 1

"Matrices can be utilised as an active tool for the creation of *robust* product designs."

The previous sections of this introduction have highlighted the major aspects of the design process, and of the products/environments upon which this research is based. When contemplating the design process in its entirety, it becomes apparent that many aspects of human and managerial behaviour, within a quality/cost conscious environment, have to be considered. Designers are under increasing pressure to achieve superior and *robust* product designs whilst satisfying ever more rigorous constraints. The use of Matrices in a role expanded beyond the conventional QFD approach, is one way by which the design process may be assisted.

1.5.2 (b) Hypothesis # 2

"The *roof of the house of quality,* can be used to introduce Engineering Science results into the robust design parameter selection procedure".

Engineering science is a vital part of the design process, it allows ideas to be tested on paper, and provides an insight into likely performances at parts and concept levels.

Means of achieving an index measure, which describes a physical quantity, and can thus be evaluated by a matrix, are not immediately obvious. i.e putting meaningful numbers into the 'Roof' of the 'House of Quality.'

1.5.2 (c) Hypothesis # 3

"Design Matrices can be utilised to identify major product cost drivers."

Cost is a major constraint for the majority of design environments. Both component parts and human effort translate directly into financial terms, which must be accommodated within a defined price. The *design functions,* within the top-level chart (stage 1), as shown in **1.2.2,** should also be the major cost drivers. If this is the case, then improved methods for systematically predicting cost, both prior to, and during projects, may be possible.

The above hypothesis are to be further explored against existing published literature and tested using industrial case studies which involve the complexity of real Engineering products and environments.

1.5.3 Industrial Requirements

Performed to satisfy the requirements of two contrasting industrial environments.

1.5.3 (a) Mass Produced Industrial Process requirements

The *self-pierce* riveting product as described in **1.4.1,** requires rapid improvement if it is to benefit from the large potential automotive market, which is emerging. The fastener element of the process as manufactured by Aylesbury Automation, has remained largely unchanged since its inception in the 1960's. Used mainly to fasten steel components, it is now proving inadequate to meet the markets current demands. Changes to the fastener design, which allow the creation of quality joints, particularly in aluminium alloy material, must be made. Many parameters exist in both the fastener and the setting tooling which can influence joint quality, but to what degree is unknown. External parameters, such as those relating to the joint material, also have an un-quantified influence upon the joint quality.

Achieving a cost-effective product which is *Robust* to both internal and external influences, whilst providing joints of a quality to satisfy current customer requirements, is the primary need of Aylesbury Automation. In addition, an improved understanding of the process mechanics must be found.

1.5.3 (b) Bespoke Machine Design requirements

The overriding requirement is to deliver a solution which satisfies all the customer's requirements on time, to budget and with acceptable profit margins.

1.5.4 Specific Objectives

The specific objective of this research is to provide two contrasting industrially based case studies, which can be used to test the relevance of the working hypotheses. The effectiveness of design matrices and associated design methodologies will be compared in each case.

Chapter Two

Literature Survey

Chapter 1 introduces much of the generic background to the design environment. This theme is now continued, surveying literature, which focuses on developments in the use of 'Design Matrices', 'Experimental Design' and Cost issues.

In relation to the *self-pierce* riveting process, closer analysis is made of the joint mechanics, particularly in relation to 'Plastic Deformation'.

2.1 Design Methodologies

2,1,1 Design Function Deployment (DFD)

Design Function Deployment, DFD, has been developed as a comprehensive design system incorporating the matrix structures of QFD, concurrent engineering and design models, methods and systems. The underlying model for DFD has six stages, as laid down by Jebb et. al 1993. It starts with the identification of all the customers for the product (customer, being in the context of all those who contact the product through out its life cycle) and establishing their needs together with their respective importance ratings. From this list of prioritised requirements, design functions are translated as, 'Identifiable and actionable design requirement', which are again prioritised, only this time by means of a Quality plan. The resulting 'Product specification' describes the 'Product concept' in the form of a list of functions in a 'Solution neutral' form. In the second stage, various 'Solution concepts' called architectures, which potentially satisfy the product concept are proposed and evaluated. The third stage, develops the architectures into different embodiment and subsequent detailed designs called layouts. In the fourth stage, materials and corresponding manufacturing processes to make the parts are established. In the fifth stage, production plans are established to produce the proposed components, in the required quantities within acceptable quality and cost constraints. Finally, in the sixth stage, the optimal design solution is selected from a range of alternatives.

As discussed in **1.1.6**, 'Design methods' are techniques for aiding the design process. Within the total DFD structure, a second level is included to accommodate such design methods and tools, below which a third level houses supporting databases, rule bases and knowledge bases. The complete DFD structure, as shown in fig 2.1, illustrates the *prescriptive* six-stage design model within the three levels of activity. The iterative nature of design is accommodated by feedback between all stages of the model with the descriptive modules being freely available at any point throughout the design process.

Wynn et. al (1993) discuss the benefits of the DFD approach for promoting *robustness* in design. By the identification of 'noise' sources at each stage of the process, actions can be taken to avoid or alleviate such effects.

Kimpton and Sivaloganathan (1998) give a more recent application of the DFD process for the design of an elevating platform. Following through the conventional DFD process to final production, it is interesting to observe that no constraint of safety was applied at any point in this analysis. The result being, that the final product appears highly dangerous.

2.1.2 Concurrent Engineering (CE) within DFD

The globally competitive nature of manufacturing has brought about the need to bring new products to the market place on ever reducing time-cycles. In place of the traditional sequential chain of activities, concurrent engineering accommodates the overlapping of all activities within the manufacturing organisation. Such a structure avoids the isolation of any one department, particularly design, which must now obtain inputs from all other departments involved in the product life cycle. Hundal (1997) shows a diagrammatic comparison between traditional and concurrent engineering structures (fig 2.2).

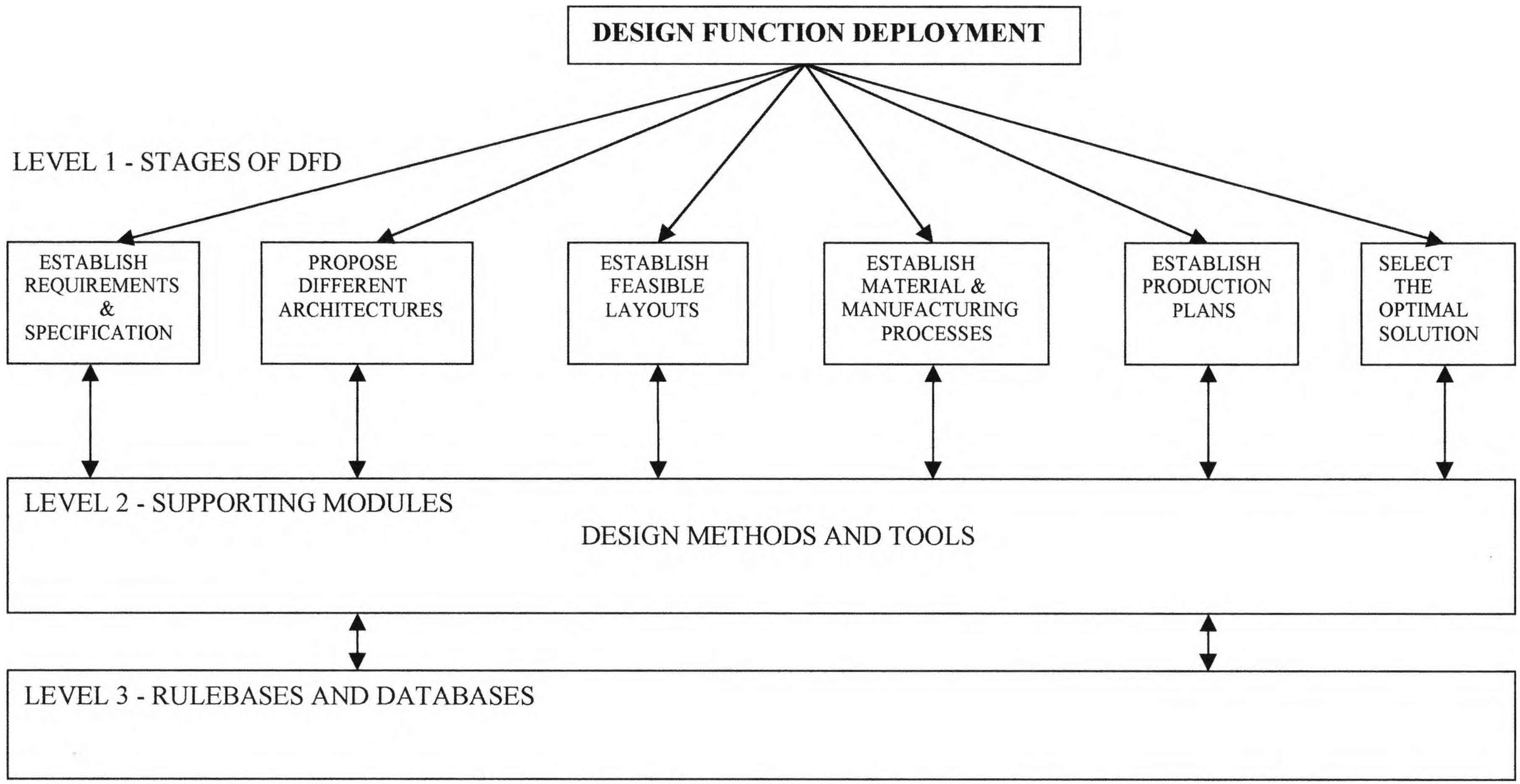


Fig 2.1 The Structure of the DFD System

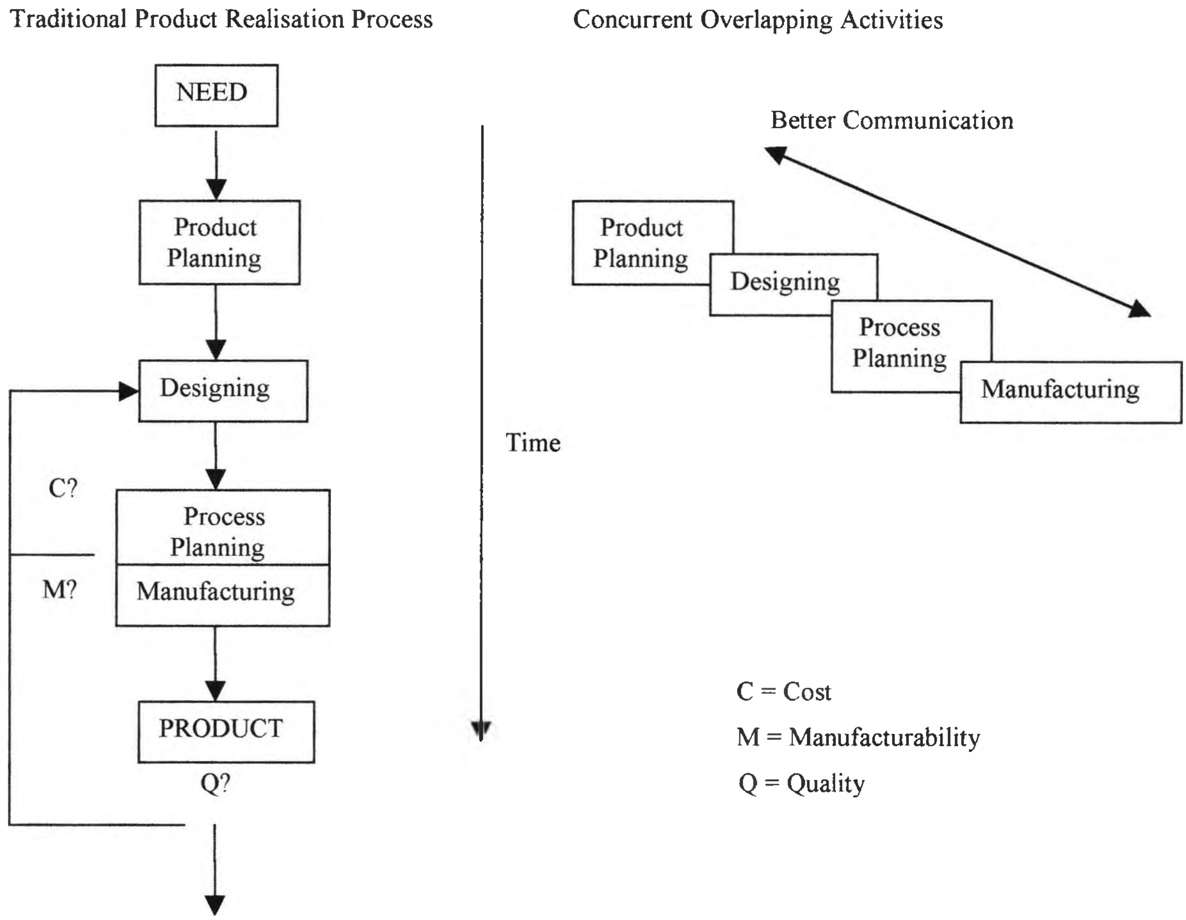


Fig 2.2 Comparison Between Traditional & Concurrent Engineering (Hundal 1997)

The most commonly quoted definition of Concurrent Engineering is given by Winner et al (1986).

> A systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from concept through disposal, including quality, cost and user requirements.

Concurrent Engineering builds upon the importance of the design process, (particularly in financial terms) as highlighted in **1.3.2**, A point clarified by Syan and Menon (1994) in their description of the objectives of CE.

> To ensure that the decisions taken during the design of a product result in a minimum overall cost during its life cycle. In other words, this means that all activities must start as soon as possible, to induce working in parallel, which additionally shortens the overall product development process.

The key ingredient to concurrent engineering is multi-disciplinary inputs (Sivaloganathan et. al (1995)). Representatives from all departments (and customers) collaborate to bring their combined knowledge and experience to shape the product, from idea to obsolescence. Such information brought forward into the design process must therefore be of the highest quality if it is to effectively improve the final product. Recent work by Pham and Dimov (1998) advocate the use of 'Artificial Inteligence' techniques to acquire, structure and represent knowledge about previous manufacturing and planning cases to support future design and planning activities. The modern product realisation paradigm is that *the process must be designed at the same time as the product.*

Design Function Deployment, DFD, was developed by Jebb et al (1993) within the framework of Concurrent Engineering. The first stage of level one of the DFD system ensures that elicited customer requirements, including other necessary inputs from marketing, finance, purchasing, design, manufacture and suppliers are considered in a concurrent manner, before translation them into design functions. Hence stage one of DFD, provides for the essential teamwork ingredient, by the integration of various functions, influencing product development at the onset of design.

At DFD level two, auxiliary programs of several design methods, tools and techniques can be used in a parallel manner, as design proceeds from conceptual to detail stages and subsequent release for production. These tools include Functional analysis, Objective tree, Morphological charts, FMEA, Finite element analysis, Design for cost, Solid body modelling, Design for manufacture and Robust Engineering design. The use of such tools ensures that design concepts are not only functional, but can be manufactured, assembled and used to the satisfaction of all customers, i.e concurrent design of product and associated processes is achieved.

DFD level three, contains databases, rule bases and knowledge bases for use in the previous two levels. By allowing concurrent access to both past and present design information, by all interested groups, interfacing (communication) delays can be reduced.

It can be concluded therefore, that Design Function Deployment (DFD) provides an environment conducive with a Concurrent Engineering approach.

2.1.3 Design Reuse within DFD

Increased use of parts and subsystems which have proven success in past designs, is a powerful way of producing further products cost effectively, with predictable performance, in a short lead time. Most designers will prefer to implement concepts and lessons from the past, a fact confirmed through research by Khadikar and Stauffer (1995). Although the largest accumulation of expertise is stored in the designed products of the past, efficient exploitation of this information has been prohibited by:

(i) The lack of a methodology to structure past designs for reuse.

(ii) The lack of a suitable database of successful past designs.

For a design reuse system to be effective, it should provide assistance to the designer, in the form of information appropriate to the stage of design activity. According to Shahin et al (1998), design reuse can become part of the DFD process as a design method housed in level two, with design data being stored in the following four formats:

(i) *Product Concept,* as a prioritised list of functions.

(ii) *Solution Concept,* as a Function tree.

(iii) *Embodiment Design,* as a parts tree.

(iv) *Detailed Design,* as some geometric model with facilities for easy modification.

Fig 2.3 shows the data formats relevant to the different stages in DFD.

In the majority of situations, past designs can only be studied by looking directly at the products or detailed drawings. This necessitates the extraction of good functional subsystems for reuse in new designs, translated into a format compatible with the DFD process. Sivaloganathan and Shanin (1998) propose a four-step interpretation process for this purpose, shown in Fig 2.4. Several practical case studies have been carried out, which show this technique works well in helping the designer to structure the product into the necessary design process for incorporation in the design reuse system.

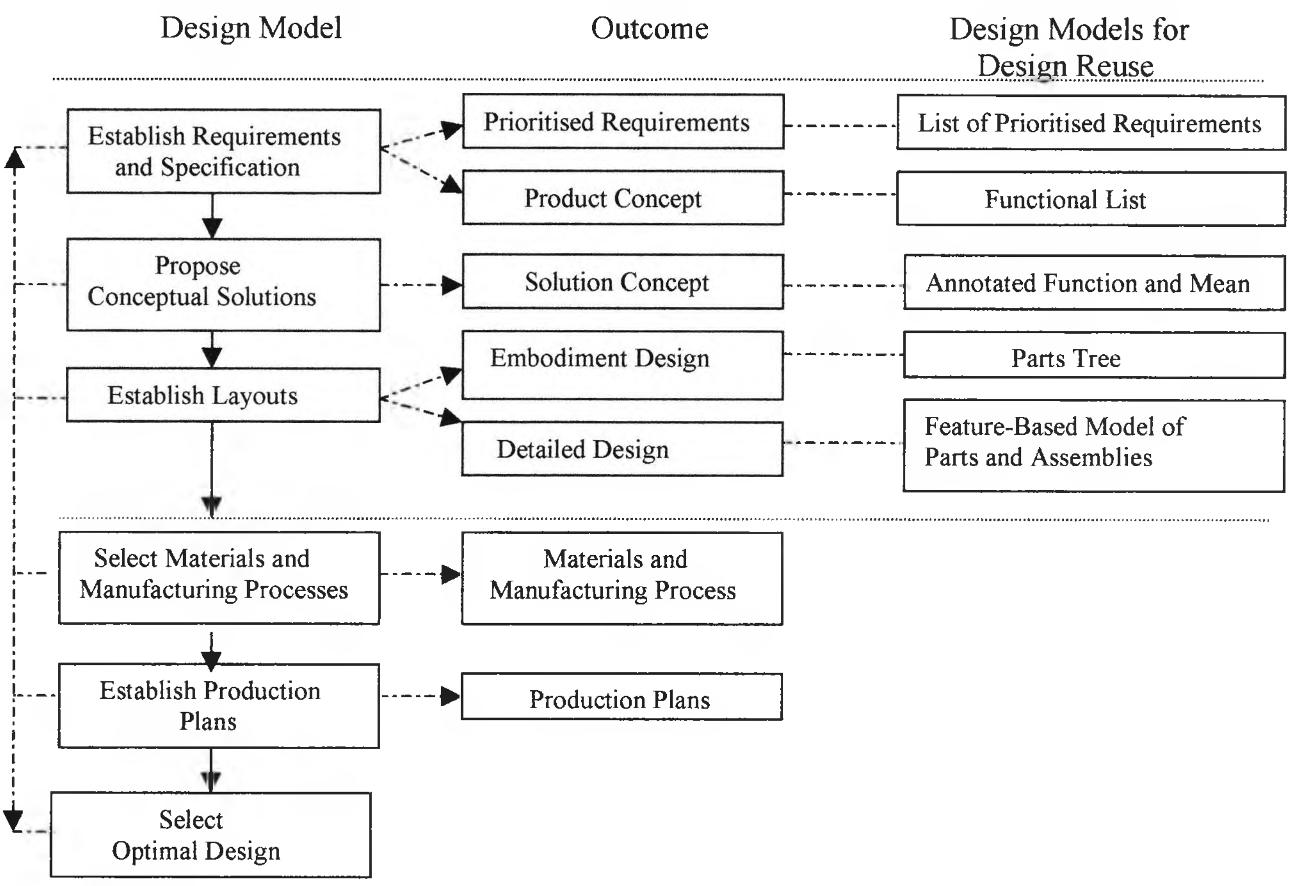


Fig 2.3 DFD Structure with Related Outcomes and Data Models (Shanin et.al 1998)

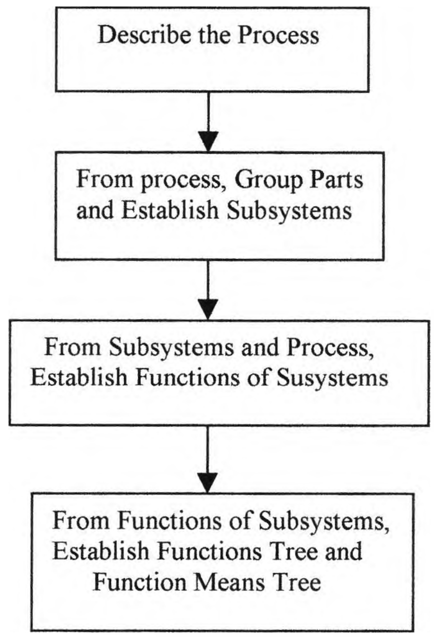


Fig 2.4 The Design Interpretation Process (Shanin et. al 1998)

2.1.4 Further Developments in QFD/DFD Matrix Methods

The 'correlation roof' part of the QFD chart as shown in fig 2.5, is used to identify and evaluate any interactions believed to take place between functions. Either positive correlation's, which have a favourable effect on the desired response or, negative correlation's, which have an adverse effect, may both be found.

Many design researchers generally regard the 'correlation roof' to still offer further scope for assisting design optimisation. As stated by Cohen (1995):

> "the correlation roof is probably the most under exploited part of the House of Quality. Few QFD applications use it fully, yet its potential benefits are great".

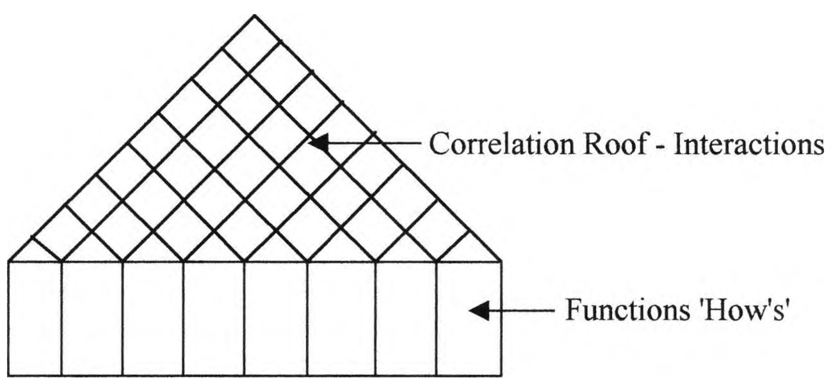


Fig 2.5 Correlation Roof of 'House of Quality'

2.1.4 (a) Correlation Chain

Comincini (1994) proposed moving the correlation process from the 'Roof' into the main relationship matrix in order to associate more clearly the correlated parameters (Hows) with their related outputs (Whats). This is claimed to enable an algorithmic approach to linking the 'Hows' and the 'Whats'.

The 'correlation chain' method is described by Comincini (1994), in relation to design modifications and their subsequent comparison with previous DFD analysis. These are claimed to be effective when:

(i) Retrieving correlation chains relevant to the subject.

(ii) Identifying all parameters that see their performance parameter stressed by the new condition.

(iii) Identifying all necessary steps in order to accept and implement the required modification.

(iv) Evaluating cost comparisons between new and previous designs.

An example of a correlation chain structure is shown in fig 2.6. On the left-hand side of the chart, the 'What's' are divide into two sections. The first one lists all known basic or past specifications and the second one lists the customer's additional requirements. Along the top row of the chart, the 'How's' are placed (in this case sub-assembly options) and a second column is added to facilitate cost comparisons. It is claimed by Comincini (1994), that fast comparison between all the elements, composing the previous and newly formed correlation chain, addresses the retrieval of all the connected elements relevant to the requested modification. Further more the correlation chart can be used to determine dependent and independent variables.

The weakness in such an approach, is that any interrelationship between the 'How's,' is now lost, with the correlation process becoming a direct relationship between 'How's' and 'What's'. Although not mentioned by Comincini, it would seem possible that such a shortcoming could be resolved, by simply adding the 'correlation roof' above the 'How's' as normal.

Comincini (1994) also describes a method of using DFD charts for both detailed Engineering design, and for preparing cost based customer specifications and sales quotations. As a major influence on final product cost, the 'make or buy' policy is highlighted as an important design decision. Comincini further suggests that the technical design functions of the top-level design matrix should also be the major cost drivers.

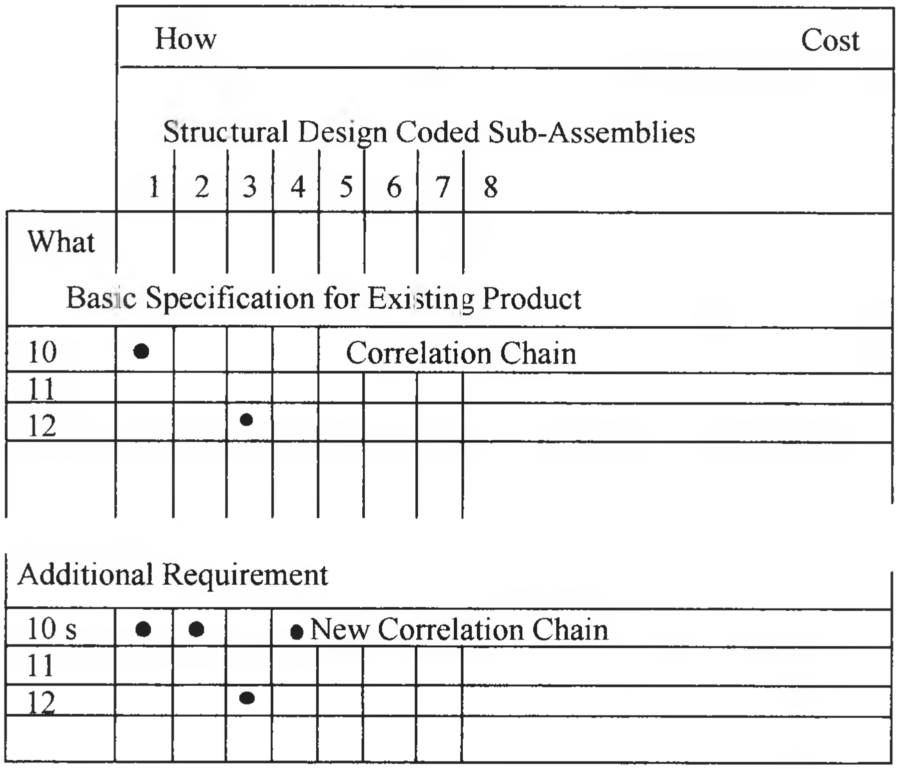


Fig 2.6 Correlation Chain (Comincini 1994)

2.1.4 (b) Square Matrix Method

Atherton (1997) proposes replacing the 'correlation roof' of the QFD matrix with a square matrix as shown in fig 2.7. It is claimed that difficulties arise in identifying all the relationships without first defining which factors are dependent or independent. These causal relationships are clarified by using the none symmetrical matrix. From this asymmetry of causal relationships it is proposed that an order for addressing each factor will be determined which will dramatically reduce the solution space for two aspects of the design problem.

(i) The *procedural domain,* which includes all design requirements, some of which cannot be measured or target values set, which are recorded at a general level in QFD phase one.

(ii) The *physical domain* which can now be quantified. Once the independent factors are set the others must follow from physical laws.

Atherton (1997) further proposes the use of correlation chains (see **2.1.4 (a)**) to evaluate influences identified in the square matrix.

The use of the methodology is described by Atherton (1997) in relation to a QFD phase one analysis. The process is divided into the following five stages.

(i) List important design requirements: Usually a team approach to establish design functions as direct response to customer inputs.

(ii) Identify direct and substantial influences: Using the square matrix fig 2.7, influences between design functions are identified and highlighted. For this example of a solar powered vehicle, it can be seen that wheel space is shown to directly influence passenger space etc.

(iii) Form network of correlation chains: The influences identified in the square matrix are drawn directly as a network of correlation chains, fig 2.8.

(iv) Develop hierarchy of correlation chains: influences are arranged into a 'top down' pattern, fig 2.9.

(v) Design procedure: interpretation of analysis and further actions to be taken are finally determined. For the hierarchy example shown in fig 2.9 it would be suggested that the design be tackled in three stages.

- Addressing air drag, crash resistance and wheel space requirements.
- Determining space requirements for passengers, engine and luggage.
- Establishing the appearance of the body.

The above methodology is shown by Atherton (1997) to be successfully applied over four industrial case studies.

		Y	Y		Y	G
Y					F	
				E		
Y	Y		D			
Y		C		Y		
	B					
A						
Air Drag	Crash Resistance	Passenger Space	Engine Space	Wheel Space	Luggage Space	Appearance
A	B	C	D	E	F	G

Fig 2.7 Square Matrix (Atherton 1997)

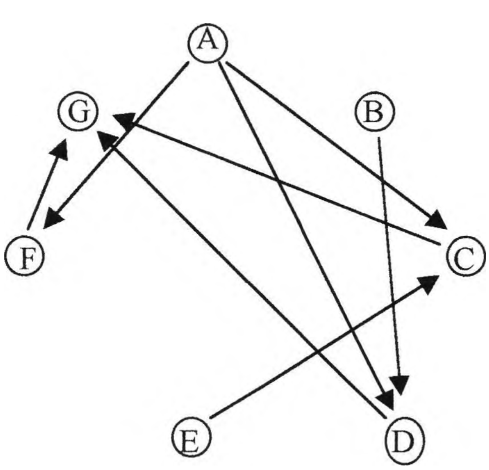


Fig 2.8 Network of Correlation Chains

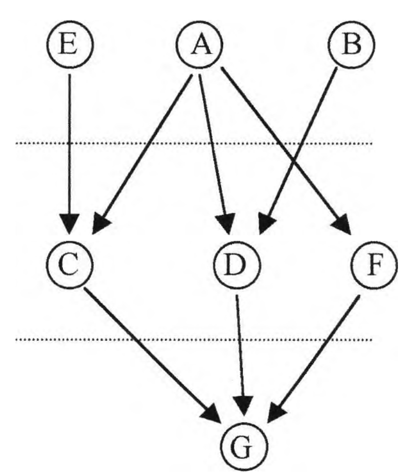


Fig 2.9 Hierarchy of Correlation Chains

2.2 Product Design to Cost

2.2.1 Sources of Cost

All manufactured products generate costs through all phases of their life cycle, both prior to use, and in some cases beyond. It is essential that the manufacturing organisation is able to both identify and control such costs if it is to remain a competitive supplier.

Cost elements within an organisation can be identified under the four categories of, People, Equipment, Materials and Environment. This fits in with the Accountants sources of cost, being:

(i) Direct Material
(ii) Direct Labour
(iii) Direct Expenses
(iv) Overheads
1. Production
2. Administration
3. Selling and Distribution

These are the direct and obvious expenses associated with any manufacturing activity, which permit the derivation of selling price through equation **(1.8).** However, further substantial costs can occur due to none-conformance and attendant failure costs. Such failure costs include rework, scrap, warranty claims, product liability claims and recall. It has been found through the 'Quality assurance programme' (1992-96) that 75 per cent of faults originate in the product development and planning stage and that 80 per cent of faults remain undetected until the final test or in service

The costs of quality, are typically quoted by Kehoe (1996) to be between 5 and 30 per cent of a company's turnover with 50 per cent of the total quality costs being attributed to failure costs alone. Since most of these failures can be traced back to the design stage, it is again the design process, which can most influence the final product success.

Research by Swift et al (1997) presents an approach called 'Conformability Analysis', which provides a means of estimating the potential costs of failure associated with a design. Any such failing can hence be rectified prior to production. Where manufacturing variability is identified as the cause of a significant proportion of product quality problems, Swift et al (1997) goes on to associate the risk of manufacturing variability with the process capability index C_{pk}. If the process characteristic can be assumed to be normally distributed, then C_{pk} can be related directly to a parts per million (ppm) defect rate. It is further suggested, that through the integration of Failure Mode and Effect Analysis (FMEA), the exposure of the product can be assessed in terms of its failure cost in production or service. The underlying notion being, that as failures become more severe, they cost more.

2.2.2 Methods of Cost Reduction

Within any comprehensive design approach, such as that advocated by the DFD methodology, many design issues relating directly to the final product cost will have been addressed by the design team. Issues such as design for manufacture, material selection, economic batch sizes etc will have been considered during the designing process and hence become integrated into the final design. One of the potentially most influential decisions to be made is whether to employ a 'make or buy' policy for components/sub-assemblies.

2.2.2 (a) Use of Standard Parts

A very powerful influence on final product cost can be derived from the use of standard component parts in the design. Such parts could be existing components already used within the manufacturing organisation, or standard catalogue parts purchased directly from a vast range of potential suppliers. Purchased parts undoubtedly offer the most economic approach as opposed to 'design and make'. Many components have always been purchased from specialised manufactures, such as electrical, electronic, pneumatic, bearings etc. But less obvious components do exist and it is important that the designer is kept continually aware of what is available. For example, as part of a recent design project, a small pivoting conveyor, was required to be secured when placed in its up right position. This was to allow safe access to the space bellow during maintenance without the danger of the conveyor falling down and causing injury. A very simple task, which was achieved by the use of entirely standard purchased components. For comparison purposes, an estimate was carried out as to the likely cost of designing and manufacturing to achieve the same solution. Table 2.1 gives a graphic comparison between these two costs, with the 'purchased part' solution costing only **12%** of the alternative 'design and make' approach. Although an extreme example, this does illustrate the savings which can be achieved.

'Purchased Part' approach		'Design and Make' approach	
	Cost £		Cost £
Latch Pivot Rod Knob Parts selection = 1/2 hour Fitting time = 1/2 hour	6 9 5 3 25 25	Design and detail = 3 hours Obtain quotations and admin = 1 hour Parts manufacture = 8 hours Raw materials Fitting time = 1/2 hour	150 50 400 12 25
Total	£75	Total	£637

Table 2.1 Cost Comparisons

Culley (1998) further explores the use of standard parts, within the context of 'design reuse'. Delivery of supplier information has been traditionally in the form of catalogues, trade shows and visits from representatives. More recently electronic catalogues have emerged through the use of CD-ROM technology, which permit the dissemination of vast amounts of information at a relatively low cost. Although very good, Culley (1998) considers such catalogues are not complete for use in a comprehensive design reuse approach and suggests the following elements should be incorporated.

1. Automatic analytical selection
2. Textural, pictorial and empirical data
3. Cost estimation techniques
4. Knowledge based selection
5. Design audit facilities
6. User enhancers

Rapid retrieval of product data allows an early decision to be made regarding a 'make or buy' policy.

A BSI publication, Mucci (1994) provides technical and sourcing data, for a large range of commonly used components.

2.2.2(b) Value Engineering

One long established technique for improving product design is that of 'Value Engineering' or 'Value Analysis'. The value of a product is defined by the equation:

$$\text{Value} = \frac{\text{Product function and performance}}{\text{Product cost}} \qquad \textbf{(2.1)}$$

Value engineering aims to obtain maximum performance for minimum cost, through the employment of cross functional teams evaluating every step in the product realisation process. The main focus is on the design process, materials and the manufacturing process where the 'team' asks questions pertinent to each of these areas. From this new perspective, design modifications are implemented.

2.2.3 Cost Estimating

It is essential for all manufacturing organisations to be able to estimate costs for new or revised products quickly, accurately and economically. Increasing emphasis on cost during the design phase has further led to the requirement for better ways to estimate cost. Ullman (1997) considers estimating production costs for new products, to be one of the most difficult, yet important tasks for a design engineer.

The use of 'cost models' is a method intended to reduce the reliance on design experience when performing cost estimates. Hundal (1997) describes two basic forms of cost model.

1. *Function Costing*, provides a breakdown in cost for a known product as a parts related proportion of the function it is required to perform. For example, French and Widden (1993) show a cost model linking the cost and shape of a bearing as follows.

$$C = G_m B(D + d)$$

Where B = breadth

D, d = outer and inner diameters

G_m = coefficient related to machine costs.

2. *Parametric Costing*, offers one of the few cost estimating techniques available at the concept design stage. In parametric modelling, cost is expressed as a function of important design parameters, which utilise regression techniques and cost databases to arrive at a predicted cost.

Schreve (1998) gives a model formulation in relation to cost estimation of fabricated parts. Developing a parametric model based upon nominal production activity rates, a reasonable correlation of cost performance was achieved across two independent companies.

2.2.4 Cost in QFD

Attempts have been made to integrate a 'design to cost' methodology within a QFD framework. If successful, the QFD methodology would become a far more attractive approach and gain more universal acceptance in industry.

'Design to cost' is the methodology which decides the design strategy based on cost, it ensures that cost is considered in every design decision, which affects final product or process cost. QFD on the other hand does not include cost effective targets (other than as a direct single customer requirement). As part of a research project with Lucas Engineering and Systems (LE&S), Ding (1991) proposed, and attempted to apply, a 'Cost in QFD' system to one of the companies products. The subsequent approach consisted of a six stage analysis involving the identification of cost drivers, estimating the cost of alternative design features and combining this cost data into a 'cost model'. From this point the process appears to have been unsuccessful, mainly due to a lack of effective cost data. Nor is it clear how such data was actually used in the QFD matrix.

One useful outcome of this project however, was that 'design variety' was identified as a major cost driver, prompting further work to be carried out in formulating a matrix based methodology for estimating the cost of variety and variety reduction.

Products are designed to perform certain functions required by the customer. Ding (1990) makes the statement that:

> "Variety in customer requirements seems to be the driving force for variety in design features."

Variety in design features, effects every process step from design through to manufacturing. Therefore variety effects the total product cost.

A seven stage process is proposed by Ding (1990) to apply QFD to design feature variety.

1. Feature and function analysis.
2. List of variety.

3. Potential reduction in variety.
4. Production line arrangements.
5. Cost influencing factors of variety.
6. Variety cost estimation
7. Cost savings due to variety reduction.

By means of a successful case study with LE&S, matrices have been applied in the rationalisation of product variations.

2.3 Experimental Design

2.3.1 Design Decisions

At some point in the design process, decisions have to be made in order to select an appropriate course of action, usually from a range of alternatives. Starkey (1992) describes decisions as being Fundamental, Intermediate or Minor and goes on to describe them as the *real workload* of the engineering designer. Many such decision will be based upon physical laws, logical deduction or be entirely intuitive.

The application of controlled experimentation as a means of achieving *robust* product design, was discussed in **1.2.4.** Through parameter design, levels of product and process factors are determined such that the product's functional characteristics are optimised and the effect of *noise* factors is minimised. Where a decision must be made in selecting a particular course of action, experimentation allows such decisions to be made with a maximum degree of confidence.

2.3.2 Dynamic Systems

Taguchi (1987) made a profound addition to his earlier work in the form of the *dynamic characteristic.* Where previously only static signal parameters had been taken into account, it now became possible to analyse a system performance over its dynamic range rather than at just one static point. Grove & Davis (1992) explain the nature of the *dynamic* system in relation to energy transfer through a simple input-output device, fig 2.10.

Fig 2.10 Energy Transfer (*ideal function)*

This can be shown as a linear relationship, between input energy (*signal*) and output energy in the ideal state (*response*), fig 2.11.

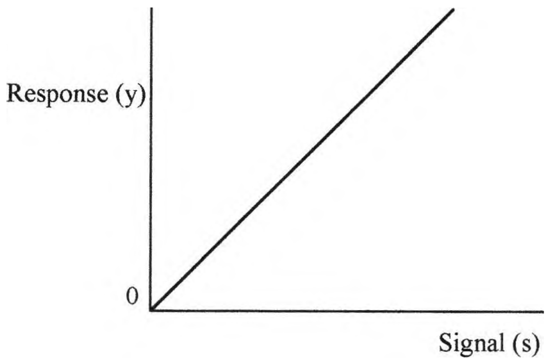


Fig 2.11 Linear relationship between input and output energy (Grove & Davis)

The above ideal system, will infact be subject to noise, such noise may affect the response by disrupting the system as well as the signal. Fig 2.12 shows the same system with hypothetical data added for a dynamic system subject to two levels of noise, N- and N+.

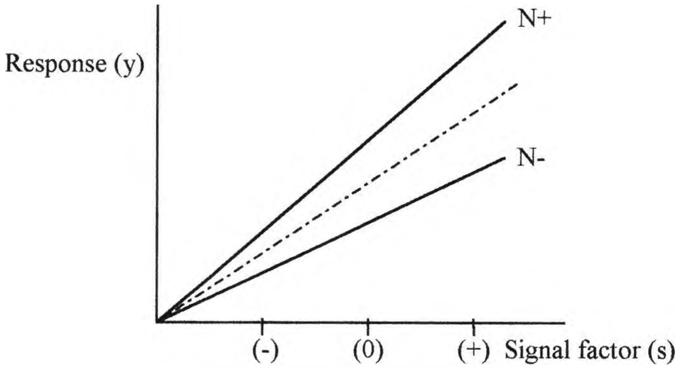


Fig 2.12 Dynamic system subject to noise (Grove & Davis)

In this case, an interaction between the signal factor and the noise factor must exist, since the effect of the noise increases with strength of the signal.

The linear relationship between signal and response can be expressed as:

$$y = \beta S \qquad \textbf{(2.2)}$$

where β = slope between y and s.

The equation **2.2** cannot be said to satisfy fully the experimental data implied by fig 2.12, none-linearity and the intended noise factor variation must also be accounted for. A value for β (say $\hat{\beta}$) can be selected to more closely represent the intention of the experiment. The possibility offered by Grove & Davis (1992), is to choose $\hat{\beta}$ so that the sum of squares residuals is minimised, i.e deviation from chosen line $y = \hat{\beta} S$ is minimised. Then $\hat{\beta}$ is given by:

$$\hat{\beta} = \frac{\sum y_I S_I}{\sum S_i^2} \qquad \textbf{(2.3)}$$

Taguchi goes on to consider the extent of variation around the 'fitted' equation $y = \hat{\beta} S$. For this he applies an adaptation of the Standard deviation equation, denoted by s_t. Finally the S/N (signal to noise) ratio is given as:

$$\text{S/N ratio} = 10 \log_{10} \left(\frac{\hat{\beta}}{s_t} \right) \qquad \textbf{(2.4)}$$

In the dynamic approach, several signal values are applied for each experiment trial. To accommodate signal and noise parameters, Taguchi adds a further 'outer' array to the 'inner' orthogonal array, fig 2.13. Experiments can then be conducted for each factor combination, giving results relative to set signal and noise levels.

Inner Array				Outer Array					S/N
				-	+	-	+	Noise	
Run	A	B	C	-	-	+	+	Signal	Ratio
1	-	-	+	Experimental Data					
2	+	-	-						
3	-	+	-						
4	+	+	+						

Fig 2.13 L4 Array for Dynamic System

When studying a process such as *self pierce riveting,* where the use of energy is of particular importance, the *dynamic* Taguchi approach will be of particular interest.

2.3.3 Experimental Data Analysis

Having generated data from a planned experimental programme, the interpretation of that data in to a format that allows decisions to be made regarding the process, is next required.

Experimental data generated from a programme structured on an orthogonal array allows a direct interpretation of the effects of factor levels upon the desired *objective function.* Taking the average value of the *objective function* for a factor at level 1 and compare it against the average found at level 2, allows a determination of which factor levels should be selected to give the best overall performance. As shown graphically in fig 2.14, setting factor A at level 2 has a detrimental effect on the results (assuming objective function is to be maximised). Such simple analyses are possible due to the *balance* in the experiment.

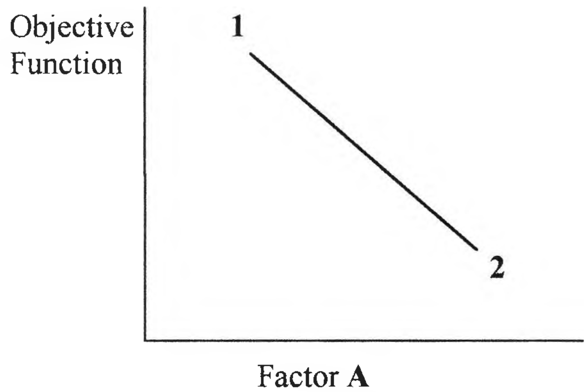


Fig 2.14 Main Effects

The significance of each effect on the final results can be determined by statistical methods. The usual approach to significance testing in multi-factor experiments is by Analysis of Variance (ANOVA). Developed in the 1920's by Fisher, this presents a rigorous way of testing individually for all available effects and interactions. The procedure for carrying out an ANOVA is well documented in many texts such as Grove & Davis (1992). Results are built into a table which accommodates factor effects, sum of squares for each effect, degrees of freedom, mean squares and finally the F statistic. Using tables for the F distribution it is possible to determine the significant of each individual factor.

2.4 Developments in the *Self Pierce* Riveting Process

2.4.1 Joint Quality Monitoring

The growing importance of the *self pierce* riveting process, in the demanding automotive manufacturing environment, was discussed in **1.4.1.** Driven primarily by *quality* demands, a means of assuring joint integrity on a 100% basis was required. Although visual examination can give a good indication of joint quality, a means of generating 'in process' data as an analogy to quality had to be found. Research at the University of Paderborn during the late 1980's, lead to the development of process monitoring equipment. By utilising measurements of applied force, simultaneously with the measurement of displacement, a graphical picture of 'in process' behaviour can be produced. A typical example of the form of such a curve is shown in fig 2.15. In personal communications with Lappe and Prof Budde at the University of Paderborn, it had been determined that of the three possible parameters that could be practically measured during joint formation, those of Time, Displacement and Force, that Force and Displacement gave the better analogy to a quality characteristic. Illustrations of such a characteristic in relation to the stages of the joining process are given in Budde et.al (1992).

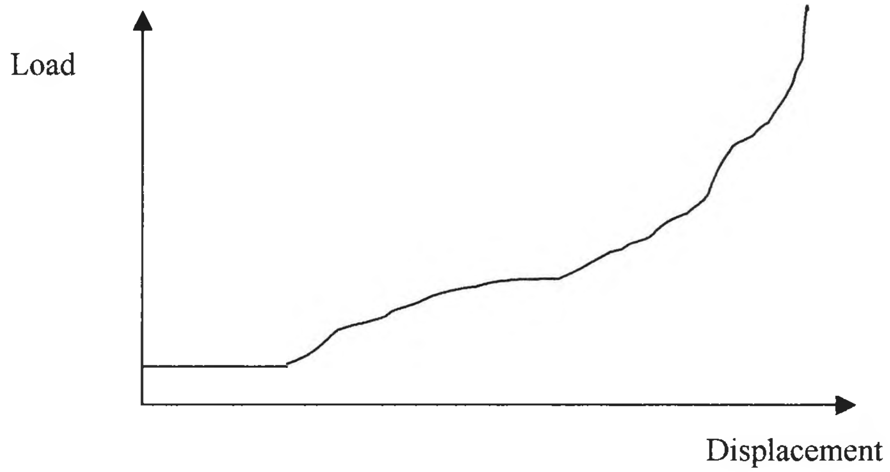


Fig 2.15 Typical Load v Displacement Curve for the *Self pierce* Riveting Process

A very detailed analysis of the statistical validity of using Force and Displacement monitoring, as a repeatable measure of joint quality, is made by King et.al (1996a). Natural variations in the rivet, material being joined and the equipment carrying out the process, will all have an influence on the shape of characteristic curves generated. Determining the spread of many such repeated curves, will determine if the process is in a state of statistical control. King et.al (1996a) applied standard control charting techniques to sets of results, recorded from the setting of 100 rivets, in 20 sub-groups, under identical joint conditions. Working on the basis that control limits are placed at ± 3 standard deviations from the central value, then it can be stated that the process is in a state of control if all the sub-group averages lie within the control limits calculated. Within the scope of experimentation carried out by King, it is clear that the process is statistically in control and valid representations regarding joint quality can be made through the interpretation of Load v Displacement curves. Fig 2.16 shows the complete process monitoring system, consisting of the riveting head incorporating the appropriate transducers, a signal interface unit, riveting control system and a PC to monitor and capture the generated curves. Further work by King et.al (1996b) goes on to explain that the actual deformation of the rivet during setting, accurately follows the characteristic of the Force v Displacement curve. Through detailed analysis of *micrographs* of sectioned joints, explanations are offered which account for the dimensional movement of materials into the rivet shank expansion.

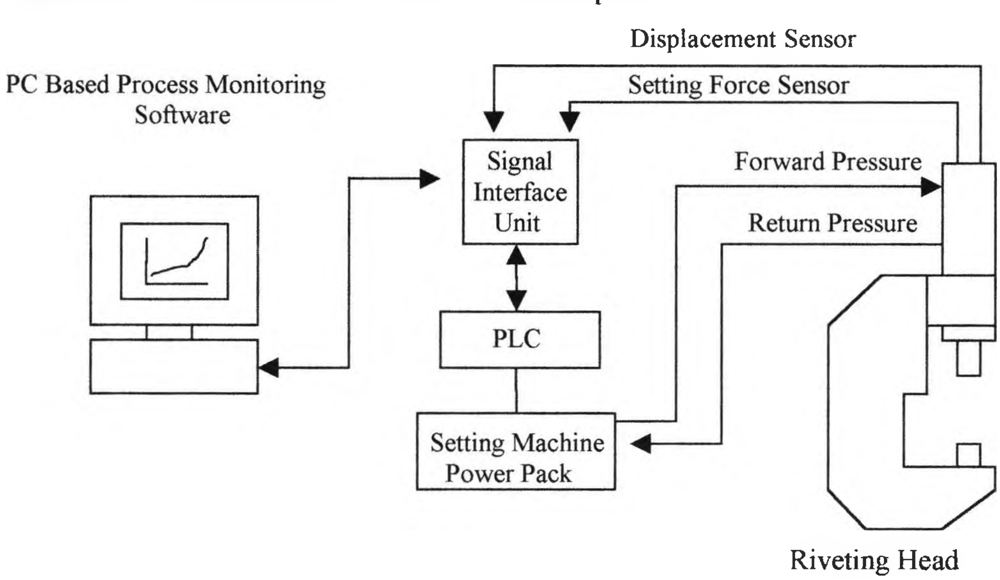


Fig 2.16 Process Monitoring System (King et. al 1996a)

Although intended as a quality-monitoring tool for production purposes, the process monitoring system can also be used in the further development of the riveted joint. From characteristic curves taken during joint formation, a direct means of comparison can be made at all stages of the process. Through interpretation of the characteristic shapes, there is great scope to study and understand the effects of parameter changes upon final joint performance.

2.4.2 Plasticity Analysis of Joint Formation

Plasticity analysis is concerned with the behaviour of materials at strains where Hooke's law is no longer valid. Unlike elastic deformation, plastic deformation is not a reversible process nor can stress and strain be related by Young's modulus. Processes that inherently involve plastic deformation can therefore be difficult to analyse by simple calculations.

The *self pierce* riveting process is one such case, where plastic deformation of both the rivet and the material being joined are what creates a mechanical joint. Elasticity will still however play a part in generating the tightness between components through the effect of *strain energy,* as stated by Hill (1994)

> The final magnitude of the permanent clamping force between components, is a function of the permanent deformation of the rivet, against the strain energy induced in the joint material, within the elastic limit.

A full mathematical analysis/simulation of the *self pierce* riveting process would therefore be a particularly difficult operation, unless with the aid of specialist software. Approximate methods of calculation may still however yield valid results for part of the process and at the very least, give a clearer understanding of the mechanics of joint formation.

The force required to cause the rivet to pierce the joint material is of particular interest when evaluating the rivet end geometry, i.e the relationship of *poke* diameter to *shank* diameter. As a means of approximately calculating such loads a method known as ***load bounding*** or ***limit analysis*** may be applied.

Two values for the load can be established, one which is certainly an over estimate (upper bound) and one which is certainly an under estimate (lower bound). Such bounds can be calculated by theorems stated by Drucker et.al (1951) in terms of the elastic-perfectly plastic material, or by Hill (1950) in terms of the rigid-perfectly plastic material. In both cases Tresca's yield criterion of constant maximum shearing stress during plastic deformation is assumed. In determination of the upper bound for plain strain applications, the theory is developed on the basis that an element of rigid material, travelling at unit velocity, encounters an assumed line of discontinuity. In crossing this line, a distortion of the element takes place along with a change in velocity and a subsequent dissipation of energy. Johnson & Mellor (1983) express this in the form:

$$\frac{dw}{dt} = K.\, u_{xx}\, s \qquad \textbf{(2.5)}$$

where K = yield shear stress

u_{xx} = Velocity change parallel to line x-x

s = length of discontinuity line x-x

2.4.2 (a) Simple Indentation Theory

A crude approximation to the piercing action of a *self pierce* rivet is that of indentation carried out by a circular punch. Shield & Drucker (1953) and Levin (1955) both offer complex theorems relating to punches of various shapes, typical of what would be found in many metal forming industries. Johnson & Mellor (1983) on the other hand give a simple example relating to a plain flat frictionless punch, in this case piercing a semi-infinite material.

At yielding, material directly under the punch will tend to move downwards and outwards, being pushed up against the outside edge of the punch. This is represented by an assumed field of lines of discontinuity, formed as a series of equilateral triangular blocks (fig 2.17).

With the punch moving down at unit speed, a hodograph can be drawn to represent vector quantities in the velocity plane (fig 2.17) and the upper bound for the yield point pressure is given by adding together the $k.u_{xx}.s$ terms for each of the five lines.

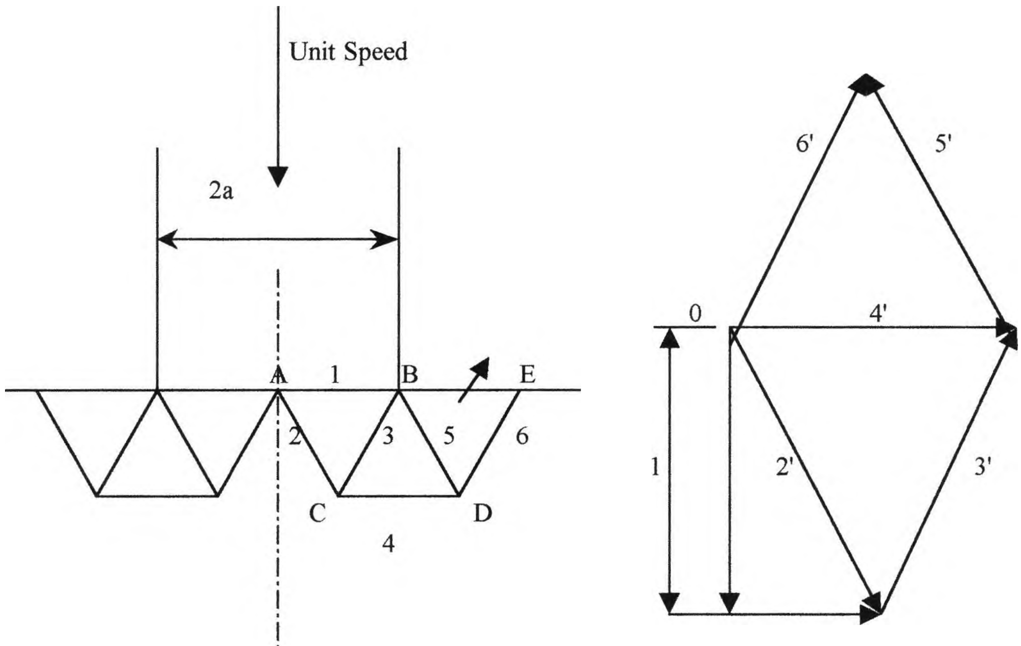


Fig 2.17 Simple indentation, Flow Diagram and Hodograph (Johnson & Mellor 1983)

Equation **2.5** can be expressed as:

External Energy = Internal Energy

Which when applied to a punch of area 'a', yields the equation:

$$P.1.a = K. \sum u_{xx.}\, s_{xx} \qquad \textbf{(2.6)}$$

Where P = Applied pressure

1 = Unit velocity

For the Hodograph above, **2.6** becomes:

$$P.1.a = K[\, AC.\, u_{AC} + BC.\, u_{BC} + CD.\, u_{CD} + BD.\, u_{BD} + DE.u_{DE}\,]$$

Thus $P.1.a = 10a.K/\sqrt{3}$

or $P/2K = 2.89$ **(2.7)**

Johnson & Mellor (1983) give an alternative selection of equal isosceles triangles for the flow diagram, this yields a maximum value for the upper bound estimate of:

$P/2K = 3$ **(2.8)**

2.4.2 (b) Indentation by the *Self Pierce* Rivet

As shown in **1.4.1** the shank of the rivet is effectively hollow at the point where initial piercing of the joint material takes place. In order to investigate how the material actually flows during piercing, it has been possible to stop the process the instant it begins. With samples of less than 1mm of rivet penetration, it can be seen that material flow is actually towards the hollow rivet centre rather than towards the outside, as in the case of the flat punch. The flow diagram drawn in fig 2.18 represents this condition.

Drawing the flow diagram for half the rivet section, only this time with the slip planes drawn at an angle of 45^0 to the material surface, yields the hodograph shown in fig 2.19. As for the flat punch, the upper bound for the *yield point* pressure can be expressed in the form of work carried out at each line of discontinuity. Where force (F) is substituted for pressure across the rivet half section, an equation can be derived from:

$$\text{External Work} = \text{Internal Work}$$

$$F/2 \times 1 = K[\,A/G + B/G + C/G + A/B + B/C]$$

$$F/2 \times 1 = K[\,(a/\surd 2)\surd 2 + a \times 2 + (a/\surd 2)\surd 2 + (a/\surd 2)\surd 2 + (a/\surd 2)\surd 2\,]$$

which reduces down to give.

$$F/2 = 6aK$$

Where $P = F/2a$, above equation becomes, $P = 6K$

Which can be expressed in the form $P/2K = 3$, which is identical to equation **(2.8)**.

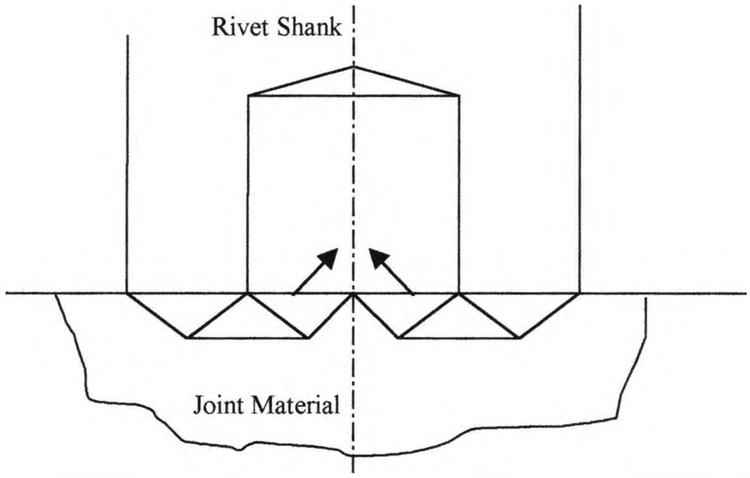


Fig 2.18 Material Flow when Pierced by a Hollow Rivet

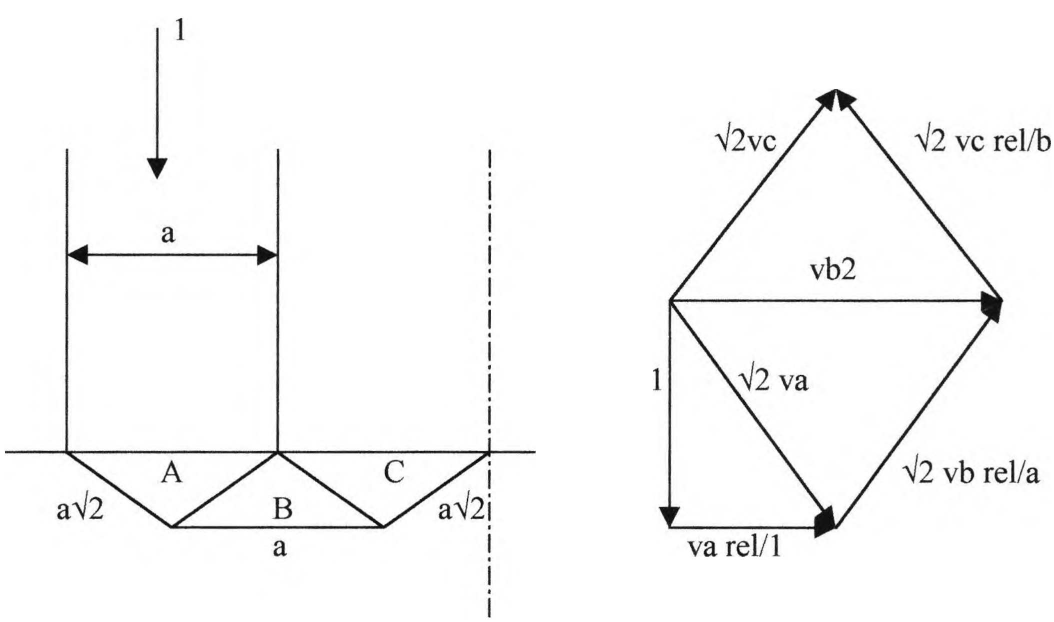


Fig 2.19 Slip Planes and Hodograph for a *Self Pierce* Rivet

2.4.2 (c) Proof of Upper Bound Values for *Self Pierce* Indentation

As a result of research carried out by King et. al (1996a), which is discussed in **2.4.1,** it is possible to collect accurate data regarding joint formation in the form of Load v Displacement curves. By studying the shape of many such curves, it can be seen that distinct phases of the process are repeatable under the same conditions of rivet and joint material. For example, fig 2.20 shows the typical shape of curves produced when joining an aluminium alloy material. At the point where the rivet contacts the joint material, a rapid increase in load first takes place, normally over a displacement of 1mm. This first stage of the process accounts for bringing the joint materials into tight contact whilst taking up any 'slackness' in the system, ending at the point where plastic indentation of the material begins. A distinct feature of joints in aluminium alloys is the very flat nature of the piercing stage as can be seen in fig 2.20. Maintaining such a constant load up to the rivet clenching stage, implies that no deformation of the rivet has taken place and that there is no additional resistance build up due to friction or obstruction. As clenching takes place, both the rivet and joint material are forced outwards under the influence of the anvil (see 1.4.1), generating a rapid increase in load of up to 40kN.

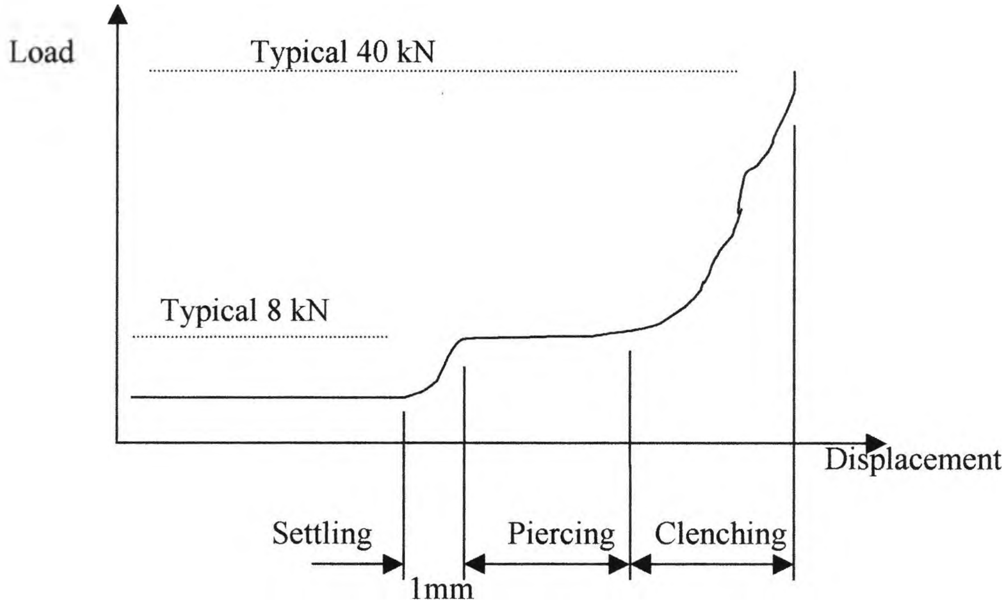


Fig 2.20 Load v Displacement Curve for Aluminium Alloy (type 5251-H3)

When considering the validity of the upper bound equation derived in **2.4.2 (b)**, we are only concerned with initial piercing stage of the process. For the data shown in fig 2.20, a rivet with a shank diameter of 4.8mm and a poke diameter of 2.7 mm was used. This gives a resulting indentation area of $1.25.\ 10^{-5}$ m^2 under an applied load of 8kN, hence applied pressure becomes $P = 645$ MN/m^2.

Working from equation **(2.8)**, where for type 5251 aluminium alloy, $K = 132$ MN/m^2, P can be determined as:

$P/2K = 3$ therefore $P = 6K = 792MN/m^2$.

The analysis therefore gives a predicted upper bound of 792 MN/m^2 against an actual figure of 645 MN/m^2. Although this represents almost a 20% error, for a deliberate and approximate over pressure prediction, it is considered to be within the bounds of acceptability.

Other curves produced for joints in aluminium alloy, only with different material thickness, show identical shapes to fig 2.20. The only difference being that the piercing stage changes in length with the thickness change.

A similar validation of equation **(2.8)** can be carried out for joints made in steel material. Again, as for aluminium alloy material joints, a range of highly repeatable Load v Displacement curves could be produced giving typical shapes as shown in fig 2.21. Unlike with aluminium alloy, the applied load continues increasing over the majority of the piercing region followed by some relaxation prior to entering the clenching region. In this case, the rivet experiences a build up of resistance, possibly due to strain hardening of the joint material and increased frictional effects. For predicting the point at which plastic indentation begins, there is no clearly recognisable characteristic on the curve that can be used, it is therefore necessary to take a load at 1mm displacement from initial rivet contact. At the end of such a settling period a typical value of 7kN is obtained which equates to an applied pressure of $P = 560$ MN/m^2.

Working from equation **(2.8)**, where for CR4 grade sheet steel, the effective shear yield stress is $K = 98$ MN/m^2, P can be determined as:

$P/2K = 3$ therefore $P = 6K = 588$ MN/m^2

The analysis therefore gives a calculated upper bound of 588 MN/m^2 against an actual figure of 560 MN/m^2. This represents a very close prediction for initial material indentation.

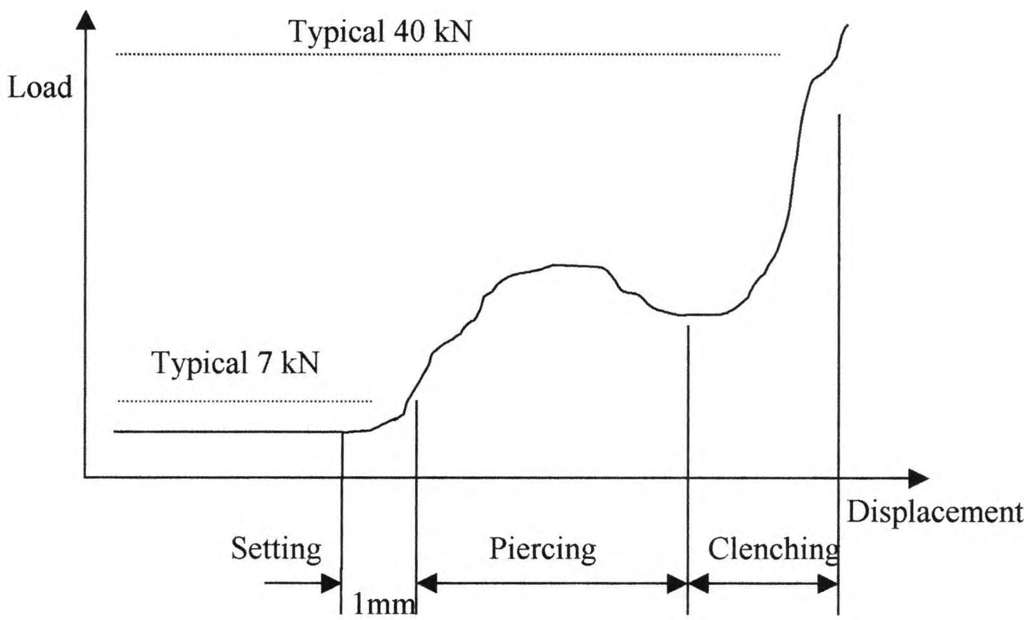


Fig 2.21 Load v Displacement Curve for Steel (type CR4)

From the above examples, it can be concluded that limit analysis represents a valid method for calculating the likely force required to initially pierce a joint material. Although only representing a small part of the process, it does offer a quick and simple method for comparing the performance of different rivet shank end configurations.

2.4.3 Further Process Modelling

Modelling of the entire *self pierce* riveting process requires a complex analysis method which can deal with plastic deformation, material break-through, elasticity and frictional characteristics. Computer simulation using specialised software offers the only practical possibility for conducting such an analysis. Research by Budde & Klasfauseweh (1990) discusses the creation of a 'finite element' model for a simple punch and die system. Although simulating a penetration process, there were no cutting elements involved, a vital feature when considering the *self pierce* riveting process. More recent research by King (1997) Utilises a software package called DEFORM™, which is described in detail by Wu et. al (1996) and Tang et. al (1994). King (1997) created a model structure of the process to include five elements of tooling, rivet and material represented in a two-dimensional form. The finite element mesh was made up of four-node quadratic elements, 400 and 2000 in total for the rivet and joint material respectively. Calculation within the model used Newton-Raphson iterative procedures to determine nodal forces and displacements at each step of the process. Unfortunately the system allowed only the first 22% of the process to be simulated before the limitations of the software were reached. When considering that DEFORM™ is designed to simulate plastic flow, this result is not surprising. In order to simulate the *self pierce* riveting process, the vital break-through effect of piercing the top layer of material must be present. It is understood however that the producers of DEFORM™ [Scientific Forming Technologies Corporation], are further developing the software to allow the modelling of such phenomenon, which should, eventually, allow a more comprehensive simulation of the *self pierce* riveting process to be performed.

When considering the strength aspect of *self pierce* riveted joints, a great deal of shear, tensile and 'push out' data has been generated by King et. al (1995). This provides useful information for predicting the likely strength of joint to be achieved under similar conditions, but only by crude interpolation. Alternatively Gao & Budde (1994) propose the use of 'contact chains' to help describe and calculate likely joint strength under any set of conditions. The intention of such an approach, is to give engineers a designing tool for predicting final joint performance when changing joint parameters.

To establish a joint using a network of contact chains, several criteria must be satisfied.

1. A joint element consists of several contact chains to restrict all six degrees of freedom.
2. The chain has a certain strength to undergo the external loads.
3. The restriction of the degrees of freedom is achieved by arranging the chains.
4. The network should spatially represent the structure of a joint element in a simple way.

The use of such chains is described by Gao and Budde (1998), in the calculation of Tensile failure, Bearing failure, Bending-out failure, Peel-out failure and Top draw-out failure. After calculating the failure load under each individual condition, overall joint strength can be determined through the combinations of failure loads within the contact chain.

2.5 Matrices, Applications in Design Case Studies

2.5.1 Design of a Flexible Manufacturing Cell

This case study was created as a result of research conducted by Comincini (1993) and represents an early example of the usage of Design Function Deployment (DFD).

The main target of the project was to design a generic form of Flexible Manufacturing Cell (FMC), which would answer the global needs of a whole range of diverse, sub-contract machining industries. Through the recording of a vast amount of How and What functions, the DFD charts gave rise to the possibilities of exploring an extended standardisation process of elements throughout the machine components. Such a large and visible database of information allowed rapid and efficient access by a much larger interest group than would normally be possible. Promoting a modular design approach, DFD aided the development of a rational design, with the correct dimensioning of all elements, whilst addressing the preference for 'Make' or 'Buy' of components/elements.

Comincin (1993) reviews the advantages of using DFD as follows:

1. DFD translates the customers language, intended as the accumulation of direct or indirect requirements, and structures the necessary analysis in an accessible way.
2. DFD records the product life from the very beginning of its life cycle. All information can be efficiently retrieved providing a reliable base for further developments or modifications based on full knowledge of past experiences.
3. The correct use of DFD allows the possibility to suitably meet all the legal aspects of 'product liability'.
4. The discovery of 'correlation chains', (see 2.1.4 (a)) provides a very effective way to evaluate design changes or modifications without missing any of the design interactions.

Although dealing with a mature product, Comincini was able to produce a design concept, resulting in an FMC which satisfied the original customer specification. Concluding with the belief that there are three starting points in the design process;

(i) Customer requirements
(ii) Manufacturing constraints
(iii) Availability of existing or ready made components, generating the 'make or buy' policy.

DFD is stated to have provided a formal method to link all of these requirements, together with the designer's experience and professional judgement.

2.5.2 Design of a *Self-Pierce* Riveting Gun

Although this case study is concerned with developing a new product to replace an older existing model, the design process was applied solely on the basis of satisfying identified customer needs. In other words a new product development approach was taken. Driven by growing market demands (see 1.4.1), the customer focused framework of DFD was used as the vehicle for a systematic design approach, the main detail of which is laid out in Appendix A.

Application of the matrices, at different stages of the design process, was performed primarily to the procedures laid down by Jebb et. al (1993) and discussed in 2.1.1. Through life cycle modelling and the introduction of customer representative teams, it was possible to formulate a clear and quantified, 'customer orientated' product specification at stage 1. A format for presenting such data was devised as shown in fig A.5, accommodating importance ratings, target values and the facility for comments and observations relating to any interactions. Building on such an 'accessible' knowledge base, potential concept solutions could be targeted at the requirements of greatest importance to the customer. A stage 2 analysis permitted the generation of a descriptive and prioritised specification of potential design solutions.

In using multiple stages in the design process, the danger is that the extent of information may grow progressively at each stage, to the point where it becomes impossible to handle. To alleviate this situation, an intermediate step was added after stage 2 as a means of 'focusing in' more clearly on the best alternative design solutions (sub-system characteristics).

'On the board' design could then take place, guided closely by the quantified data generated at stages 1 and 2. Resulting 'parts characteristics' were subsequently evaluated using a stage 3 analysis which lead to the manufacture of two prototype units.

Overall the new product developed became a great success, selling into diverse and demanding fastening environments around the world. The application of matrices within the DFD approach was certainly a major factor in the final product outcome. By focusing and driving the design process at each stage, the possibility of jumping immediately to a less than optimum solution was avoided.

This case study has shown the successful use of matrices for the design of a relatively small product (less than £10,000). Even on this small scale however, the danger of experiencing an 'explosion of Information' is very real if not tightly controlled. For larger projects in particular, computer recording and processing of data would be essential for data control.

2.6 Summary of Literature Review

Matrices have been applied successfully over a number of years, in both the context of QFD and DFD methodologies. They can be viewed as design systems in their own right, or as an intrinsic part of a more comprehensive methodology. Acting primarily as an evaluation tool, they have been shown to hold a pivotal role in relation to 'Robust Design', 'Experimental Methods' and 'Design for Cost'. In relation to the *self pierce* riveting process, greater understanding of the process mechanics have been gained, providing a strong basis on which to develop new and improved products.

Chapter Three

Self Pierce Riveting Process Development with Matrices

In **1.4.1,** it was established that the *self-pierce* riveting process (as supplied by Aylesbury Automation) has an enormous potential, particularly in the automotive sector, to become a primary fastening method, largely in place of 'spot welding'. To further the work of King (1995) and Hill (1994), improvements must be made to the actual process performance if its full potential is to be realised. Design action must therefore be taken, which will yield a product capable of satisfying as fully as possible, all identified customer needs.

The case studies shown in **2.5.1** and **2.5.2**, demonstrate the use and adaptation of QFD matrices in the design of Engineering products. When considering the design of an active process, a systematic approach may be developed, which is capable of evaluating varied performance criterion, in the establishment of *robust* parameter designs and settings. For the *self pierce* riveting process, a means of economically homing in on the best factor combination of both rivet and tooling (anvil) parameter settings is required. With likely performance criterion of energy usage, joint strength, dimensional measures and visual evaluation being involved, a design system must be developed which can assimilate such varied criterion into a collective measure of overall process performance.

3.1 Developing a Process Design Specification

<u>3.1.1 Customer Identification and Life Cycle Modelling</u>

The customer, as in the potential purchaser of a piece of equipment or process, is the driving force behind generating that product need. Understanding the 'voice' of such customers therefore gives the 'direction' in which a product must develop. When considering inputs to the design process, the term customer need not be restricted to purely the purchaser. All those who have contact with the product, throughout its entire life cycle, can also be termed customers. It therefore follows, that the scope of all customers embraces both the traditional role of the purchaser, accompanied by all of those involved in the product through design, manufacture, use, maintenance to its eventual disposal. The nature of the product under analysis will further determine the definition of all customers.

As discussed in **1.3.1,** products can be segregated under different groups and classifications. Utilising the approach of Finkelstein & Finkelstein (1991), for this project, we are particularly interested in products in terms of their origins and use which provides for three classifications, namely; *Primary, Intermediate* and *Final.* Also it is possible to classify products in terms of their endurance, either *Consumable* or *Durable.*

For the *Self-Pierce Riveting* process, such a product can be interpreted as being both *Intermediate* and *Durable,* whilst incorporating a *Consumable* element. This allows the identification and definition of all appropriate customers with reference to the full product life cycle. Table 3.1 shows seven identified customers, with a description of each activity, from which a model describing the full-predicted product life cycle can be formulated, (fig 3.1). For this model, three distinct groups of activity combine to describe the life cycles of the placing equipment, fastener and the final product (host) of which it becomes a part. The requirement for the process initiates activity for both the fastener and delivery equipment (riveting gun), with interrelationships occurring between the two. Likewise at the design stage, both equipment and fastener have to be considered in combination.

No	CUSTOMER	ACTIVITY
1	Purchasing Organisation (process specifier)	Identify a need for the process within their product and organisation resulting in integration into the production process.
2	Purchasing Organisation/Individual (end product user)	Use the product into which the process has become absorbed.
3	Process User	Carry out the actual function of integration into the host
4	Quality Assurance	Responsible for monitoring the strength integrity of the host as a function of the process.
5	Manufacture	Manufacture of consumable element and all associated support equipment.
6	Supplying Organisation	Provide the company environment intended to profit from the sale of process/consumable.
7	Legal/Professional Organisations	Set standards and enforcement of legislation.

Table 3.1 *Self-Pierce* Riveting Process Customer Identification

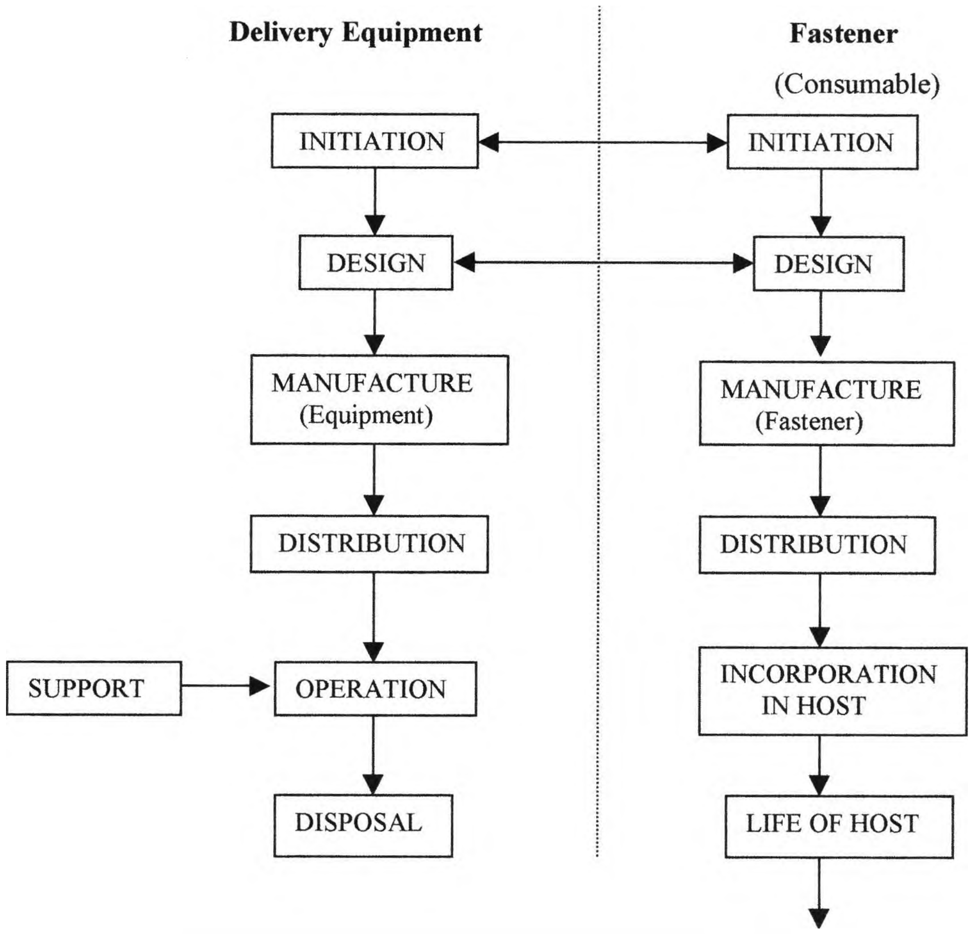


Fig 3.1 Life Cycle Model for the *Self Pierce* Riveting Process

3.1.2 Customer Requirements Analysis

Design Function Deployment (DFD) as discussed in **2.1.1,** utilises the QFD matrix structure at stage one, to establish and evaluate all identified customer requirements. Although a number of examples of the DFD methodology being used for product development are available (see Comincini 1994, Hill 1994, Atherton 1997 and Shahin et. al 1998), for an active process, DFD is still unproved. It will therefore be necessary, to adapt and build the methodology, along with the *self-pierce* riveting process, to suit the needs of process development at each and every stage.

Having identified all customers associated with the *self pierce* fastening process (table 3.1), the task of establishing their true requirements has next to be performed. This information has to be in the form of simple none solution specific statements of need from each customers own perspective. Information was gathered from all appropriate sources aided by means of pre-emptive questionnaires (see Appendix B), giving a few initial-provoking ideas to stimulate the process of identifying new requirements. As a further action, each respective customer also made a subjective assessment of order of priority, to help in the eventual production of a 'quality plan'. Table 3.2 shows a small extract from the requirements listing.

CUSTOMER	No	CUSTOMER REQUIREMENTS	ORDER
Purchasing organisation	1	Short delivery	13
	2	Consistent parts quality	3
	3	Quantifiable joint performance	2
Process user	21	Easy to apply	1
	22	Perform reliably	2

Table 3.2 Extract from Customer Requirements Listing

Having obtained a comprehensive listing of raw customer requirements the next stage was to clarify them through a process of classification into three categories namely; primary, secondary and tertiary. The primary requirements were selected as the broad overall needs when considering the three major categories of activity of; consumable, process and host performance as identified by the product life cycle model. Within each primary grouping, secondary categories were formed to describe more closely the type of detailed customer requirements established which, themselves were clarified in the form of the tertiary requirements.

Table 3.3 shows an extract of this break down process, for this example, within a single, primary requirement category.

PRIMARY	SECONDARY	TERTIARY
1. Joint Creation	1.1 Performance	1.1.1 Tight component clamping
		1.1.2 Minimal residual distortion
		1.1.3 Joint thickness tolerant
	1.2 Application	1.2.1 Easy to carry out
		1.2.2 Operate reliably
		1.2.3 Rapid process
		1.2.4 Join pre-coated materials
	1.3 Acquisition (fastener)	1.3.1 Rapid delivery on demand
		1.3.2 Low cost per joint

Table 3.3 Extract from Classified Customer Requirements.

A numerical means of fully quantifying all tertiary customer requirements is presented by means of the quality plan. Following through the standard DFD procedure as described by Jebb et. al (1993), each requirement was first given a rating on a scale of 1 to 9 depending upon its respective value to its own customer source. Along side these were further added assessments of the current company standing in that area of customer satisfaction on the same measure of performance.

To formulate the actual plan, a value for a realistically obtainable 'quality target' was first assessed for each requirement. From this an improvement plan was calculated by dividing the target value by the current product performance. Assessments of Sales advantage, are recommended by Jebb et. al (1993) as the following index values, 1= no advantage, 1.2 = medium advantage and 1.5 = high advantage. A selected index value was placed alongside each requirement as a measure of its desirability to a prospective purchaser.

From this accumulated data, an overall quantified assessment of each requirement, could be made in the form of **Absolute Weight** ratings, calculated by the following equation:

Customer Rating x Improvement Plan x Sales Advantage = Absolute Rating (3.1)

From this **Relative weights** were normalised on a scale of 1 to 9.

Part of the complete Quality plan is shown in Table 3.4

PROCESS QUALITY PLAN								
Serial No	Tertiary Customer Requirements	Customer Rating	Current Rating	Plan			Weight	
				Quality Target	Improvmnt Plan	Sales Adv'	Absolute Weight	Relative Weight
1.1.1	Tight component clamping	5	3	5	1.67	1.5	12.5	6
1.1.2	Minimal residual distortion	5	3	5	1.67	1.5	12.5	6
1.1.3	Joint thickness tolerant	3	3	3	1.00	1.2	3.6	2
1.1.4	Joint properties tolerant	3	3	4	1.33	1.2	4.8	2
1.1.5	Maximum joint strength	5	4	5	1.25	1.5	9.4	5

Table 3.4 Extract from Process Quality Plan

Taking each tertiary customer requirement in turn, the task of design function generation was next carried out to fully deploy all requirements into actionable solution neutral statements. Starting with the generation of a basic listing, design functions were classified themselves into groupings of Primary, Secondary and Tertiary. Under a single Primary requirement of the '*Self-pierce* riveting process', secondary groupings of fundamental activities such as 'Joint formation' were made. Into each secondary grouping could then be placed the Tertiary design functions to be analysed and evaluated by means of the main DFD 1 chart. Table 3.5 shows an example of the classified design function listing.

PRIMARY	SECONDARY	TERTIARY
1. Self pierce riveting Process	1.1 Joint formation	1.1.1 Efficient piercing
		1.1.2 Minimal metal displacement
		1.1.3 Shank flair tenancy
	1.2 Fastener formation	1.2.1 Measurable rivet parameters
		1.2.2 Consistent rivet formation
		1.2.3 Consistent rivet properties
		1.2.4 Large batch manufacture

Table 3.5 Extract from Classified Design Functions Listing

Following the standard DFD chart format, classified customer requirements (whats) were loaded down the left-hand column, whilst classified design functions (hows) were loaded along the top row. The importance values for each customer requirement, as calculated in the quality plan, were also added to the chart. Relationships between 'Whats' and 'Hows' were identified and evaluated in the matrix as either:

1 - Weak, 3 - Medium, 9 - Strong

From this, the importance ratings for each design function could be calculated, as the column sum of the product of the relationship value and customer requirements importance ratings. For the interactions between design functions, where such relationships were identified, a value was given at the intersection point in the 'roof" of the chart as:

+2 = Strong Positive, +1 = Positive, -1 = Negative, -2 = Strong Negative

Normalising the importance ratings on scale of 1 to 9 completed the DFD 1 chart, which is shown fully in Appendix B.

Having completed the DFD 1 analysis, information generated up to this point can best be summarised by means of a 'process requirements' specification. A detailed document can therefore be produced which gives a numerical importance weight to each design function along with notes explaining the consequences of any interactions and any other information gathered during the process. Table 3.6 shows an extract from the full specification, in this case showing three design functions of equal importance along with any relevant comments. Full copies of this specification and all other charts generated during the DFD stage one process are given in Appendix B.

DESIGN FUNCTIONS	WEIGHT	COMMENTS AND INTERACTIONS
1.4.1 Robust rivet parameters 1.4.3 Robust to material fluctuations 1.4.4 Robust joint parameter relationships	9	Highest importance factor - Confirms known weakness of process generally lacking in overall robustness, this includes the effects of rivet parameters in terms of shape, size and properties, also the effects of the fluctuations of size and properties of the material into which the joint is being formed. In addition the effects of each parameter on each other needs to have a robust relationship. Application of *Robust design* to the process is to be a key requirement of this project. All functions of robustness have a positive interaction relationship and as such should be considered together as a single requirement.................

Table 3.6 Extract from DFD 1 Process Requirements Specification

3.1.3 Process Concept Modelling and Analysis

Before proceeding to the second stage of the DFD methodology, it was considered necessary to fully evaluate many of the features and parameters of the *self-pierce* riveting process as known from previous experiences. Beginning with the identification of the major types of parameters and their sources, the joint formation is primarily a result of the following three components;

1. Rivet 2. Joint Material 3. Anvil Profile

And for each of these components, a number of parameters can be identified. Fig 3.2 shows a listing of 16 such parameters in relation to the static elements of the process. Dynamic effects of placing equipment performance can also be built into the study.

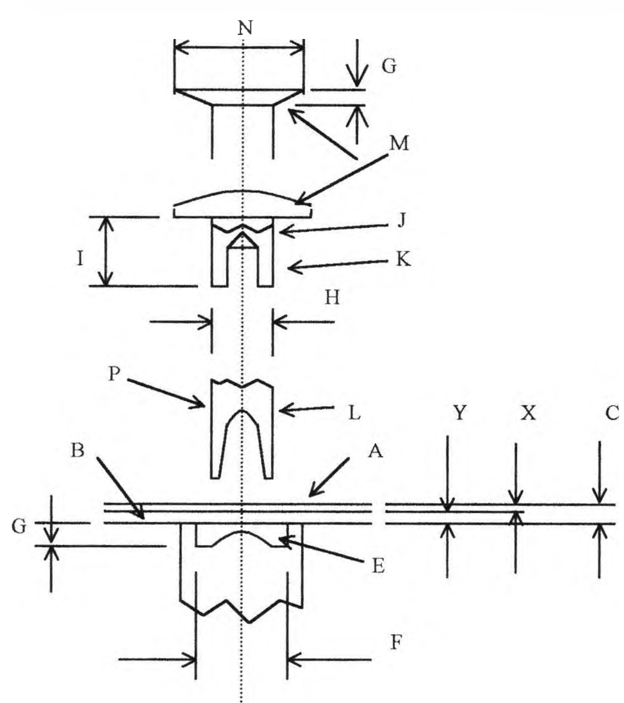
By means of the *Cause and Effect* diagram, fig 3.3, both primary, static and dynamic parameter are brought together, added to which are assessments of dimensional limit. These are the causes, but to quantify the effect, the only measure of performance available is ultimately the overall quality of the final joint produced.

Considering next how this final effect can be quantified, several factors go in to constituting what is a good joint.

First and most important is strength. By means of conducting standard tests, particularly under shear and tensile loading, direct measures of performance can be made. Furthermore, as a result of research carried out by King (1997), a good deal of standard test data exists against which useful comparisons can be made.

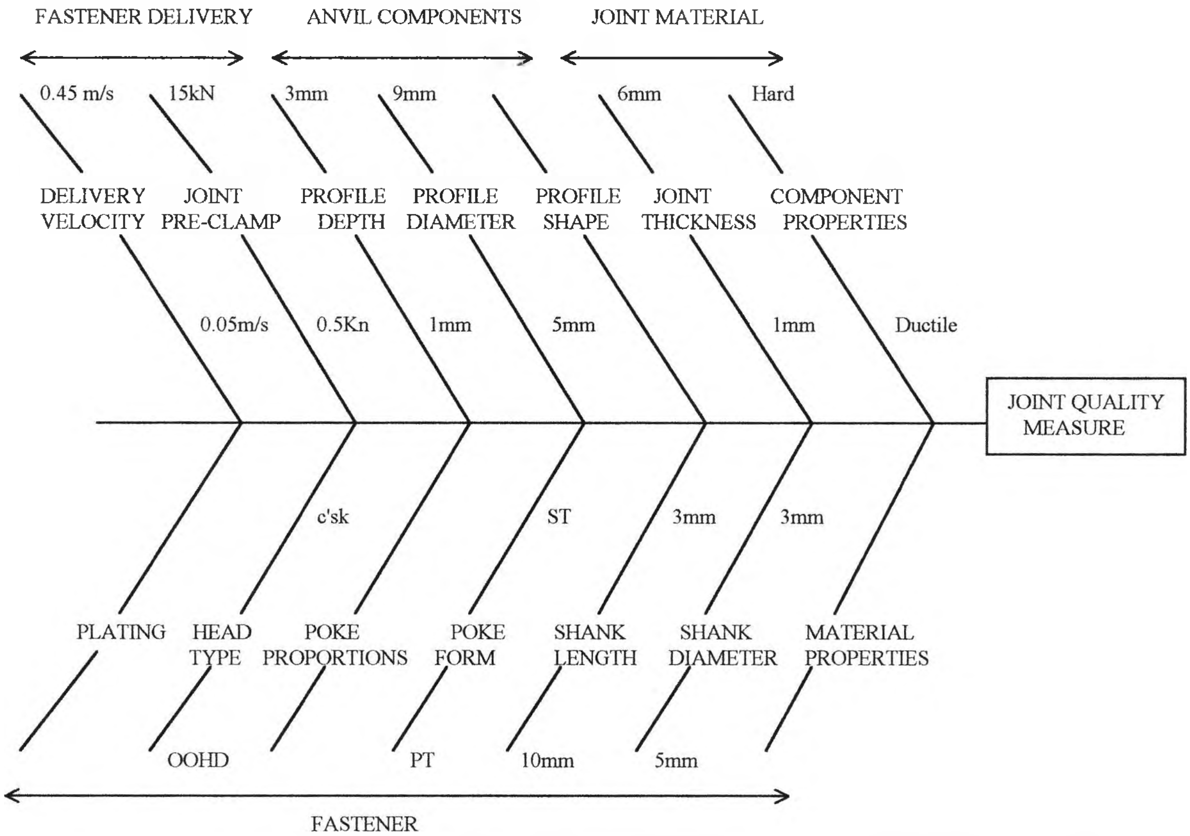
Secondly, factors of joint appearance, which cannot be directly given a numerical evaluation, must be considered. These include; the condition of the 'clench' part of the joint i.e smooth with no cracking, shank expansion (flaring) ideally targeted as 1.5 x the rivet shank diameter and the head being down in tight contact with the top joint surface. Fig 3.4 shows such features of a successful joint.

It therefore becomes clear, that to evaluate a *self-pierce* riveted joint performance fully, a method must be found to produce an overall joint **Quality Measure.**



A. COMPONENT MATERIAL PROPERTIES
B. COMPONENT MATERIAL COMBINATIONS
C. JOINT THICKNESS
D. JOINT THICKNESS RATIO (X:Y)
E. ANVIL PROFILE SHAPE
F. ANVIL PROFILE DIAMETER
G. ANVIL PROFILE DEPTH
H. FASTENER SHANK DIAMETER
I. FASTENER SHANK LENGTH
J. FASTENER MATERIAL PROPERTIES
K. FASTENER POKE FORM
L. FASTENER POKE PROPORTIONS
M. FASTENER HEAD FORM
N. FASTENER HEAD DIAMETER
O. FASTENER HEAD THICKNESS C'SK ONLY
P. FASTENER SURFACE PROPERTIES

Fig 3.2 Joint Process Parameters - Static



Where PT = Punched tubular, ST = Semi- tubular, OOHD = Ordinary oval head

Fig 3.3 Primary Cause and Effect Diagram

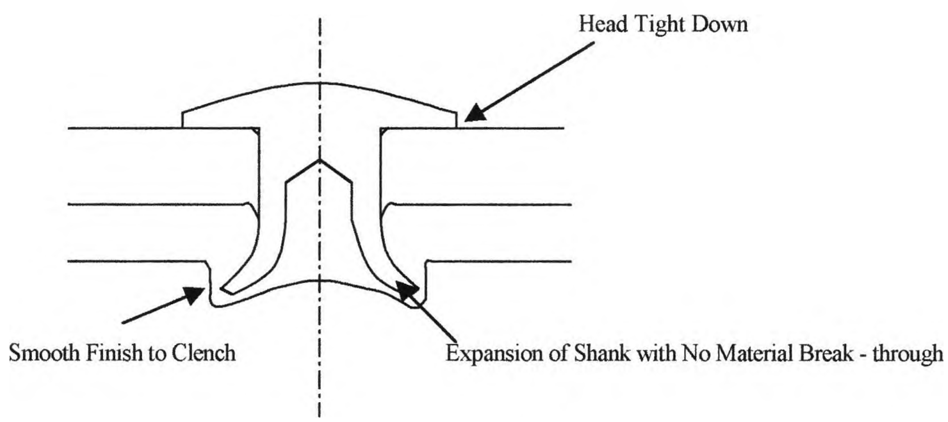


Fig 3.4 Joint Appearance Factors

3.1.4 Process Parameter Evaluation

The sources from which all potential process parameters can be derived, have now been identified as follows:

1. Process Specification (DFD1)
2. Process Concept Models
3. Cause and Effect Analysis

The Process specification (DFD1), consists of an engineering interpretation of all true customer needs, retained in solution neutral form and being numerically prioritised.

Process concept models attempt to explore, in an illustrative manner, the parameters and relationships, which go into the active process. By means of the cause and effect analysis, those parameters, which are influential in achieving the desired performance response, are identified along with their targeted maximum and minimum values.

Following the conventional DFD methodology, the next phase of the process would now be to take each of the specification items from the DFD1 stage in turn, and where appropriate, propose potential *solutions* or *architectures* to satisfy that requirement. In dealing with an existing process however, a good deal of basic information regarding aspects of the primary elements of the process can in effect be drawn upon from an existing knowledge base. This allows us to identify immediately many of the more important parameters by simply brainstorming them out within the company and clarifying them by means of the cause and effect diagram. The required objective function for these actions being to achieve a desired standard of *Joint performance specification.*

Considering the actual DFD stage1 specification items, the highest rated of these related, for the main part, to the need to incorporate *Robustness* into all the major parameters of rivet, anvil and joint material. Since most components of the process are subject to variability of one type or another (i.e material properties fluctuation, dimensional tolerance etc) and hence could be categorised as noise parameters, the need for *Robustness* in the context of tolerance against variation becomes self evident. Identifying those parameters, which are most critical to process performance, must therefore be achieved. This allows a concentration of design effort on selected parameters, with the objective of moving the product away from such critical regions whilst either retaining or improving on the objective function of *joint performance.*

In progressing to the second stage of the DFD methodology, following the standard procedure would result in the generation of new architectures or concepts, to be evaluated against the established DFD stage 1 specification. For developing the *self-pierce* riveting process, within the confines of the generic form of the rivet, it became apparent that design would be best targeted at specific regions of the process which themselves could be evaluated by the DFD process. This allows us to retain the largest possible potential solution space for proposing alternative details of process features at the next stage.

Under each primary element of the process, generic regions, which describe broadly the parameters identified in the process modelling, are listed in table 3.7. A further classification was added to describe the nature of each items variability. All those regions relating to the rivet manufacture have been classified as *Fixed/ Tolerance variables,* this takes into account both existing job knowledge regarding the criticality of their parameters, along with the tolerance capabilities of what is, in effect, a cold forging process. Classifications of *Fixed variables,* consider the normal tolerance variability to not be significantly influential on process performance. *External constraints* are for those parameters set by specification items of the process, dictated (within limits) by the process customer.

Evaluation of these identified generic regions was next carried out by means of the QFD matrix, in what would equate to DFD stage 2. Information is loaded onto the chart, starting with stage 1 specification items 'what's', along with their relative importance ratings going into the left hand column, and the generic regions for evaluation into the top row. Calculations performed in the relationship matrix, using the same procedure as for stage 1, yielded both absolute and relative importance weightings for each region of the process. It was considered impractical to complete the interactions, (roof) part of the matrix, since evaluating such complex interrelationships, would be beyond the scope of well informed judgement. Opportunity for analysis of function interactions will become possible through the application of controlled experimentation as described in **1.2.4.**

As with stage 1 DFD, a detailed specification was produced describing the analysis results along with any additional comments. Table 3.8 gives an extract from the full specification, which is given in Appendix B along with the full second stage DFD chart.

PROCESS ELEMENT	GENERIC REGION	CLASSIFICATION
1. Fastener	1.1 Shank proportions	Fixed/Tolerance variable
	1.2 Poke features	"
	1.3 Poke proportions	"
	1.4 Head features	"
	1.5 Material properties	"
	1.6 Surface properties	Fixed variable
2. Tooling components	2.1 Anvil profile features	Fixed variable
	2.2 Anvil profile proportions	
	2.3 Delivery attitude	"
3. Machinery	3.1 Pre - clamp	Fixed variable
	3.2 Delivery velocity	"
4. Joint material	4.1 Material properties	External constraint
	4.2 Thickness range	"

Table 3.7 Process Generic Regions Identification

PROCESS FEATURES	WEIGHT	NOTES AND COMMENTS
2.1.2 Poke Features	9	Highest importance factor - Relates to the shape and form of the hole produced in the end of the rivet shank. Preliminary experiments with different forms have confirmed the highly influential nature of this feature in achieving joint quality. In proposing alternatives it will however be necessary to design around the limits of the cold forming process.

Table 3.8 Extract from DFD 2 Process Specification

3.2 Developing New Product Variants

3.2.1 Primary Rivet Features

Working from the DFD2 specification, the first stage was to consider the rivet in isolation, selecting those parameters, which were of a high weight rating and could be physically defined. Those selected are shown in table 3.9.

PROCESS FEATURE	WEIGHT
2.1.2 Poke features	9
2.1.5 Material properties	8
2.1.3 Poke proportions	6

Table 3.9 Rivet Features

The objective hence becomes the need to propose solutions, which represent the above process features, whilst satisfying the customer requirements determined in **3.1.2.**

Methods of concept generation as discussed in **1.1.5,** draw heavily on the fact that most new designs are in fact derivatives of existing concepts, developed through either synthesis or analogies. When proposing solutions at the fine level of detail, which has now been focused upon, the mental process of design should become much simpler. With the benefit of substantial product knowledge, linked with previously derived empirical data and a logical application of Engineering science principles, a range of alternative fastener features was proposed, table 3.10.

In order to evaluate the proposals a suitable *Quality measure* has first to be selected. From the analysis of joint formation conducted in **2.4.2,** and the subsequent conclusions arrived at by King (1997), regarding modelling the full riveting process, the process can be split into two distinct stages.

1. *Piercing*; where unconstrained plastic deformation of the joint material takes place yet the rivet does not deform. Calculations in this region are possible.
2. *Flaring*; where both joint material and rivet are distorting outwards under the

influence of the setting tool (anvil). Meaningful calculations in this region are currently not possible.

Since the fastening process consists essentially of the two stages of operation, *Piercing* and *Flaring*, optimisation of the performance of both these functions will be required. The problem exists however, that these two key functions are in a state of conflict with each other. For the *piercing* part of the process, the rivet is required to be hard and rigid, whereas for the *flaring* stage malleability is required. A method of analysis must therefore be found, which can harmonise such conflicts, whilst still responding to the broader issues of the *Quality Measure.* **3.2.1(a)** demonstrates the creation of such an approach.

	Alternative Fastener Features
1	Taper Poke
2	Poke Depth
3	Poke Diameter to Shank Diameter Ratio
4	Material Hardness
5	Land Width
6	Corner Effects
7	S.T Form Poke

Table 3.10 Proposed Fastener Features

3.2.1 (a) Conflict Analysis and Quality Measure Evolution

To evaluate these conflicts, a correlation index was derived for each alternative design against each function of *piercing* and *flaring.* Termed the *objective function*, a scale of -5 to +5, (-5 being the maximum detrimental effect with +5 being the maximum beneficial effect), was proposed as a reasonable assessment criterion for evaluating the conflicting functions.

To fully evaluate any alternative designs, it was necessary to judge their likely performance in satisfying the more fundamental higher-level process requirements of the *Quality Measure***.** Factors to be included in this measure must encompass fundamental aspects of the process, which are of key importance in satisfying customer requirements. From both extensive prior product knowledge and the issues raised by customer requirement analysis in **3.1.2**, the following were judged to represent the main aspects of joint performance.

(1) Joint Strength - Fundamental objective is to obtain the best possible joint strength between materials and should hence be the dominant factor.
(2) Aspect Measure - Gives visual indication of likely quality of joint, compactness and smoothness of clench exterior are both important customer demands.
(3) Joint Loading - The force necessary to create a joint, desirable to minimise where possible.
(4) Cost - An essential component of any product targeted to succeed in a competitive market place.

Although all of the above are important, relative weightings for each component within the *Quality measure* must be found. To achieve this, customer requirements from the stage 1 specification, which tangibly relate to the four components of the *Quality measure,* were brought forward. Feeding this information into a chart, the relative weight for each requirement was placed into a relationship matrix beside each component, the resulting row summation's of weights gave the components relative order. Table 3.11 shows the matrix used. A further normalisation process was finally carried out to give an overall ten point index value, the resulting equation for the *Quality measure* becoming:

QM = 4 x Joint strength + 3.5 x Aspect measure + 1.5 x Joint Loading + 1 x Cost **(3.2)**

For each alternative design, it now becomes possible to relate its worth to the overall primary requirements (through the *Quality measure*), in addition to satisfying the immediate objective functions. This will take the form of a measure of the total conflict expected, when trying to satisfy opposing objectives. To achieve this the following formula is proposed:

Conflict Measure = Column Sum of Correlation Indices x Assessed QM Index

(3.3)

The analysis of results can then be made depending upon the polarity of the calculated value as follows;

0 - Maximum conflict

+ Value - Beneficial factor

- Value - Detrimental factor

Stage 1 Requirements / QM Components	Robust Rivet Parameters	Efficient Piercing	Shank Flare Tendency	Maximum Shank Flare	Minimum Metal Displacement	No Pierce Through	Minimum Force to Form	Large Batch Manufacture	Sum	Approximate Weights
Joint Strength	9	7	5	5					26	**4**
Aspect Measure		7		5	4	3			19	**3.5**
Joint Loading		7					2		9	**1.5**
Cost								4	4	**1**
Total									58	10

Table 3.11 *Quality measure* Component Weight Derivation

The full conflict analysis for the rivet, which harmonises both the *Quality measure* and *objective functions*, is shown in fig 3.5. All of the conflict measures were found to be positive which shows that all the proposed alternative designs exhibit some degree of beneficial effect. The summary results are determined as judgements of the level of conflict determined from the magnitude of the conflict measure. From the results of this analysis, it is possible to select those alternatives, which exhibit the preferred lowest conflict for inclusion in the selected product combination.

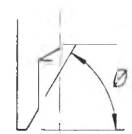
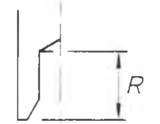
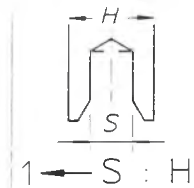
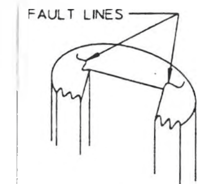
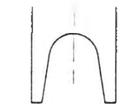
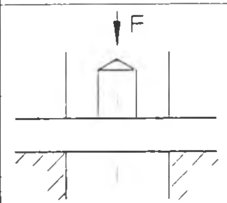
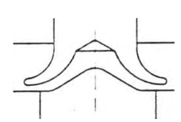
CONFLICT ANALYSIS							
	ALTERNATIVE FASTENER FEATURES						
	TAPER POKE	POKE DEPTH	HOLE TO DIA RATIO	MATERIAL HARDNESS	LAND WIDTH	CORNER EFFECT POKE	S T FORM POKE
							
OBJECTIVE FUNCTIONS	CORRELATION INDEX (-5 to +5)						
 PIERCING	+2	-1	-1	+4	+2	0	+2
 FLARING	+5	+4	+3	-2	+1	+3	+4
QUALITY MEASURE	8	6	4	5	4	2	6
ALTERNATIVE FEATURE CONFLICTS 0 - MAX + - BENEFICIAL - - DETRIMENTAL	56	18	8	10	12	6	36
	LOW CONFLICT	LOW CONFLICT	HIGH CONFLICT	HIGH CONFLICT	MEDIUM CONFLICT	HIGH CONFLICT	LOW CONFLICT

Fig 3.5 Conflict Analysis for Rivet

3.2.2 Primary Tooling (Anvil) Profile Features Satisfaction

As for the rivet, working from the DFD2 specification, features of the anvil were first considered in isolation from other factors. Selecting those parameters, which are of a high weight and can be physically defined, resulted in the two features shown in table 3.12.

PROCESS FEATURE	WEIGHT
2.2.1 Anvil profile features	5
2.2.2 Anvil profile proportions	4

Table 3.12 Anvil Features

Anvil profile features and proportions were explored in unison. The function of the anvil bears a direct correlation with the two established conflicting objective functions of *Piercing* and *Flaring*. During the *piercing* part of the cycle, a maximum clearance to allow material movement is required, whilst during the *flaring* phase a suitably formed obstruction is necessary to promote shank expansion. Hence the two requirements are again in conflict.

Alternative designs for anvil profiles were proposed based upon existing product knowledge and recognition of the material flow characteristics required during the joint forming process. Again a correlation index was judged for each alternative design against each objective function, in isolation, on a scale of +5 to -5. A *Quality measure* value derived from the same ten-point index as previous was also added to give the analysis a direct relevance to the higher-level process requirements.

The final calculated values for the **Conflict Measure** could then be used to determine the level of process conflict likely from any particular anvil feature and hence conclude as to its suitability for further development. Fig 3.6 shows the full conflict analysis.

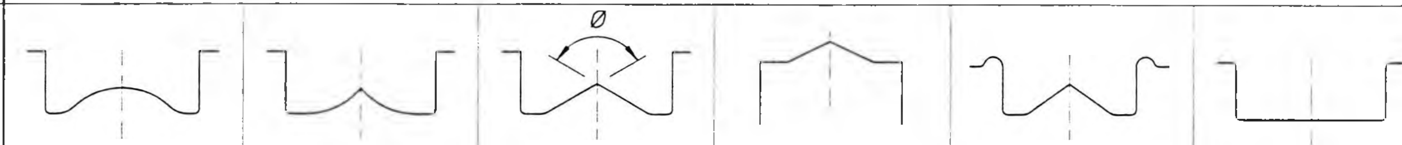
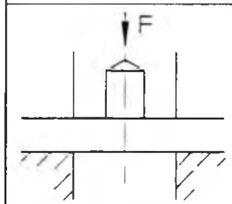
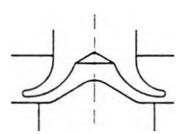
CONFLICT ANALYSIS						
	ALTERNATIVE ANVIL FEATURES					
	 CONVEX CURVE	CONCAVE CURVE	PLAIN CONE	FLUSH TOP	RAISED TOP	PLAIN PROFILE
OBJECTIVE FUNCTIONS	CORRELATION INDEX (-5 to +5)					
 PIERCING	+3	+3	+3	-2	+2	+2
 FLARING	+3	+4	+4	+3	+3	-1
QUALITY MEASURE	7	8	7	4	6	4
ALTERNATIVE FEATURE CONFLICTS 0 - MAX + - BENEFICIAL - - DETRIMENTAL	35	56	48	4	30	4
	LOW CONFLICT			HIGH CONFLICT	LOW CONFLICT	HIGH CONFLICT

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Fig 3.6 Conflict Analysis for Anvil

3.2.3 Secondary Rivet Features Satisfaction

In addition to the features already analysed, the DFD2 process yielded results of a lower priority, which for the rivet, are shown in table 3.13.

PROCESS FEATURES	WEIGHT
2.1.6 Surface properties	4
2.1.1 Shank properties	3
2.1.4 Head features	1

Table 3.13 Secondary Rivet Features

Considering first the *surface properties*, these are primarily dictated by the type of plating applied to the rivet for the purpose of corrosion resistance. There are primarily two types in common use.

A. Bright Zinc; applied by electro- plating process.

B. Organic coating; this consists of an organic micro-layer topcoat normally containing slip additives.

It would be desirable to include these two options within any subsequent experimentation programme.

Shank properties of diameter will be provisionally held at the three established and standard sizes of ; **3, 4** & **5** mm.

For the shank length, this is determined as a direct function of joint material thickness and is initially selected by means of a common 'rule of thumb' as shown below.

Rivet shank length = Total joint material thickness + 75% of the rivet shank diameter. (3.4)

In reality, other factors such as joint material properties, anvil profile design, rivet material properties and rivet poke design all influence the final selection of shank length for a particular joint thickness. It is therefore normal practice to determine the optimum shank length by means of experimentation.

Rivet *head features* come within two basic forms;

1. *Flat Countersink;* these are used when it is necessary for the rivet head to be set down flush with the joint surface leaving no projection on the upper face.

The only proposal for an alternative design relates to the shape of the under head form, where in place of the angular countersink a radius is employed, fig 3.7a.

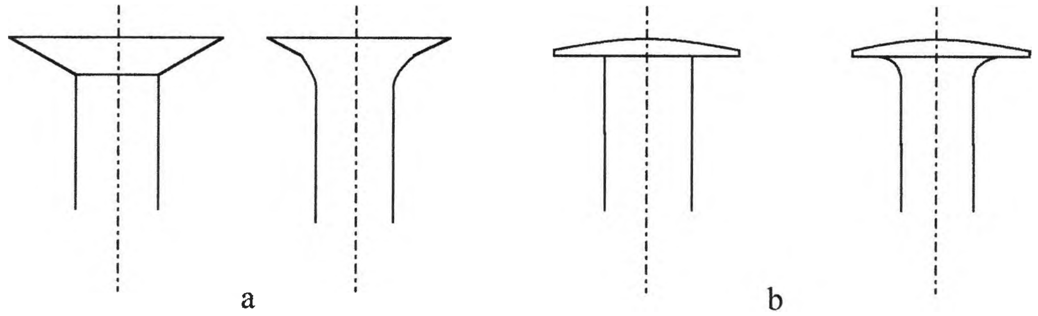


Fig 3.7 Under-Head Radius

2. *Raised Head;* different types of shape, selected only on the basis of appearance and having no direct influence upon the quality of clench formation.

As an alternative design, the only proposal is for the under head radius as above, fig 3.7b.

A constraint on the minimum head diameter for each shank size must also be applied as a function of the riveting machinery, rivet-feeding capability. A suitable head to shank diameter minimum ratio will be applied when designing the experimental product.

3.2.4 Other Process Feature Satisfaction

The outcome of the DFD2 analysis also yielded the following results for *machinery features*, Table 3.14.

PROCESS FEATURES	WEIGHT
2.3.1 Pre-clamp	4
2.2.3 Delivery attitude	1
2.3.2 Delivery velocity	1

Table 3.14 Machinery Features

Considering first the *Pre-clamp.* This feature was developed into the latest design of riveting gun, evolved as a result of a previous project, utilising the DFD systematic design approach, Appendix A. The necessity for pre-clamping has been well proven, resulting in far superior standards of distortion free joint than with none clamped systems. All experimentation should utilise this system.

Delivery attitude relates to the correct orientation and presentation of the rivet to the material surface. This is controlled effectively by the current riveting equipment. However, issues relating to shank end squareness, may influence joint formation in a similar way to a badly presented rivet. To minimise this possibility, the manufacture of rivets must be carried out to give as square an end as is possible, within the limitations of the cold forging process.

Delivery velocity is a direct function of the setting equipment and relates to the speed at which the riveting process is carried out. Although of a low importance rating, tests will be carried out (possibly as a parallel activity) over a range of velocities, to determine the true significance of this feature.

3.3 New Product Selection

3.3.1 Analysis of Possible Joint Formation

For the *self-pierce* riveting process, it was discovered in **2.4.2**, that analysis during the initial piercing stage of joint formation was possible by means of an approximation method known as *load bounding***.** Although further work by King (1997) failed to analyse joint formation beyond the first 22% of indentation, there is a great deal which can still be established from the interpretation of load v displacement curves. Such graphical data can be viewed as being the solution, what is required, is to understand the problem.

3.3.1 (a) Piercing Stage for Alternative Form Rivets

The majority of the alternative rivet forms proposed in table 3.10 and subsequently analysed in fig 3.5, specifies features relating to the shank end geometry. Fig 3.8 illustrates the typical shape of such features. By the application of *load bounding* techniques, it should be possible to derive equations, which describe the likely maximum indentation pressure required to pierce the joint material. Such equations will provide an analytical means of comparing alternative forms of rivet prior to any experimentation process.

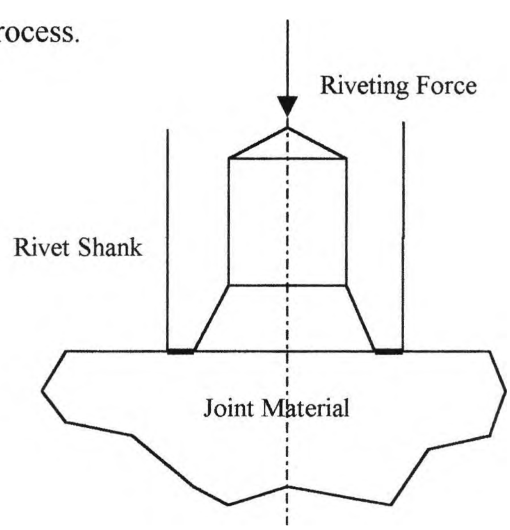


Fig 3.8 Alternative Form Rivet

After studying the published information available on *load bounding* techniques, it was decided to try model the process in two different ways and evaluate the resulting equations by means of experimentation.

A. Alternative Model 1

As shown in fig 3.9, assumption is made that the shank end extends to a point, from which a simple discontinuity field is created. The depth of penetration thus becomes extended from 1.1mm to 1.73mm for a 5mm nominal diameter rivet with a 30^0 chamfer angle.

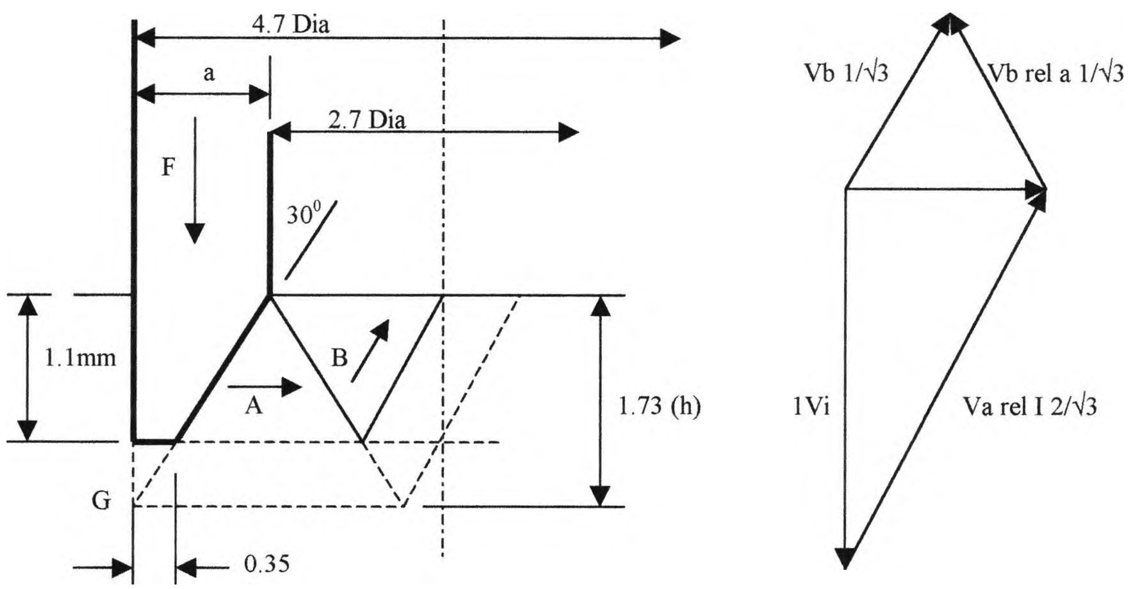


Fig 3.9 Alternative Model 1

Building on equation **(2.5),** the analysis yields the following results.

External Work	=	Internal Work
F/2 x 1	=	K[A/G + B/G + A/B]
F/2 x 1	=	$K[h.2/\sqrt{3}.\ 1/\sqrt{3} + h.2/\sqrt{3}.\ 1/\sqrt{3} + h.2/\sqrt{3}.\ 1/\sqrt{3}]$
F/2 x 1	=	K x h x2

where h = a x 1.73 and P = F/2a, above equation becomes.

P x 1 x a	=	K x a x 3.46
P	=	K3.46

Which expressed in the more typical form gives:

$$P/2K = 1.73 \qquad \textbf{(3.5)}$$

B. Alternative Model 2

In this case, the end form of the rivet is maintained with its true shape, around which a field of discontinuity lines was created. As can be seen in fig 3.10, a slug of material is now effectively being pushed forwards by the short flat section of land width, and is simultaneously driven up into the hole along an assumed flow path through section C.

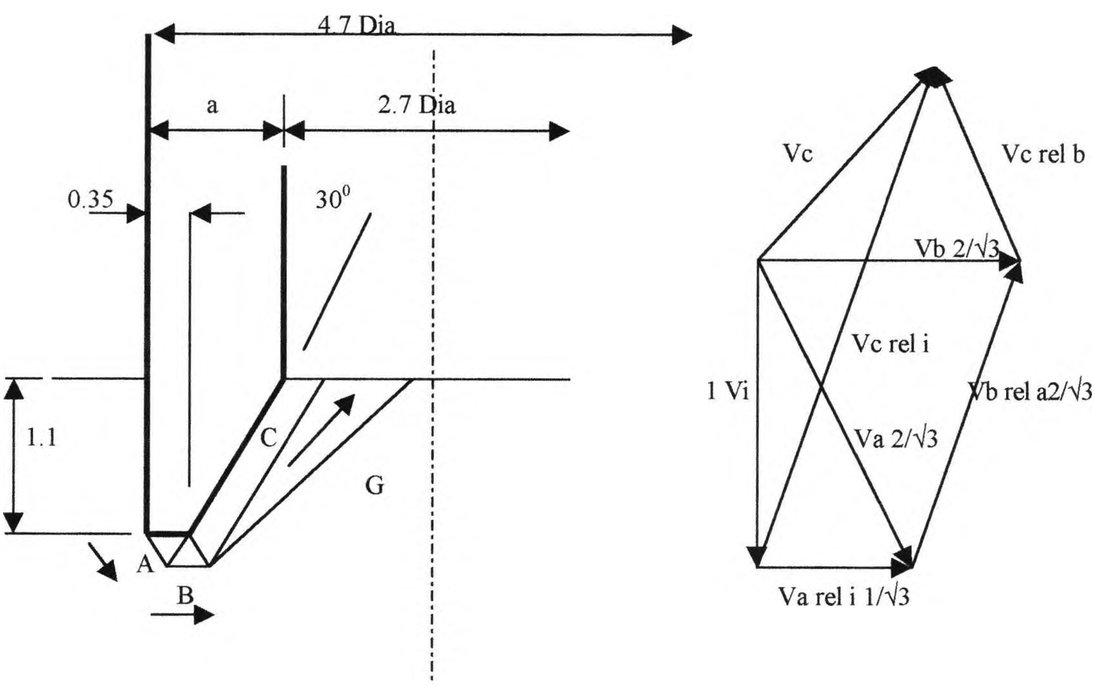


Fig 3.10 Alternative Model 2

Again, building on equation **(2.5),** the analysis yields the following results.

External Work = Internal Work

$$F/2 \times 1 = K[A/G + B/G + C/G + A/B + B/C]$$

$$F/2 \times 1 = K[(.35a)2/\surd 3 + (.35a)2/\surd 3 + a1.1 + (.35a)2/\surd 3 + (.35a)2/\surd 3]$$

$$F/2 \times 1 = K[2.7a]$$

Where P = F/2a, above equation becomes.

$$P = K2.7$$

Which expressed in the more typical form gives:

$$P/2K = 1.35 \quad \textbf{(3.6)}$$

Having derived two equations, it is now necessary to prove which, if either give valid representations for rivet piercing loads. To test the theory, a small quantity of rivets incorporating the alternative form, were subsequently manufactured.

By means of the process monitoring equipment described in **2.4.1,** characteristics of load v displacement were recorded for joints created, with the above rivet in aluminium alloy. In analysing such curves, it is necessary to take account of the 1.1mm depth at which the *upper bound* equation was subsequently derived, this must be added to the 1mm settling allowance established in **2.4.2 (c).** Fig 3.11 shows the typical form of curves produced which subsequently yielded a piercing load of **5kN** at 2.1 mm displacement.

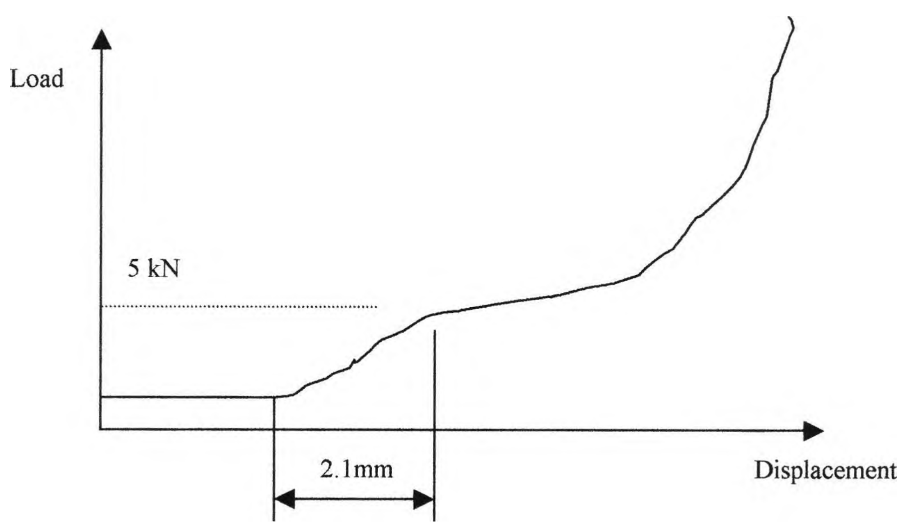


Fig 3.11 Typical Load v Displacement Curve for Alternative Form Rivets

By calculation

Since $K = 132\ MN/m^2$ and $a = 1.24.\ 10^{-5}\ m^2$

For model 1 $P = 456.72\ MN/m^2$ and $F = 5.7\ kN$

For model 2 $P = 356.4\ MN/m^2$ and $F = 4.4\ kN$

In comparison with the actual load of 5 kN, the upper bound value of 5.7 kN derived from model 1, fits comfortably with the theory of giving an approximate over estimate of likely force to pierce.

When comparing these results with those given by the original rivet in **2.4.2 (c),** it can be seen that the new form rivet achieves much lower piercing loads (5kN compared to 8kN).

3.3.1 (b) Clenching Stage

During the final stages of joint formation, the predictability of riveting forces by prior analysis, becomes a much more complex problem than for simple piercing. We can however draw information from load v displacement data, which will provide a better understanding of joint formation in this region.

Considering more closely the final section of load v displacement curves, it can be seen that two distinctly different actions are taking place, these being:

1. *Clinching:* As described in **1.4.1,** where the end of the rivet shank is being flared outwards whilst simultaneously drawing out the lower layer of joint material. The fact that separate operations are taking place in parallel makes the analysis particularly unpredictable.
2. *Head-down:* The final part of the operation sees the riveting forces reach a maximum as the rivet head is finally driven down against the material surface. The primary influence on this final loading will be the extent of waste slug compression into the hollow shank of the rivet. If the anvil cavity volume is less than that of the collected material, then load will be dissipated achieving no useful work and the system becomes choked. Any further load added will only result in straining of the riveting equipment, playing no further part in joint formation. Fig 3.12 illustrates this balancing of volumes in the process.

When studying process curves, it is important to understand that the equipment used to produce them is simply monitoring the process with no influence on the control of it. For the riveting equipment, load is applied up to the point where a pre-set force is achieved, after which the load direction is reversed and the mechanism returns to its home position. Peak load values, as read directly from process curves therefore also include elements of over-pressure and system response times which distort the final load reading. To filter out this effect, it is preferable to study loads up to the end of the clenching stage only. This point is normally distinguishable on the process curves as shown in fig 3.13.

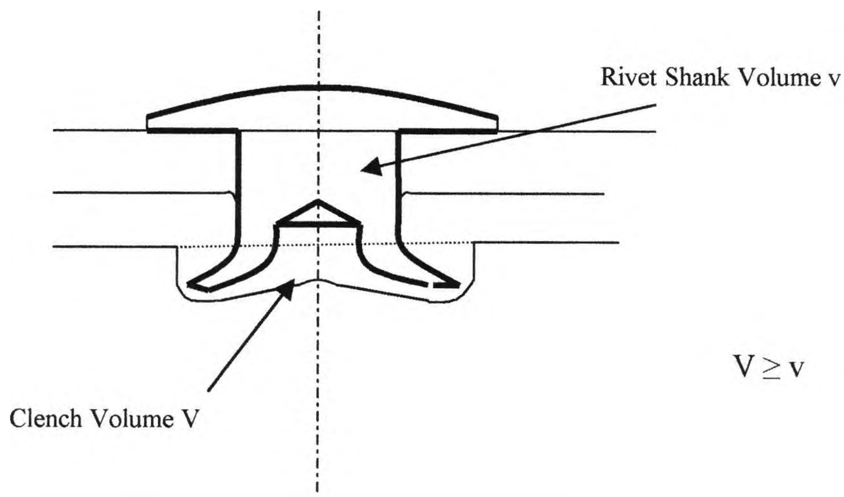


Fig 3.12 Joint Material and Rivet Volume Balance

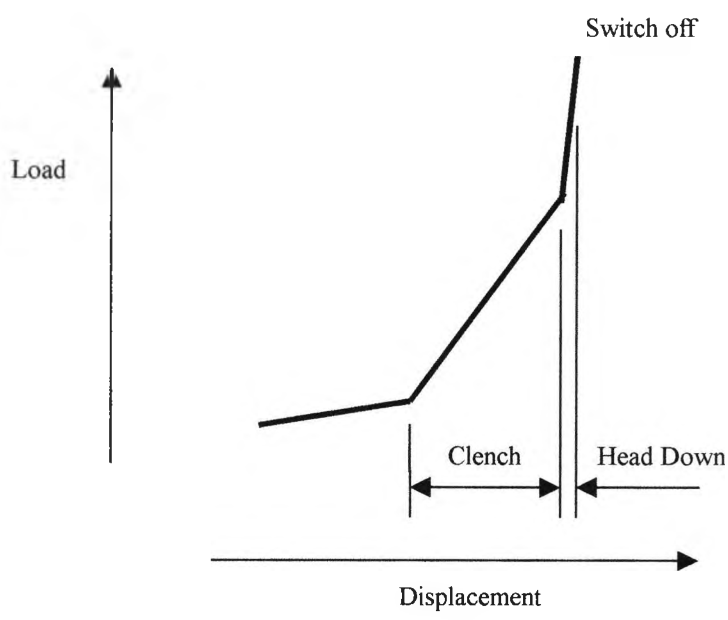


Fig 3.13 Final Phases of Joint Formation

A first approach in the prediction of likely setting loads was to establish approximate relationships of load and displacement over a range of thickness for two material types.

From results for joints created in aluminium alloy type 5251-H3 material, over a section thickness range of 2 to 5mm, final loads for the clenching stage were extracted as shown in table 3.15.

Joint Thickness (mm)	Clench Load (kN)
5	26
4	26
3	24
2	24

Table 3.15 Clench Loads for Aluminium Alloys

The data shown in table 3.15 shows a very interesting and previously un-recognised fact, that clenching load appears to fluctuate very little for different joint thickness in aluminium alloy. With only 8% load fluctuation noted, under identical conditions of rivet form and anvil, it can be concluded that setting loads, in this case, are not greatly affected by joint material thickness. This conclusion is further supported by the observations made in **2.4.2 (c),** where characteristics of constant piercing load after initial indentation were noted.

Conducting a similar analysis of joints produced in mild steel type CR4, gave the results shown in table 3.16.

Joint Thickness (mm)	Clench Load (kN)
5	30
4	30
3.2	26
2	24

Table 3.16 Clench Loads for Mild Steel

As can be observed from the data shown in table 3.16, the load distribution has now become much wider, accounting for approximately 20% variation over a 2 to 5mm thickness range. This suggests that material thickness becomes a more relevant parameter for joint load prediction, when joining mild steel components as opposed to aluminium alloys. Observations made in **2.4.2 (c),** noted an increasing load during the piercing stage, up to a point of approximately half the maximum piercing depth. Resistance build up is therefore taking place during piercing, until the rivet starts pushing material into the anvil cavity, at which point the load temporarily drops. Such resistance build-ups must therefore play a part in influencing final rivet load for mild steel joints.

3.3.1 (c) Conclusions for Joint Analysis

The *load bounding* method has been proven to give equations capable of predicting piercing loads for alternative form rivets. Further more, for the proposed shape of rivet explored, it was found that piercing loads are substantially reduced, this representing a significant benefit for the process.

During the remaining stages of the process, neither simple predicting equations nor complex analysis have been found to describe the process fully. Observations made from joint data have lead to interesting conclusions, particularly relating to aluminium alloy, where final load is found to be largely independent of joint thickness.

Such observations do give a valuable insight into the nature of process behaviour, which is sufficient for use in guiding and evaluating the selection of key process parameters.

3.3.2 Parameter Selection

From the evaluation of potential alternative designs and process behaviour, it becomes possible to select and priorities those parameters, which are to be incorporated into the product experimentation plan.

As determined in **3.1.3**, the elements of the *Self Pierce* riveting process can be segregated into four main categories, these being;

1. Rivet Features.
2. Joint Material.
3. Anvil Profile Features.
4. Setting Machinery Features.

Taking each category in turn, an interpretation is placed on the priority of each parameter.

1. From the DFD2 specification (Appendix B), primary features of the rivet achieved the highest weight. Subsequent alternative designs were evaluated by means of the *conflict analysis* fig 3.5, from which those features exhibiting the lowest level of conflict (highest index value) would be expected to give the greatest overall benefit to the process performance.

From the above two sources and applying an element of engineering judgement, evaluation in order of priority was made as follows;

A. Taper Poke - Low conflict. Additions of angular chamfer to inside edge of rivet Poke. Plasticity analysis of joint in **3.3.1 (a),** has shown how a taper poke reduces the load required to pierce the joint material. Further more loads can be predicted by means of equation **(3.5)**. Determination of optimum magnitude of angle will become subject of experimentation.

Achieving a good result with this parameter eliminates the need to pursue the 'ST Form Poke' alternative.

B. Depth of Poke - Low conflict. Depth of hole in rivet providing housing for collected material. Experiment with different hole depths.

C. Hole to Diameter Ratio - High conflict. As the outside shank diameter is pre-selected, this factor will involve the experimentation with different wall thickness as a function of poke diameter.

D. Rivet Material Hardness - High conflict. Experimentation using different raw materials and hardness treatments for rivet manufacture will be included in the programme. Selection will be limited to the wire materials available which are capable of being easily cold forged.

E. Land Width - Medium conflict. This becomes a direct function of the degree of taper added at A.

F. Corner Effect Poke - Adding potential fault lines into the rivet shank to assist in promoting rivet flare. Due to manufacturing difficulties, leave from the programme at this stage but keep on record for future possible reference.

Secondary features of the rivet (although of a lower rating) must also be included in the programme.

(I) Surface properties of the rivet, largely due to the type of coating applied. Many new forms of plating have become available in recent years, however for the purposes of this experiment, the standard Bright Zinc will be used.

(II) Shank properties of diameter will cover a standard range **3, 4** and **5 mm.** Shank properties of length will be dictated by joint material thickness in accordance with equation **(3.4)**.

(III) Head features will be restricted to the flat countersunk type as demanded by the majority of applications.

2. From the DFD 2 specification (Appendix B), the second highest area of priority was that relating to the actual material to be joined. For the purpose of this project, aluminium alloy will be the priority, since it represents the material preferred by the majority of the identified growth markets for *self-pierce* riveting.

3. The next priority of importance from the DFD 2 specification (Appendix B) was that of 'Anvil Profile Features'. As for features of the rivet, a state of conflict was identified and rationalised by means of a conflict analysis fig 3.6, alternative designs thus being rated at high or low levels.

Evaluation in order of priority was as follows;

A. Concave Curve - Low conflict. Optimum proportions of curve, profile depth and diameter to be established by experimentation.

B. Plain Cone - Low conflict. Optimum angle of cone, diameter of cone, profile depth and diameter to be established by experimentation.

C. Convex Curve - Low conflict. Optimum proportions of curve, profile depth and diameter to be established by experimentation.

D. Raised Top - Low conflict. Can be combined with any of the previous features to possibly enhance joint performance. A small scale 'try out' will be carried out as sub-set of the experimentation programme.

E. Flush Top and Plain Profile - Both high conflict factors which will be kept on record for future reference.

In addition to the above, it was felt that the variable parameters of anvil profile depth and diameter should be included in the process analysis.

4. The final category from the DFD 2 specification was that of 'Setting Machinery Features' of which three items were considered. The first two, pre-clamp and delivery attitude will be direct functions of the setting equipment being used and thus become integrated into the product development. Delivery velocity however, can be controlled as a variable and should therefore be included in the test programme.

A summary schedule of all these factors with their selected priority ratings is shown in table 3.17

	FEATURE	PARAMETER	PRIORITY
1	Rivet features (primary)	Taper Poke	1
		Depth of Poke	2
		Hole to Diameter Ratio	3
		Rivet Material Hardness	4
		Land Width	5
	Rivet Features (secondary)	Surface Properties	12
		Shank Properties	13
		Head features	14
2	Joint Material	Steel	(6)
		Aluminium Alloy	6
3	Anvil Profile Features	Concave Curve	7
		Plain Cone	8
		Convex Curve	9
		Profile Diameter	10
		Profile Depth	11
4	Setting Machinery Features	Setting Velocity	15

Table 3.17 Selected Parameter Schedule

3.3.3 Proposed Product and Constraints

Considering the physical design of the rivet, a proposed form of product can be manufactured to incorporate all the relevant parameters identified from the above analysis. In the selection of parameter settings, limiting factors (constraints) will greatly influence what levels are practically achievable. Such constraints come from effectively two potential sources.

1. Manufacturing - The cold forging process allows the economic manufacture of rivets, from wire material, at speeds of up to 350 per minute. Such a high volume process has its limitations, particularly in relation to the actual machinery available within *Aylesbury Automation.*
2. Setting Equipment Feeding Systems - For any automated placing system the ability of the rivet to be fed and controlled efficiently is of paramount importance. Those parameters, which affect the external geometry of the fastener must therefore be proportioned within limits which ensure efficient feeding.

Where applicable, upper and lower values for constraints from both sources have been quantified. Idealised targets have also been determined for each parameter, along with a preferred improvement direction. Table 3.18 shows the full schedule of constraints for the three nominal rivet shank sizes of 3, 4 and 5mm diameter.

In addition to the rivet, items of setting tooling in the form of 'anvils' are defined by the selected parameters. Fig 3.14 illustrates the main features identified.

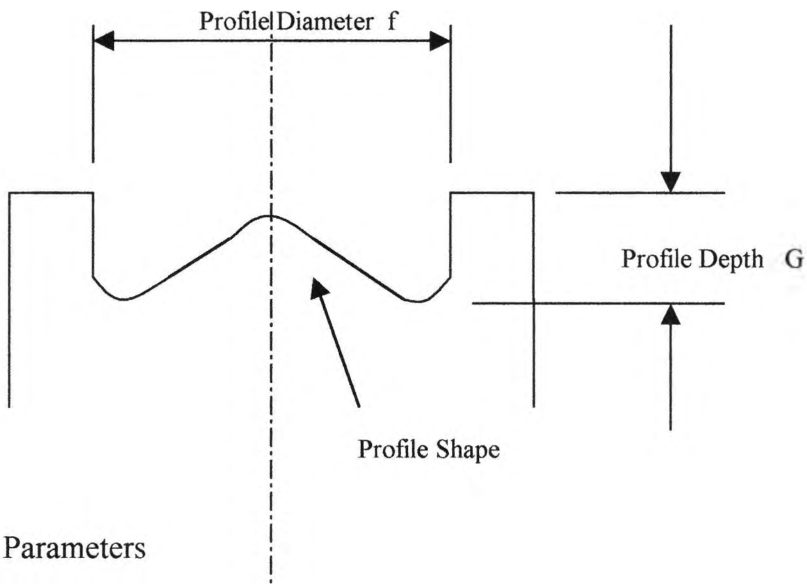
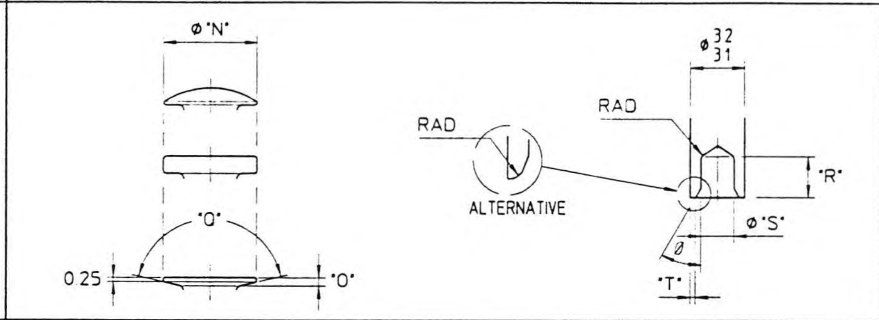
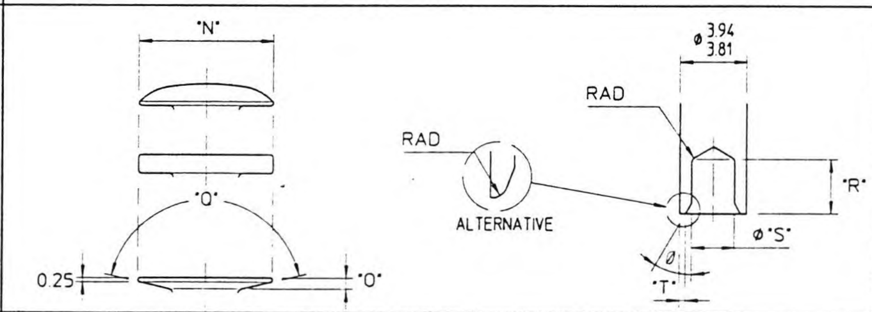
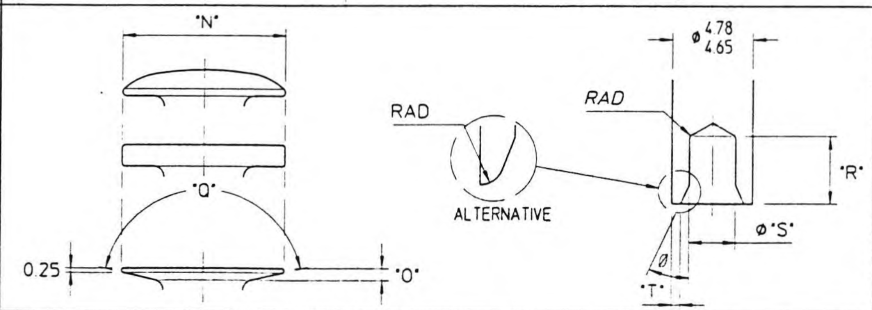


Fig 3.14 Anvil Parameters

PROPOSED PRODUCT - CONSTRAINTS







RIVET GAUGE	PARAMETER	UNITS	MANUFACTURING CONSTRAINTS		FEEDING CONSTRAINTS		TARGET	IMPROVEMENT DIRECTION
			UPPER	LOWER	UPPER	LOWER		
3mm NOM. RIVETS	J	VPN	550	200	N/A	N/A	380	0
	N	MM	8	4.5	8	5	5	0
	O	MM	0.89	0.63	1.0	N/A	0.8	0
	Q	DEG	90°	155°	N/A	N/A	130°	0
	R	MM	3	N/A	N/A	N/A	3	+
	S	MM	2	1.5	N/A	N/A	2	0
	T	MM	N/A	0.30	N/A	N/A	0.25	-
	Ø	DEG	30°	30°	N/A	N/A	35°	0
4mm NOM. RIVETS	J	VPN	550	200	N/A	N/A	380	0
	N	MM	10	6	9.5	6.9	6.9	0
	O	MM	1.42	0.81	1.42	N/A	0.95	0
	Q	DEG	90°	155°	N/A	N/A	130°	0
	R	MM	4	N/A	N/A	N/A	5	+
	S	MM	2.7	2.2	N/A	N/A	2.5	0
	T	MM	N/A	0.38	N/A	N/A	0.3	-
	Ø	DEG	30°	30°	N/A	N/A	35°	0
5mm NOM. RIVETS	J	VPN	550	200	N/A	N/A	380	0
	N	MM	10	7.5	9.5	8	8.3	0
	O	MM	1.65	0.89	1.65	N/A	1.09	0
	Q	DEG	90°	155°	N/A	N/A	130°	0
	R	MM	5	N/A	N/A	N/A	7	+
	S	MM	3	2.5	N/A	N/A	3	+
	T	MM	N/A	0.38	N/A	N/A	0.35	-
	Ø	DEG	40°	36°	N/A	N/A	35°	-

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Table 3.18 Proposed Product Constraints

Chapter Four

Selection of Rivet Factor Levels by Experimental Methods

Having established the product features and their relevant constraining limits, it now becomes possible to prove the performance of selected product combinations using simple design matrices and to determine the optimum values for all such parameter settings.

The *robust* Engineering approach to product design and the philosophy as suggested by Taguchi were explored in **1.2.4**. Placing emphasis on the parameter design stage, a method of planning and conducting controlled experimentation through the use of orthogonal arrays was introduced. Loss and its relationship to system 'noise', in the context of both quality and economic factors, was also discussed in **1.2.5**. Noise factors represent the biggest problem in most systems and minimising the effect of such variation through economic parameter settings is the basis for producing a *robust* product.

Of particular interest to analysis of the *self-pierce* riveting process, is the experimentation with dynamic systems as introduced in **2.3.2.** Although few published case studies of *dynamic Taguchi* are available, an energy absorbing process such as *self- pierce* riveting provides an opportunity to explore and further develop this approach. The satisfaction of Hypothesis 1 and 2 as stated in **1.5.1,** may also be discovered through the further application of matrices as an analysis tool.

4.1 Experimentation Planing

4.1.1 Full Size Experimental Plan

In order to focus on those factors, whose performance was of key interest, the following parameters were, elected to be set at constant pre-determined levels throughout the experimental programme.

1. Rivet Gauge - Pre-set at 5mm as common standard product size.
2. Head Type - Set to countersink.
3. Joint Material Properties - Nominally steel or aluminium but priority will be given to joining the more demanding aluminium alloy materials.
4. Setting Velocity - Keep at fixed speed whilst determining optimum rivet / anvil parameter settings,
5. Shank Length - Select a range of shank lengths to represent nominal required joint thickness capability, these were derived to be **9mm** and **6.5mm**.
6. Joint Material Thickness - In order to determine the *process robustness* to joint material thickness variation, a pre-set range of joint thickness' were selected for each rivet length to incorporate in the experimental plan. This represents a form of **Imposed noise** (signal). Table 4.1 shows the relationships between joint thickness, rivet length and the selected range of thickness variation.

Nominal joint thickness	**Rivet length**	**Imposed noise**
5.5mm	9mm	6, 5.5 & 5mm
3mm	6.5mm	3.2, 3 & 2.7mm

Table 4.1 Selected Joint and Rivet Fixed Settings

Having determined those factors, which were to be kept fixed over a specific range of experiments, it was now possible to propose an orthogonal array size appropriate to the number of remaining factors and determine the factor level settings.

In the case of the 5mm rivet, nine factors were selected for analysis, which could be accommodated by an L16 array for a two level experiment. This then leaves scope to include up to six other factors within the same experimental plan. Since the common conception existed that interactions were important, it was felt appropriate that they should also be included in the programme. In order to determine which interactions would be the most significant, consideration was given to factor priority ratings carried forward from the DFD2 analysis. As there are two main factor groups of 'anvil' and 'rivet', interactions both 'between' and 'within' these two groups should be considered.

Taking the top priority factor, this was first reacted with the next two highest factors in the same group and the top two priority factors in the second group. Since one more factor could be included with the L16 array, the first and second highest factors were also interacted.

Selection of such interactions would normally be decided on instinct or prior product knowledge. **However by means of the DFD stage 2 analysis, it becomes possible to determine which factor interactions are important as a function of their rated priority.**

Setting of factor levels was made based upon both existing product knowledge, intuition and an understanding of the plastic behaviour of material piercing derived in **3.3.1**. All information regarding factor levels, interactions and noise settings is shown in Table 4.2.

The final step in the experimental plan was to assign all factors to their appropriate column in the L16 array, which first requires the adaptation of the design matrix to ensure reproducible results. Linear graphs as introduced in **1.2.4,** are used to illustrate factor relationships for which a range of existing standards can be consulted. For this experimental plan, no standard published graph gave the required combination of factors, hence a customised graph had to be produced. Krottmaier (1993) describes such a procedure, which is utilised below.

With reference to fig 4.1:

A. Draw the experimental layout directly for factors and interactions

B. From standard graphs, pick the one which most closely represents the above.

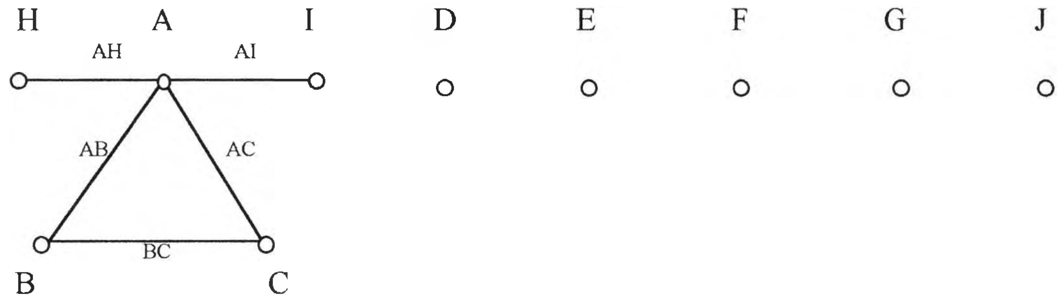
C. Adapt the standard graph to suit the experiment.

D. Assign factors and interactions to the appropriate columns of the design matrix.

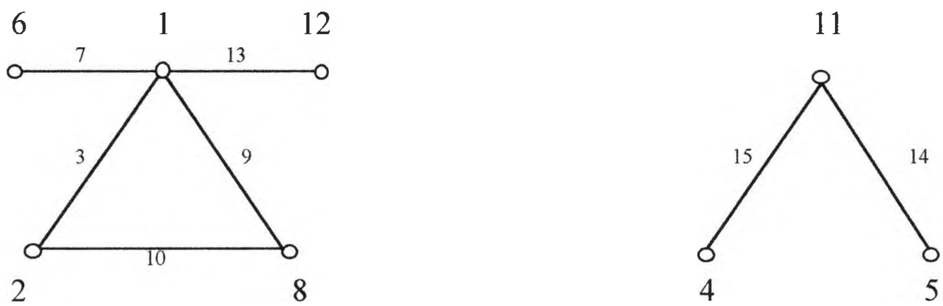
Experimentation for each of the sixteen factor combination in the array could next be carried out, with repetitions being performed under each material thickness setting (**S**). This 'outer array' representing noise factors (repetitions) and signal factors (imposed noise). Such an approach resembles a *dynamic* Taguchi system, the structure of which is shown in table 4.3.

RIVET GAUGE : 5mm JOINT MATERIAL : ALUMINIUM ALLOY(5251) JOINT THICKNESS RANGE : 3 - 5.5mm (nom) STD RIVET LENGTH RANGE : 6.5 - 9mm				
Factor	Description	Priority	Level 1	Level 2
A	Taper Poke	1	45deg	30deg
B	Depth of Poke	2	4.7mm	(7.0mm)
C	Hole Diameter	3	2.7mm	3mm
D	Rivet Material Hardness	4	400VPN	475VPN
E	Land Width	5	0.4mm	0.2mm
F	Surface Properties	12	BZP	Organic
G	Head Diameter	14	9.5mm	8.5mm
H	Anvil Profile Features	7	Cncv Cone	Cnvex Cone
I	Anvil Profile Diameter	10	8mm	9mm
J	Profile Depth	11	2.2mm	2.8mm
AB	Interaction A/B			
AC	Interaction A/C			
BC	Interaction B/C			
AH	Interaction A/H			
AI	Interaction A/I			
S1	Material Thickness	6	6mm and 3.2mm	
S2	" "	6	5.5mm and 3mm	
S3	" "	6	5mm and 2.7mm	

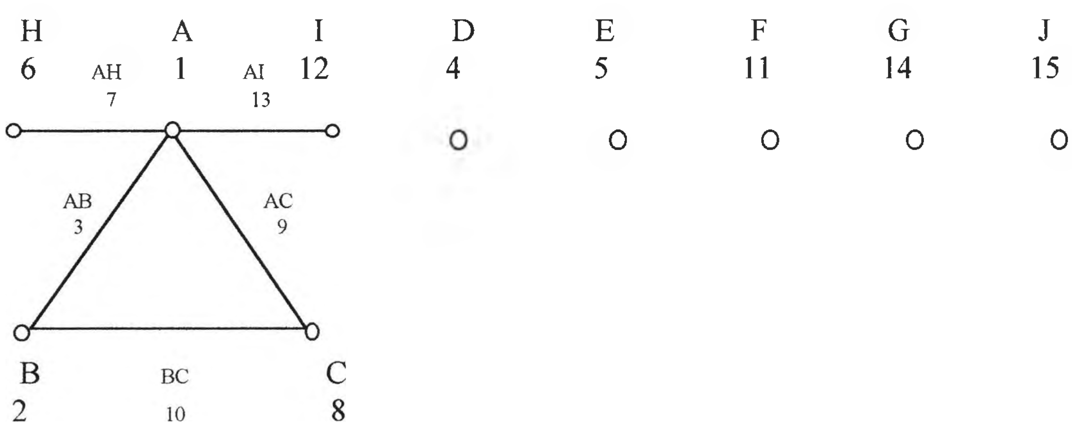
Table 4.2 Experimental Plan for L16 Array



A. Graphical Representation of Planned Experiment



B. Nearest Standard Graph



C. Adapt Standard to Suit Experiment

Factor	A	B	AB	D	E	H	AH	C	AC	BC	F	I	AI	G	J
Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

D. Assign Factors to Columns

Fig 4.1 Factor Assignment Route

Table 4.3 Layout of L16 Array Experiment

Rivet Head Type	Flat Csk	Joint Material Type	Al alloy
Rivet Gauge	5mm	Nom Joint Thickness	5.5mm
Rivet Length	9mm		

	Design Parameter Matrix															Signal Parameter Matrix						
Factor	A	B	AB	D	E	H	AH	C	AC	BC	F	I	AI	G	J	S1		S2		S3		
Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	X1	X2	X1	X2	X1	X2	Z(O)
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1							
2	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2							
3	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2							
4	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1							
5	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2							
6	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1							
7	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1							
8	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2							
9	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2							
10	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1	DATA	DATA	DATA	DATA	DATA	DATA	
11	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1							
12	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2							
13	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1							
14	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2							
15	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2							
16	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1							

4.1.2 Reduced Experimental Plan

As with any experimental programme, a balance has to be struck between the value of data to be extracted and the economics of conducting the experiment. Unfortunately due to the potential size of the L16 array experiment programme along with the limited amount of company resources available for this project, a smaller L8 schedule had to be considered. The major penalty of taking this approach however, was the loss of several parameters, which were considered to influence joint performance, furthermore the opportunity to study the effects of interactions would also be lost. As only seven factors could now be included in the experiment, selection of those parameters was made by means of the priority rating. The top five rivet factors were retained leaving space for only two anvil factors.

In order to rationalise the potential loss of experimental data, a closer analysis was made of the anvil feature in an attempt to find pre-determined relationships which would allow prior calculation, and hence prediction of certain parameter settings. This utilisation of physical relationships will reduce the need for experimental analysis.

In **3.1.3,** it was established that the ideal target for rivet flare should be 1.5 x the rivet shank diameter **(H)**. With reference to fig 3.14, the anvil profile diameter (**f**) can hence be calculated by the addition of a 1mm of material containment around the extremities of the rivet flare, giving:

$$\textbf{Anvil Profile Diameter (f)} = (\mathbf{H} \times \mathbf{1.5}) + \mathbf{2} \qquad \textbf{(4.1)}$$

This factor can hence be taken as being a direct function of rivet shank diameter and subsequently becomes fixed for each rivet gauge eliminating the need for its inclusion in the experiment.

Further consideration was given to predicting anvil profile depth **(G)** as a function of volume assumptions, the equation ultimately derived being;

$$\textbf{Anvil Profile Depth (G)} = \frac{\mathbf{V}}{\mathbf{0.52\,f^2}} \qquad \textbf{(4.2)}$$

where **V** = Anvil cavity volume = Volume of rivet below joint surface

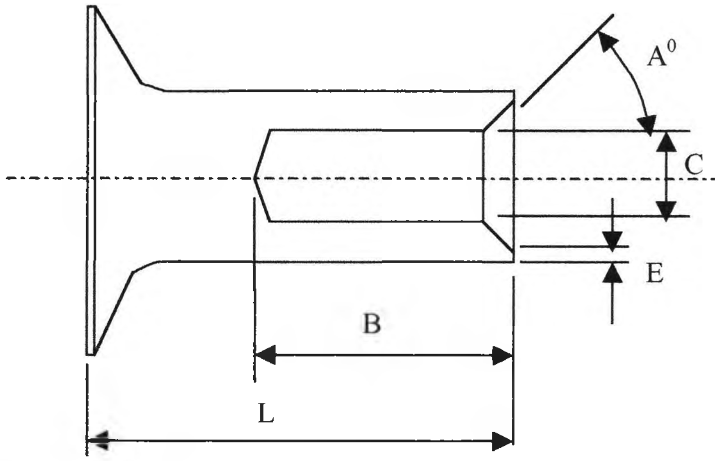
Taking the two extremes of rivet length in the experiment, two values for '**G**' were calculated and introduced as the two level values for anvil profile depth.

The resulting combinations of two profile depths and two shape features yielded four experimental anvil configurations to be used in the programme. All the selected factors and levels, along with material thickness selections are shown in Table 4.4.

From the L8 array, a range of eight experimental rivets were required for each of the two specified shank lengths. The variable factor combinations for the rivets to be manufactured are shown in fig 4.2.

As for the full L16 experiment, an experimental layout was again derived but this time only eight factor combinations had to be generated, Table 4.5.

Rivet Length L = 9 or 6.5



Experiment	A	B	C	D	E
1	45°	4.7	2.7	400	0.4
2	45°	4.7	2.7	475	0.2
3	45°	7.0*	3.0	400	0.4
4	45°	7.0*	3.0	475	0.2
5	30°	4.7	3.0	400	0.2
6	30°	4.7	3.0	475	0.4
7	30^0	7.0*	2.7	400	0.2
8	30°	7.0*	2.7	475	0.4

* B= 7.0 when L=9.0, otherwise B=4.7

Fig 4.2 L8 Experimental Rivet Plan

RIVET GAUGE : 5mm
JOINT MATERIAL : ALUMINIUM ALLOY (5251)
JOINT THICKNESS RANGE : 3 - 5.5mm (nom)
STD RIVET LENGTH RANGE : 6.5 - 9mm
RIVET SURFACE : BRIGHT ZINC

Factor	Description	Priority	Level 1	Level 2
A	Taper Poke	1	45deg	30deg
B	Depth of Poke	2	4.7mm	(7.0mm)
C	Hole Diameter	3	2.7mm	3mm
D	Rivet Material Hardness	4	400VPN	475VPN
E	Land Width	5	0.4mm	0.2mm
F	Anvil Profile Features	7	Concv	Convex
G	Anvil Profile Depth	11	2.2mm	2.8mm
S1	Material Thickness	6	6mm and 3.2mm	
S2	" "	6	5.5mm and 3mm	
S3	" "	6	5mm and 2.7mm	

Table 4.4 Experimental Plan for L8 Array

Table 4.5 Experimental Layout for L8 Array

Rivet Head Type	Flt Csk	Joint Material Type	Al alloy
Rivet Gauge	5mm	Nom Joint Thickness	5.5mm
Rivet Length	9mm	Anvil profile	

	Design Parameter Matrix							Signal Parameter Matrix						
Factor	A	B	C	D	E	F	G	S1		S2		S3		
Column	1	2	3	4	5	6	7	X1	X2	X1	X2	X1	X2	Z(O)
1	1	1	1	1	1	1	1	DATA	DATA	DATA	DATA	DATA	DATA	
2	1	1	1	2	2	2	2							
3	1	2	2	1	1	2	2							
4	1	2	2	2	2	1	1							
5	2	1	2	1	2	1	2							
6	2	1	2	2	1	2	1							
7	2	2	1	1	2	2	1							
8	2	2	1	2	1	1	2							

4.2 Conducting the Experiments

4.2.1 Objective Function

In order to measure the performance of the fastening process for each experimental factor combination, a comprehensive and measurable Objective Function must be applied. In many cases the objective function may require just the measurement of a simple single output factor such as force, height, weight etc. Such a case can be found in research carried out by Kurpad and Shina (1992), into the performance of 'blind rivets', where the objective function was taken as just the 'stem break' load during rivet installation. The *self pierce* riveting process requires a more comprehensive form of objective function.

From previous work on the assessment of conflicting process features **3.2.1(a)**, a dimensionless property termed the Quality Measure was derived. The resulting ten-point index was derived as a function of; Joint Strength, Aspect, Setting Loading and Cost. Since in this instant, potential value for the Quality Measure was only being estimated, the ten point index used offered sufficient resolution within the bounds of Engineering judgement. For an Objective Function, a value is derived directly from actual experimental observations, consequently the accuracy of how well these results are reported will be dependent on the resolution of the index applied. In order to retain parity with the Quality Measure, the same categories and proportions of contribution were applied but this time with an order of magnitude increased by a factor of 10. thus from equation **(3.2):**

$$\textbf{Objective Function (OF)} = 40 \times \textbf{Joint Strength} + 35 \times \textbf{Aspect Measure} + 15 \times \textbf{Joint Loading} + 10 \times \textbf{Cost} \qquad \textbf{(4.3)}$$

Hence;
$$\textbf{OF} = 10 \times \textbf{QM} \qquad \textbf{(4.4)}$$

4.2.2 Measurements of Results

Since the Objective Function is made up of several measurable inputs, the scale and relative indexing of each of these contributors must be established.

A. Joint Strength: This can be directly measured by means of conventional tensile testing to give a value in kN, however to translate this onto a 40 point index scale requires the setting of extreme values and the assumption of an overall relationship.

Applying past experience and process knowledge, for a nominal 5.5mm joint thickness, it can be predicted that 10kN shear strength would be a realistic maximum (40 point) that we could hope for from any single point joining process. At the other extreme (0 points) was given a nominal 2kN shear strength. The relationship between points was assumed to be linear which is shown graphically in fig 4.3.

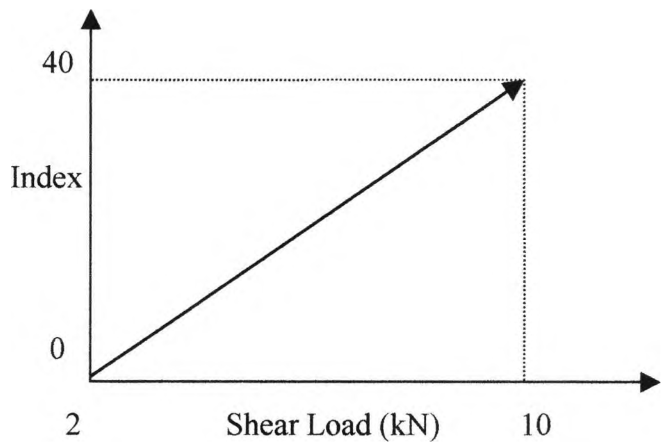


Fig 4.3 Shear Load v Index

B. Aspect Measure: This can be split into two contributors.

(I) ***Flare to Shank ratio (20 points);*** this can be simply derived by measuring a sectioned joint and equating it as a ratio of rivet shank diameter. As previously, extreme values can be set and a linear relationship between them assumed. In this case a maximum target of '1.5' giving 20 points had already been established with the bottom extreme being '1' for no flair gaining 0 points. Fig 4.5 illustrates this graphically.

(ii) *General Appearance*; this was very much a subjective assessment based on past experiences with emphasis on the need to avoid cracking and other undesirable material distortions. Scoring on a 0 to 15 scale.

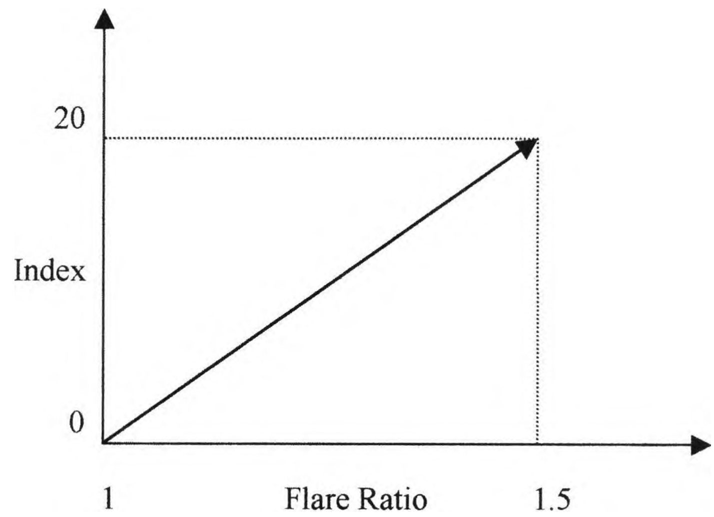


Fig 4.5 Flare Ratio v Index

C. Joint Loading: The effective load applied to form the riveted joint can be measured directly from the Load V Displacement curve. Translation of this load into a representative index again requires the determination of extreme values and characteristic relationship.

In this case the lower the load the better, taking 30kN as a realistic minimal setting load for 5mm diameter rivets, representing a maximum 15 point index. The maximum system load of 45 kN, becomes the worst case and hence '0' point index. A linear relationship is again assumed as shown in fig 4.6.

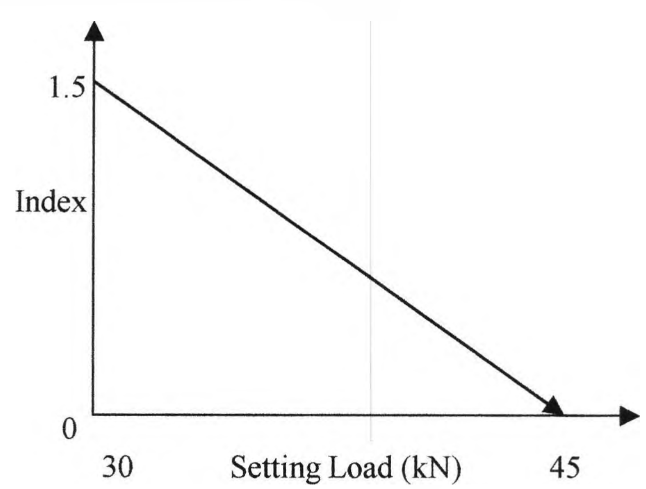


Fig 4.6 Setting Load v Index

D. Cost: Since all fasteners will be produced by means of the cost effective cold forming process, no large cost differences will be anticipated. Small relative variations will occur as a function of forging complexity.

4.2.3 Experimentation and Results Gathering

For each factor combination, both rivets and anvils were produced in order to carry out the experimentation process as laid down in table 4.5.

Experiments were conducted with a protocol aimed at keeping external influences to the process at a minimum at all times. During each experimental run, results were gathered and converted into none dimensional values by means of the relationships established in **4.2.2.** Under each setting of imposed noise (S) and repetition (X) a full set of results were recorded, including the final calculation of 'objective function', in accordance with equation **(4.3)**. Table 4.6 shows an example of a record chart for **S1, X1** where the rivet length is 9mm, similar charts of results were generated for each level of imposed 'noise' and repetitions.

All experiments were conducted using equipment incorporating joint 'quality monitoring' capability, (see **2.4.1**). This allowed the recording of a further set of results, for each individual experiment, in the form of **Load V Displacement** graphs taken during each rivet setting operation. Fig 2.15 shows the typical form of such curves. As established in **3.3.1**, a great deal can be learned about process behaviour by studying process curves. In particular, the determination of energy usage during joint formation will be of special interest as a parameter, which can be purposely minimised.

Table 4.6 Experiment Chart S1/X1 (9mm rivet)

Experiment No L8C **Noise Setting S1** **Repetition X1**

Rivet Head Type	Flt Csk	Joint Material	Al Alloy
Rivet Gauge	3/16	Nom Joint Thickness	6mm
Rivet Length	9mm		

Experiment	Joint Strength (KN)	Joint Strength (Index)	Aspect (Flair)	Aspect (Index)	Set Load (KN)	Set load (Index)	Cost (£)	Cost (Index)	Objective function
1	7.829	29	1.21	11.4	40.88	4.12		6	50.52
2	7.651	29	1.24	12.6	41.31	3.69		5	50.29
3	7.162	25	1.19	11.6	40.66	4.34		5	45.9
4	7.161	25	1.2	11.5	40.88	4.12		5	45.6
5	7.651	29	1.15	8	41.5	3.5		5	45
6	8.051	30	1.26	19	41.88	3.12		6	58.12
7	7.740	29	1.25	19.4	41.38	3.62		5	57
8	7.695	29	1.22	19.3	41.6	3.4		5	56.7

Objective Function (OF) = 40 x Joint Strength + 35 x Aspect Measure + 15 x Joint Loading + 10 x Cost

4.3 Statistical Analysis of Results

The objective of this experimental plan has been to determine factor combinations which would give both optimum product performance whilst being *Robust* to external influences (noise).

From the seven factors explored by the experimentation process, data in terms of *Objective Function* and *Process Energy* absorption has been created. By using this information and analysing it statistically, along with a study of factor effects, an optimum product will be definable.

Determining which factors are significant to the product performance is carried out by means of **ANOVA** (analysis of variance) techniques, the results of which highlight the factors where design effort would best be applied to maximum effect. Many standard texts such as Krottmaier (1993) describe the process in detail, which is introduced in **2.3.3**.

In **1.2.5** the relationship between 'quality loss' and 'process noise' was introduced in both monetary and performance terms. For these experiments, several different approaches to handling both pre-determined, and random noise in the process, have been applied and correlated together, to give further confirmation of dominant factors.

4.3.1 Indirect Variance Analysis

Where it is not necessary to determine the exact correlation between the inner and outer matrices, but to only determine factor combinations that are robust to outer influences, the analysis can be carried out directly using the variance s^2 that causes the outer matrix.

In order to carry out a variance analysis, the logarithmic normal distribution for s^2 has to be transformed into a normal distribution. This gives a characteristic value for each factor combination that describes the variance behaviour of each combination.

Transformation $$Z(\Theta) = 10 \log s^2 \qquad \textbf{(4.5)}$$

Considering each level of the signal **(S)** to represent potential process noise, i.e joint thickness variation, the average repetition values **(XAV)** under each signal setting becomes the repetition value for the purpose of analysis.

$$s^2 = \frac{1}{n-1} \Sigma(X_{AV} - \bar{X})^2 \qquad \textbf{(4.6)}$$

Calculation of performance characteristic for the two groups of experiments carried out (6.5mm and 9mm long rivets) is shown in tables 4.7 and 4.8 This information is added onto the full experimental data chart which includes both measured performance values and process energy absorption, tables 4.9 and 4.10.

S1	S2	S3			
X_{AV}	X_{AV}	X_{AV}	$\bar{X}$	S	Z(Θ)
56.9	58.4	54.4	56.5	2.02	6.12
50.6	59.7	53.8	54.7	4.62	13.28
52.7	58.5	54.7	55.3	2.95	9.38
50.1	50.4	51.7	50.7	0.85	-1.39
49	57.1	53.9	53.3	4.08	12.21
49.8	57.3	54.6	53.9	3.8	11.59
53	59.8	61.3	58	4.42	12.91
47.9	55.1	49.8	50.9	3.73	11.43
					Σ 75.53

Table 4.7 Performance statistic for 6.5mm long rivet

S1	S2	S3			
X_{AV}	X_{AV}	X_{AV}	$\bar{X}$	S	Z(Θ)
50.2	49.2	53.8	51	2.42	7.68
49.5	53.2	51.7	51.5	1.86	5.39
47.6	54.8	55.5	52.6	4.37	12.8
45.9	52.9	49.6	49.5	3.5	10.88
43.7	53.9	55.3	51	6.33	16.02
57.3	57.1	56	56.8	0.7	-3.1
56.8	57.4	57.3	57.2	0.32	-4.95
55.5	59	57.3	57.3	1.75	2.43
					Σ47.15

Table 4.8 Performance statistic for 9mm long rivet

To determine which factors have the most significant influence on the final process performance, a variance analysis was carried out as follows.

Correction factor $$CF = \frac{(\Sigma xi)^2}{n} \qquad \textbf{(4.7)}$$

Where CF = Sm (sum of squares of mean) which is deducted from each equation to give the individual factor effect.

For 6.5mm long rivet:

$$CF = \frac{75.53^2}{8} = 713$$

And for the sum of squared deviations, typically:

$$SA = \frac{(\Sigma A1)^2}{n} + \frac{(\Sigma A2)^2}{n} - CF \qquad \textbf{(4.8)}$$

$$SA = 187.5 + 579.3 - 713 = \underline{53.86}$$

Summarising results into an ANOVA chart gives:

	f	*S*	*V*	F
A	1	53.86	53.86	24.15 *
B	1	14.8	14.8	6.64
C	1	17.95	17.95	8.05
D	1	4.170		
E	1	0.30		
F	1	44.2	44.2	19.82*
G	1	36.5	36.5	16.37
(e)	(2)	4.47	2.23	
T	7	171.78		

Where Variance of factor $V = \frac{S}{f}$

and $F = \frac{V(x)}{V(e)}$

from the table of F values ** F ½ (99%) = 98.5

* F ½ (95%) = 18.5

The above analysis shows only factors A and F to be significant at the 95% level.

Carrying out the same analysis for the 9mm long rivet, yields the following ANOVA chart of results.

	f	S	V	F
A	1	86.64	86.64	18.1
B	1	2.740		
C	1	84.8	84.8	17.6
D	1	31.64	31.64	6.56
E	1	6.90		
F	1	90.1	90.1	18.7*
G	1	85.2	85.2	17.7
(e)	(2)	9.64	4.82	
T	7	388		

The ANOVA shows factors A and F to be significant at the 95% level for the 6.5mm long rivet, with factor F also being significant at the same level for 9mm long rivets. Factor A in this case is just outside the significance range.

In conclusion, for this statistical analysis, factors A and F would be given priority in the fastener and associated tooling design.

Table 4.9 Experimental Data, 6.5mm long Rivet

Rivet Head Type: Flt Csk	Joint Material Type: Al alloy, Type 5251 H22
Rivet Gauge(Nom): 5mm	Nom Joint Thickness (S2): 3mm
Rivet Length: 6.5mm	Rivet Plating: None

	Design Parameter Matrix							Noise (Signal) Parameter Matrix													
Factor	A	B	C	D	E	F	G	S1 (3.2mm)				S2 (3mm)					S3 (2.7mm)				
Column	1	2	3	4	5	6	7	X1	X2	AV	J	X1	X2	X3	AV	J	X1	X2	AV	J	Z(Θ)
1	1	1	1	1	1	1	1	55.3	58.6	56.9	95.8	58	58.2	58.9	58.4	89	53.9	55	54.4	90.5	6.12
2	1	1	1	2	2	2	2	48.7	52.5	50.6	69.8	58.5	60.8	59.9	59.7	71	53.9	53.7	53.8	76	13.28
3	1	2	2	1	1	2	2	52.4	53	52.7	65	58.3	60.1	57	58.5	86.6	54.6	54.9	54.7	70	9.38
4	1	2	2	2	2	1	1	50.8	49.5	50.1	83.6	49.4	50.3	51.6	50.4	67.6	52.6	50.8	51.7	81	-1.39
5	2	1	2	1	2	1	2	49.1	49	49	72.6	56.7	59.1	55.4	57.1	78	53.3	54.5	53.9	69	12.21
6	2	1	2	2	1	2	1	50.8	48.8	49.8	78.2	58.5	56.3	57	57.3	72.4	54.4	54.8	54.6	61.2	11.59
7	2	2	1	1	2	2	1	53.6	52.4	53	72.3	60	60	59.4	59.8	82.6	62.3	60.3	61.3	63.9	12.91
8	2	2	1	2	1	1	2	49.2	46.7	47.9	76.5	52.6	55.8	57	55.1	75.8	50.2	49.5	49.8	64.5	11.43

AV = Average of repetitions.
J = Process energy absorption in Joules.
S = Joint thickness settings (against which process should be robust).
X = Repetitions

Z(Θ) = Performance Statistic ($Z(\Theta) = 10 \log s^2$) Where $s^2 = \frac{1}{n-1} (X_{AV} - \bar{X})^2$

Table 4.10 Experimental Data 9mm long rivet

Rivet Head Type: Flt Csk	Joint Material Type: Al alloy Type 5251H22
Rivet Gauge(Nom): 5mm	Nom Joint Thickness (S2): 5.5mm
Rivet Length: 9mm	Rivet Plating: None

	Design Parameter Matrix							Noise (Signal) Parameter Matrix													
Factor	A	B	C	D	E	F	G	S1 (6mm)				S2 (5.5mm)					S3 (5mm)				
Column	1	2	3	4	5	6	7	X1	X2	AV	J	X1	X2	X3	AV	J	X1	X2	AV	J	$Z(\Theta)$
1	1	1	1	1	1	1	1	50.5	49.9	50.2	182	49.5	49.1	48.9	49.2	153	54	53.6	53.8	166	7.68
2	1	1	1	2	2	2	2	50.3	48.7	49.5	137	53.1	52	54.5	53.2	139	50	53.5	51.7	141	5.39
3	1	2	2	1	1	2	2	45.9	49.4	47.6	151	56	55.2	53.3	54.8	124	54.4	56.6	55.5	133	12.8
4	1	2	2	2	2	1	1	45.6	46.2	45.9	158	53.6	51.8	53.4	52.9	131	49	50.3	49.6	157	10.88
5	2	1	2	1	2	1	2	45	42.5	43.7	160	55.6	54.8	51.2	53.9	140	53	57.6	55.3	135	16.02
6	2	1	2	2	1	2	1	58.1	56.6	57.3	141	58.2	56.5	56.6	57.1	133	55.6	56.4	56	129	-3.1
7	2	2	1	1	2	2	1	57	56.7	56.8	155	57.2	58.2	56.8	57.4	144	59.6	55	57.3	129	-4.95
8	2	2	1	2	1	1	2	56.7	54.3	55.5	134	54.8	62.2	60.2	59	131	53.7	61	57.3	122	2.43

AV = Average of repetitions
J = Process energy absorption in Joules.
S = Joint thickness settings (against which the process should be robust).
X = Repetitions.

$Z(\Theta)$ = Performance statistic ($Z(\Theta) = 10\log s^2$). Where $s^2 = \frac{1}{n-1}(X_{AV} - \bar{X})^2$

4.3.2 Quality Cost Analysis

As reviewed in **1.2.5**, Taguchi has proposed the measuring of quality in terms of a financial loss to society. Closely related to this we can use a statistical measure of the quality of the product known as the *Signal to Noise Ratio* (S/N), which measures the performance and the effect of noise on that performance:

$$\frac{\text{Signal}}{\text{Noise}} = \frac{\text{Energy of the signal}}{\text{Energy of the noise}} = \frac{\text{Effect of the signal parameter}}{\text{Effect of the noise parameter}}$$

The form of the S/N ratio is directly tied to the loss function and is an evaluation of the stability of performance of a quality characteristic.

For the experimental data collected, noise will be present due to two reasons.

1. Variation between experimental repetitions (X1, X2,...)
2. Pre-set noise levels introduced into the experiment as joint thickness variation (S1, S2,...).

There are three forms of the S/N ratio; nominal is best, larger the better and the smaller the better. Since for this experiment, the direction for the performance, or objective function is towards a maximum, larger the better is the approach to be taken.

From equation **(1.6)**, S/N ratio (η) can be expressed in the form;

$$\eta = -10 \log \frac{1}{n} \sum \frac{1}{y_i^2} \qquad \textbf{(4.9)}$$

For each row of experimental data, a value for η was calculated across the full range of S's and X's and carried out for both 6.5mm and 9mm long rivets. (Table 4.11).

	6.5mm	9mm
EXP	η	η
1	35.1	34.1
2	34.8	34.75
3	34.9	34.4
4	34.1	33.93
5	34.6	34.07
6	34.66	35.09
7	35.26	35.14
8	34.19	35.16
T	277.61	276.1

Table 4.11 S/N ratio

As for the performance statistic (ZΘ),important factors can again be identified by means of the variance analysis. The following two completed *ANOVA's* show the results for S/N ratio for both lengths of rivet.

ANOVA 6.5mm long rivet

	f	*S*	*V*	F
A	1	00		
B	1	0.070		
C	1	0.85	0.85	28.62 **
D	1	0.56	0.56	19.06 **
E	1	0.01440		
F	1	0.346	0.346	11.65 *
G	1	0.0640		
(e)	(5)	0.1484	0.0297	
T	7	0.96		

where ** $F_{1/5}$ (99%) = 16.26

* $F_{1/5}$ (95%) = 6.61

ANOVA 9mm long rivet

	f	*S*	*V*	F
A	1	0.973	0.973	6.75
B	1	0.2060		
C	1	0.2120		
D	1	0.1060		
E	1	0.97	0.97	6.73
F	1	0.38	0.38	2.638
G	1	0.0520		
(e)	4	0.576	0.144	
T	7	2.899		

where ** $F_{1/4}$ (99%) = 21.2

* $F_{1/4}$ (95%) = 7.71

Although the above two sets of results are part of the same experiment, there appears to be very little similarity between the factors demonstrating significance. From this and other analysis, the trend generally appears to show the 6.5mm long rivet experiment as demonstrating stronger significance of factors.

4.3.3 Dynamic Considerations

In **2.3.2** the Taguchi approach for dealing with the dynamic aspects of continuous response to continuous signal changes was introduced. Through the imposing of external noise influences in terms of material thickness changes, (**S**) an 'outer array' has been generated which is further subject to noise as a function of repetition error. Calculations of the S/N ratio, can subsequently be performed by using equation **(2.4)**. Krottmaier (1993) gives an alternative equation for the S/N ratio in terms of the performance statistic.

$$Z(\Theta) = 10 \log \left[\frac{S_{Signal} - (f_{Signal} \times V_{(e)})}{S_{(e)} + (f_T - f_{(e)}) \times V_{(e)}} \right] \qquad \textbf{(4.10)}$$

For this experiment the signal parameter is in effect an imposed value of noise which represents the three levels of joint thickness S1, S2 & S3.

Hence,

High S/N - Effect of imposed noise high, random noise low

Low S/N - Effect of imposed noise low, random noise high

Considering the 6.5mm long rivet only, the resulting calculations yielded the following (table 4.12).

EXP	$Z(\Theta)$
1	0.06
2	6.766
3	11.8
4	-3.37
5	10.58
6	8.856
7	12.55
8	4.09

Table 4.12 Dynamic Performance Statistic

Using this data it is again possible to identify the most significant factors by carrying out an ANOVA

ANOVA 6.5mm long rivet

	f	*S*	*V*	F
A	1	54.1	54.1	56.9**
B	1	0.2260		
C	1	2.3350		
D	1	43.52	43.52	45.8**
E	1	0.2870		
F	1	102.36	102.36	107.75**
G	1	28.07	28.07	29.55*
(e)	3	2.848	0.95	
T	7	231.67		

Where **F 1/3 (99%) = 34.12
*F 1/3 (95%) = 10.13

4.3.4 Factor Significance

In order to clarify the general trend for factor significance across the three types of ANOVA performed, the selected factors were identified in a summary sheet (Table 4.13). For the 6.5mm rivet the data clearly shows factor F to be significant irrespective of the analysis approach, with factors A & D also being significant across two of the three methods.

	Direct Variance		S/N Achieving a Max		S/N Pre-set & Random	
Factor	95%	99%	95%	99%	95%	99%
A	*					*
B						
C				*		
D				*		*
E						
F	*		*			*
G					*	

Table 4.13 ANOVA summary

4.3.5 Energy Effects

Minimisation of joint loading and subsequently the energy absorbed by the process, are key factors in the determination of an optimum product design. During the conducting of experiments, recordings were made of Load v Displacement characteristics for each joint created (**4.2.3).**

In general: Energy into system = Energy used + loses **(4.11)**

Which for this process (performed by means of hydraulic pressure) can be broken down as:

Energy from motor = Energy to pierce joint + Energy to flare rivet + Energy to form joint material + Energy to overcome process friction + Energy absorbed by structure + Equipment loses **(4.12)**

Considering work done by a force, the area under the load v displacement curve represents this as the integral of the curve function.

If F(x) is the force in N and x is the distance in m, in a small displacement δx the work done, δW is given approximately by $\delta W = F\delta x$. Hence as the point of application moves from x = a to x = b, the work done is.

$$W = \lim \sum_{b}^{a} F\,\delta x = \int_{b}^{a} F\,dx \qquad \text{Nm (J)} \qquad \textbf{(4.13)}$$

A simple way of calculating this area, and hence arriving at the energy absorbed by the process can be performed by means of 'Simpsons' rule, as follows.

$$\text{Where} \quad W = A = \frac{s}{3}\left[\,(F+L) + 4E + 2R\right] \qquad \textbf{(4.14)}$$

Where (F+L) = First plus last ordinates

4E = 4 x the sum of even ordinates

2R = 2 x the sum of odd ordinates

s = Width of each strip

For each factor combination and noise level setting, the process energy absorbed was subsequently calculated.

6.5mm Rivet Length								
	Factor	A	B	C	D	E	F	G
S1	Average 1	78.55	79.1	78.6	76.4	78.9	82.1	82.5
	Average 2	74.8	74.35	74.85	77	74.6	71.3	71
	Effect	-3.76	-4.75	-3.75	+0.6	-4.3	-10.8	-11.5
S2	Average 1	78.5	77.6	79.6	84	81	77.6	77.9
	Average 2	77.2	78.1	76.1	71.7	74.8	78.15	77.9
	Effect	-1.3	+0.55	-3.45	-12.3	-6.2	0.55	0
S3	Average 1	79.4	74.2	73.7	73.3	71.5	76.2	74.1
	Average 2	64.6	69.8	70.3	70.7	72.5	67.7	69.9
	Effect	-14.7	-4.35	-3.4	-2.62	+0.97	-8.5	-4.2

Table 4.14 Energy Effects for 6.5mm Long Rivet

9mm Rivet Length								
	Factor	A	B	C	D	E	F	G
S1	Average 1	157	155	152	162	152	158.5	159
	Average 2	147.5	149.5	152.5	142.5	152.5	146	145.5
	Effect	-9.5	-5.5	+0.5	-19.5	+0.5	-12.5	-13.5
S2	Average 1	136.7	141.2	141.7	140.2	135.2	138.7	140.2
	Average 2	137	132.5	132	133.5	138.5	135	133.5
	Effect	+0.3	-8.7	-9.7	-6.7	+3.3	-3.7	-6.7
S3	Average 1	149.2	142.7	139.5	140.7	137.5	145	145.2
	Average	128.7	135.2	138.5	137.2	140.5	133	132.7
	Effect	-20.4	-7.4	-1	-3.45	+3	-12	-12.5

Table 4.15 Energy Effects for 9mm Long Rivet

Considering the factor settings in relation to the amount of energy absorbed, this can be best visualised by means of a *response table.* From the orthogonal array, the calculated energy values at each factor level were averaged and the respective effect of going from level 1 to level 2 calculated. This gives either a positive or negative result due to the direction of change. Fig 4.7 shows an illustrative example of a single factor effect. For each rivet length and noise level setting, a full range of effects were calculated giving the results shown in tables 4.14 and 4.15.

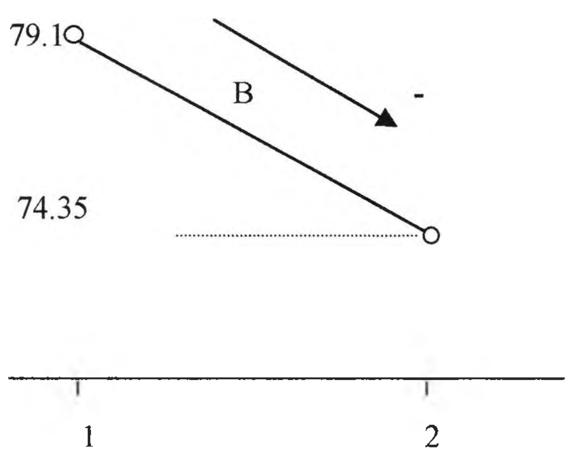


Fig 4.7 Energy Effect Factor 'B' (6.5mm long rivet)

The objective of the energy analysis is to determine which product design produces the best results with the minimum amount of energy being used by the process. To visualise if any obvious patterns exist in this data, a summary chart was formed showing the factor level settings which gave the **lowest** energy usage, table 4.16.

	Ax	Ay	Bx	By	Cx	Cy	Dx	Dy	Ex	Ey	Fx	Fy	Gx	Gy
S1	2	2	2	2	2	1	1	2	2	1	2	2	2	2
S2	2	1	1	2	2	2	2	2	2	1	1	2	0	2
S3	2	2	2	2	2	2	2	2	1	1	2	2	2	2
(1)	1		1		1		1		4		1		0	
(2)	5		5		5		5		2		5		5	

Where x = 6.5mm rivet length, y = 9mm rivet length

Table 4.16 Summary of Energy Effect Factor Levels

As can be seen from table 4.16, with the exception of factor E, level-setting **2** clearly dominates as the setting which satisfy the criterion for minimal energy usage.

4.3.6 Main Effects

The influence of main effects of factors in terms of the overall objective function is the primary selection criterion for this analysis.

As a result of the statistical analysis previously carried out, the data had been transformed into various formats of performance statistic. Although main effects could be studied by means of these overall performance measures for each experiment, the breaking down and analysis of direct data under each noise set level was considered preferable. In order to simplify the data, the results for each experiment repetition were averaged for each level of noise setting, main effects were subsequently calculated using these values, the results of which are shown in tables 4.17 and 4.18.

6.5mm Rivet length								
	Factor	A	B	C	D	E	F	G
S1	Average 1	52.6	51.6	52.1	52.9	51.8	51	52.4
	Average 2	49.9	50.9	50.4	49.6	50.7	51.5	50
	Effect	-2.7	-0.7	-1.7	-3.3	-1.1	+0.5	-2.5
S2	Average 1	56.75	58.1	58.3	58.4	57.3	55.6	56.5
	Average 2	57.3	55.95	55.8	55.6	56.75	58.8	57.6
	Effect	+0.55	-2.15	-2.5	-2.8	-0.55	+3.2	+1.1
S3	Average 1	53.7	54.2	54.8	56.1	53.4	52.5	55.5
	Average 2	54.9	54.4	53.75	52.5	55.2	56.1	53.1
	Effect	+1.21	+0.2	-1.06	-3.6	+1.77	+3.61	-2.4

Table 4.17 Main Effects for 6.5mm Long Rivets

9mm Rivet length								
	Factor	A	B	C	D	E	F	G
S1	Average 1	48.3	50.2	53	49.6	52.7	48.8	52.6
	Average 2	53.3	51.4	48.6	52.1	49	52.8	49.1
	Effect	+5.05	+1.25	-4.4	+2.46	-3.7	+4	-3.5
S2	Average 1	52.5	53.3	54.7	53.8	55	53.7	54.1
	Average 2	56.8	56	54.7	55.5	54.3	55.6	55.2
	Effect	+4.3	+2.7	0	+1.7	-0.7	+1.9	+1.1
S3	Average 1	52.7	54.2	55	55.5	55.7	54	54.2
	Average 2	56.5	54.9	54.1	53.7	53.5	55.1	55
	Effect	+3.8	+0.7	-0.9	-1.8	-2.2	+1.1	+0.8

Table 4.18 Main Effects for 9mm Long Rivets

Following the same procedure as developed for the energy analysis, the relative factor levels were summarised into a single chart as shown in table 4.19. In this case the levels being given were for those settings which gave the **maximum** magnitude of *Objective function* value.

	Ax	Ay	Bx	By	Cx	Cy	Dx	Dy	Ex	Ey	Fx	Fy	Gx	Gy
S1	1	2	1	2	1	1	1	2	1	1	2	2	1	1
S2	2	2	1	2	1	0	1	2	1	1	2	2	2	2
S3	2	2	2	2	1	1	1	1	2	1	2	2	1	2
(1)	1		2		5		4		5		0		3	
(2)	5		4		0		2		1		6		3	

Where x = 6.5mm long rivet, y = 9mm long rivet

Table 4.19 Summary of Factor Levels for Main Effects

For energy and main effects the above simple analysis takes no account of the magnitude of their effects, however where no strong cost constraints between factors apply, this is a valid omission.

4.3.7 Formation of Design Selection Matrix

Three sources of information from the experimental programme are now available.

1. Statistical analysis
2. Energy effects
3. Main effects

In addition, as for any data generated from factorial experiments, the need to translate results with a degree of Engineering knowledge and common sense must be included. Since one of the primary requirements of the product is to be robust over the full range of noise settings, a simple analysis would be to take the numerical sum of all favourable level settings, which satisfy the respective criterion of both energy and main effects. In combining what are in effect very different performance measures, it is important that some correction factor be applied to balance the relative effects of energy and objective function. As a judgement of relative importance, the main effects were deemed to be more important than the energy effects, by a factor of 3. Combining these two effects into a single weight can then be carried out, giving the following numerical ranges:

Energy	0 - 6
Main Effect (OF)	0 - 18
Weight	0 - 24

The potential for further exploring the 'Correlation Roof' of the 'House of Quality', was realised in **2.1.4**. Furthermore the requirements of Hypothesis # 1 and 2 demand the creation of both robust product design and the introduction of Engineering Science results into the design selection procedure.

In keeping with the above, the mechanism selected to bring together **effects analysis**, **statistical analysis** and the **product factor levels** was modelled on *The Roof of the House of Quality*, the result being the **Design Selection Matrix,** fig 4.8.

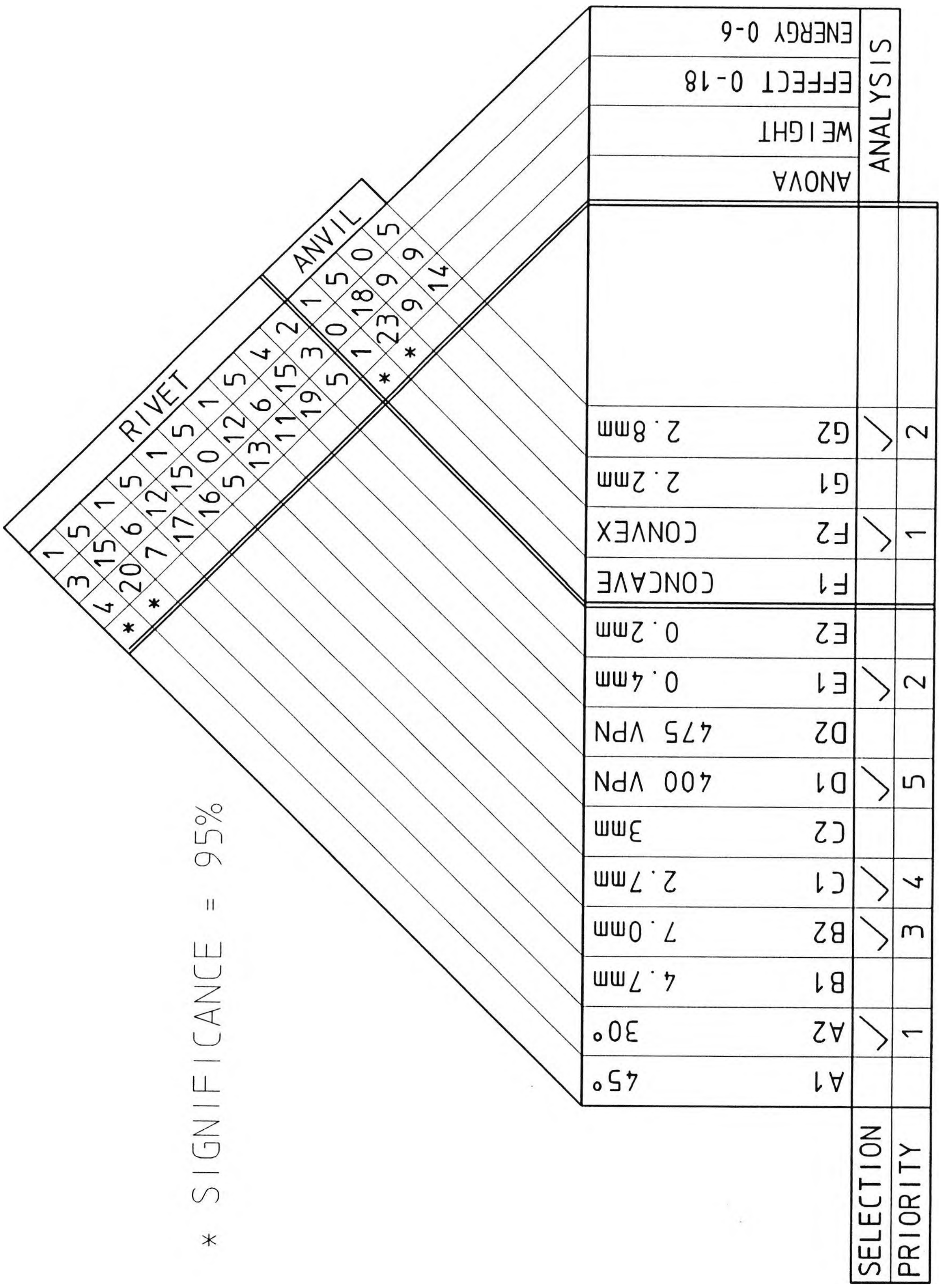


Fig 4.8 Design Selection Matrix

This represents the product of RED (Robust Engineering Design) and Engineering science brought together in a single design selection matrix.

Factors sub-divided into their respective levels, along with quantitative information, are loaded into the horizontal grid of the matrix. To the side of this information is placed the methods of analysis, consisting of ANOVA, energy effects, main effects and their subsequent combination into a numeric weight figure. Intersection points are next found between the analysis methods and factor levels through the roof of the matrix. At each such intersection, the previously calculated effects analysis results can be placed. A simple numerical assessment of preferred factor level settings could then be made along with their priority order for inclusion in the final product, both weight and statistical significance combine to allow this selection. Since this fastening process includes the two elements of *rivet* and *anvil,* a further decomposing of the roof matrix was possible, as a result of which both elements could be individually prioritised.

This stage represents the core objective of the bringing together of RED, DFD and Engineering Science through a simple matrix method.

After extracting results from the selection matrix and applying any Engineering interpretation felt necessary, the product for verification testing can be proposed. Table 4.20 shows the important factors along with their selected level settings for inclusion in both the rivet and anvil designs.

Factor	Level	Setting
Taper Poke	A2	30
Depth of Poke	B2	7.0mm
Hole Diameter	C1	2.7mm
Rivet Material Hardness	D1	400VPN
Land Width	E1	0.4mm
Anvil Profile Features	F2	Concave
Anvil Profile Depth	G2	2.8mm

Table 4.20 Selected Factor Settings

Fig 4.9 gives the full manufacturing drawing for the two lengths of rivet.

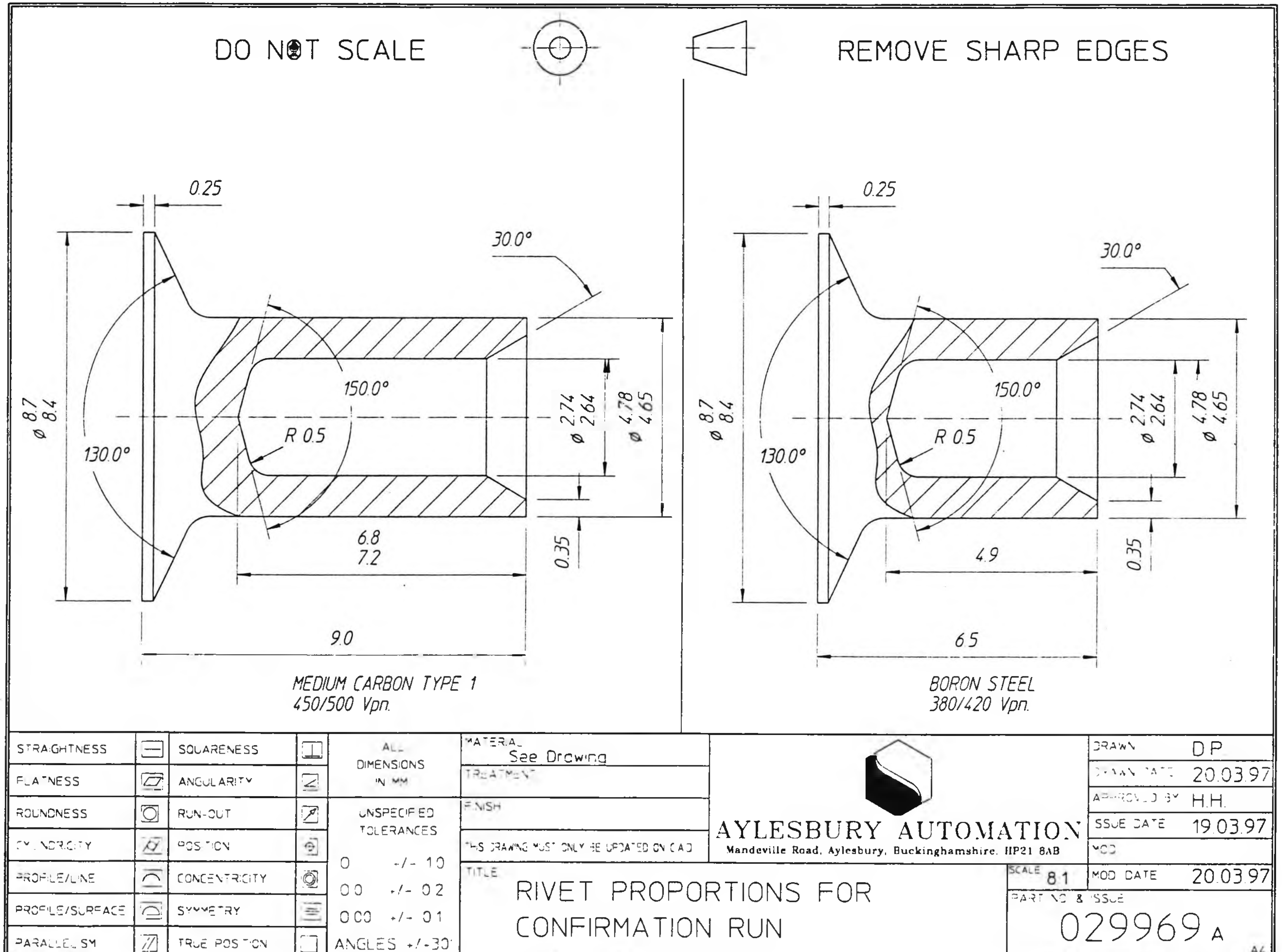


Fig 4.9 Proposed Rivet Design

In view of other project data, an important departure from the experimental findings was made in respect of the 'Rivet material hardness'. For the 9mm long rivet a harder Medium carbon at 450/500 VPN was used whilst for the 6.5mm long rivet a combination of this and a softer Boron material at 380/420 VPN were to be compared in the confirmation experiment.

4.3.8 Performance Prediction

Performance of a proposed product is possible by means of a theory based on least squares. This approach is given by Grove & Davis (1992) which yields the following equation.

Prediction = y + 1/2[Inner product of row of 1s with row of effects] **(4.15)**

For the proposed optimum rivet design, taking experimental data from table 4.17 and averaging over the full signal/noise range, yields an orthogonal contrast for each factor, table 4.21.

Factor	A	B	C	D	E	F	G	Total Av
	-1	-1	-1	-1	-1	-1	-1	56.5
	-1	-1	-1	+1	+1	+1	+1	54.7
	-1	+1	+1	-1	-1	+1	+1	55.3
	-1	+1	+1	+1	+1	-1	-1	50.7
	+1	-1	+1	-1	+1	-1	+1	53.3
	+1	-1	+1	+1	-1	+1	-1	53.9
	+1	+1	-1	-1	+1	+1	-1	58
	+1	+1	-1	+1	-1	-1	+1	51
Divisor	4	4	4	4	4	4	4	y =54.2
Contrast	-0.25	-0.85	-1.75	-3.2	0	+2.6	-1.2	

Table 4.21 Factor Contrasts (6.5mm long rivet)

The selected factor combination from table 4.20 can then be expressed in relation to its factor contrast, table 4.22.

A2	B2	C1	D1	E1	F2	G2
+1	+1	-1	-1	-1	+1	-1
-0.25	-0.85	-1.75	-3.2	0	+2.6	-1.2

Table 4.22 Selected Factor Contrasts (6.5mm long rivet)

From table 4.22 data, prediction for the overall *objective function* for the 6.5mm long rivet can be calculated as follows:

Prediction $= 54.2 + \frac{1}{2}[(+1)(-0.25) + (+1)(-0.85) + (-1)(-1.75) + (-1)(-3.2) + (-1)(0) + (+1)(+2.6) + (+1)(-1.2)]$

$=$ **56.8**

Similarly for the 9mm long rivet, averaging out data from table 4.18.

Factor	A	B	C	D	E	F	G	Total Av
	-1	-1	-1	-1	-1	-1	-1	51.06
	-1	-1	-1	+1	+1	+1	+1	51.46
	-1	+1	+1	-1	-1	+1	+1	52.63
	-1	+1	+1	+1	+1	-1	-1	49.46
	+1	-1	+1	-1	+1	-1	+1	51
	+1	-1	+1	+1	-1	+1	-1	56.8
	+1	+1	-1	-1	+1	+1	-1	57.16
	+1	+1	-1	+1	-1	-1	+1	57.26
Divisor	4	4	4	4	4	4	4	y = 53.35
Contrast	+4.4	+1.55	-1.76	+0.78	-2.16	+2.32	-0.53	

Table 4.23 Factor Contrasts (9mm long rivet)

Again taking selected factor combinations from table 4.20, yields:

A2	B2	C1	D1	E1	F2	G2
+1	+1	-1	-1	-1	+1	+1
+4.4	+1.55	-1.76	+0.78	-2.16	+2.32	-0.53

Table 4.24 Selected Factor Contrasts (9mm long rivet)

Prediction $= 53.35 + \frac{1}{2}[(+1)(4.4) + (+1)(1.55) + (-1)(-1.76) + (-1)(0.78) + (-1)(-2.16) + (+1)(2.32) + (+1)(-0.53)]$

$=$ **58.79**

This analysis therefore provides us with a prediction of the likely *objective function* value, achievable with the new product design.

4.4 Developed Product Analysis

4.4.1 Verification Experiments

Products with optimised factor combinations were produced for both Rivets and Anvils to allow confirmation test joints to be made and evaluated. For the 9mm long rivets, six repetitions of experiments were carried out for each noise level setting (S1, S2 and S3) and evaluated in terms of the *objective function*, in exactly the same manner as for the original experimental tests. For the 6.5mm long rivets, the same procedure was followed, however in this case, two sets of results were generated to accommodate two types of rivet material and hardness.

For the 9mm long rivet, the experimental results are summarised in table 4.25.

Repetition	**S1**	**S2**	**S3**
1	64.3	53.5	52.05
2	60.15	58	51.32
3	60.71	57.8	50
4	59.98	58.4	48.8
5	60.56	54.6	49.63
6	60.13	57.3	50.69
Average	60.97	56.6	50.415
Std Dev'	1.653	2.04	1.18

Table 4.25 Test Data Summary (9mm long rivet)

Taking the average of all joint thickness settings in table 4.25, yields a value of **56** for the *objective function.* This shows the prediction of **58.79** to be a slight over estimate of expectations, although this only represents a 5% error.

For the 6.5mm long rivet, two alternative rivet materials were compared in the experiment. These were designated by 'M' for medium carbon steel and 'B' for boron treated steel, table 4.26 summarises the results.

Repetition	**S1**	**S2**	**S3**
1M	58.3	59	54.32
2M	60.3	58.5	55
3M	58.7	58.9	54.7
Mean	59.1	58.8	54.67
Std Dev'	1.058	0.264	0.34
1B	51	54.2	49.6
2B	51	51.9	49.4
3B	53.3	52.17	51.7
Mean	51.76	52.7	50.23
Std Dev'	1.328	1.26	1.13

Table 4.26 Test Data Summary (6.5mm long rivet)

As previously, the overall mean *objective function* can be calculated, in this case for each of the two material types.

For Boron Steel = **51.56**

For Medium carbon steel = **57.52**

In comparison with the predicted value of **56.8,** performance of Boron steel under performed by almost 10%, whereas medium carbon slightly exceeded predictions. This would suggest that using a rivet of a higher hardness gives a better overall performance, despite its known tendency to crack within the clench during joint formation. Further work into the application of high performance steels, capable of combining high hardness with malleability is required.

Further observations can be made regarding the process variability through calculations of the process standard deviation, values for which are shown in tables 4.25 and 4.26. The only significant observation to be made here, is the very low deviation experienced with the harder medium carbon rivet, by comparison with the much softer Boron steel rivet. Such a characteristic further strengthens the argument that harder grade rivets give superior joint performance.

4.4.1 Conclusions for New Product Design

As all previously generated data related to combination of new product variations, in order to evaluate the new product design fully, it was necessary to generate new test data for the original product design in a compatible format. Rivets of 6.5mm in length and made from the harder 'medium carbon' grade of steel, were set and evaluated by the same methods used in **4.2.3**. The results found are summarised in table 4.27.

Repetitions	S1	S2	S3
1	34.7	37	39.48
2	36.1	33.7	35.76
3	35.6	39.1	36.2
4	35.28	37.95	35.85
Average	35.42	36.94	36.82
Std Dev'	0.343	5.395	3.174

Table 4.27 Test Data for Original Rivet Design

Overall average value for the *objective function* from the above data is **36.4.** When compared with the average value of **57.52** achieved by the new design of rivet, a clear and distinct improvement to the product has been made. In addition, it can be seen that the overall standard deviation is both lower and more consistent over the three joint thickness settings.

It can thus be concluded, that the method of product design developed has permitted the design and specification of parameters, to yield a product performance far higher than that previously achieved.

As a point of interest, the 'golden proportion' as reviewed in **1.1.7** may offer scope for assisting the product design process beyond that of simple aesthetics. Considering some of the dimensional parameters of the new rivet design, we can compare what was eventually arrived at, to what the ratio of **1.618:1** would have yielded.

For a shank wall thickness of 1mm, the 'land width' would be 0.382 compared to the optimum value arrived at of 0.4mm.

Also for a shank diameter of 4.7mm, the 'poke' diameter would be 2.9mm compared to the optimum value arrived at of 2.7mm.

Although not precise, the results given by the 'golden proportion' are very close to those arrived at after an extensive experimentation programme. Further research into the potential uses of this natural ratio may well be justified.

As a result of this development and optimisation of the *self-pierce* riveting process, **Ferrari** of Italy have purchased this technology for the primary fastening system on a new sports car model code named **F131.** This will be manufactured in large numbers, by traditional Ferrari standards, and will be unique in the automotive industry by having a body shell, held together almost entirely by *self- pierce* rivets. In all over 1,000 joints are made in each vehicle body, replacing what would traditionally have been resistance (spot welding) methods. Furthermore the production line equipment used to carry out the process, was that developed by the design project as described in Appendix A.

Fig 4.10 shows some of the joints produced in samples of the F131 vehicle.

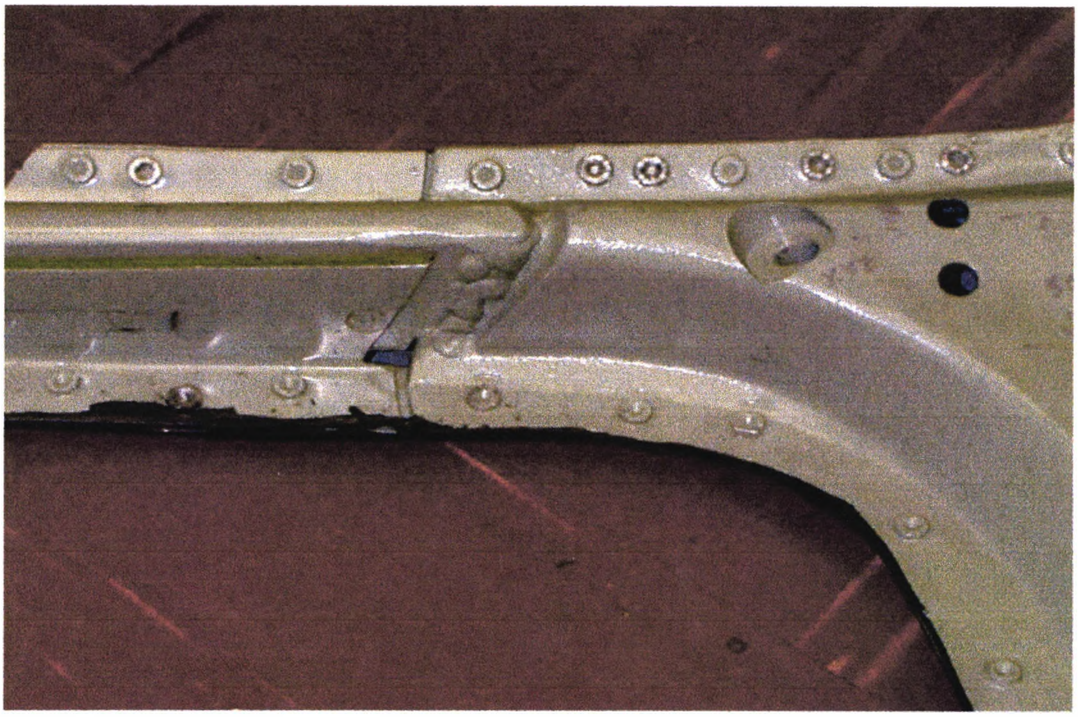


Fig 4.10 Ferrari F131 Riveted Joints

Chapter Five

Machinery Design with Matrices

In chapters 3 and 4, a design methodology was both developed and successfully applied in the creation of a new and optimised fastener process. Prior to this, examples of machinery/product design, performed within the DFD methodology framework, were also reviewed in chapter 2.

Following on from the above, the opportunity was taken to study the design process (particularly in relation to cost) within a small company structure, both building and adapting methods for machinery design within a particularly demanding environment.

5.1 Proposed Approach

5.1.1 Design Environment Considerations

A small company, engineering design environment was described in **1.4.2**. Operating in a highly demanding special purpose machinery market, the company **Spm,** has developed an enviable reputation for both designing and building 'made to order' machinery within very short lead times. In many cases, business is won on the bases that no other competitor is able to offer a viable technical solution to satisfy a customer's unique requirement.

Much of an organisations success can be attributed to its size and structure, particularly in relation to the product types which account for its business activity **(1.3.1)**. Research carried out by Kagioglou et.al (1998) compares the new product design activity (NPD) between large, medium and small organisations, focusing on the benefits and shortcomings of each approach. Larger organisations typically operate bureaucratic paper driven systems, which usually lead to extended development times and general inefficiencies. Driven by formal procedures and review criterion, they lack the flexibility to deal with the more functional barriers encountered by the design team and so owe more to management control than to original thought. An improvement to such a structure is proposed by Cooper (1994) who suggests the replacement of rigid mile stones (or gates) with 'Fuzzy' gates, whilst still retaining control mechanisms within the design process. By contrast, small and medium sized firms rely heavily upon the flexible diversity of expertise of the individual and so by default operate a concurrent engineering approach to product development. Kagioglou et.al (1998) gives examples of organisations representative of different sizes, all engaged in the design and manufacture of product *items*.

In the case of the design environment within **Spm**, due to its extremely small size, there is effectively only one department within the organisation, all members of which contribute directly to the value of the end product. Having such a flat structure has many benefits, particularly in terms of 'efficiency of effort'. A conventional company structure would involve sales, management, design, purchasing, production control, assembly and usually more, all working as individual departments but still communicating together as a collective team. For such a structure, communication becomes an essential skill, to be applied almost continually by all team members. From the authors own experiences of working in a variety of sizes of engineering organisations, routes of communication, no matter how well they are applied, result in a great deal of none 'value added' time being spent. Furthermore at each communication interface between departments, the chance of information becoming 'corrupted' is always a danger.

At the opposite extreme to this 'compartmentalised' company structure is that of the 'total individual', here one person takes on a collective roll dealing with all aspects of a project from sales negotiation to eventual manufacture. In such circumstances the need for internal company communication is almost eliminated, replaced by the entirely productive effort of the individual. With design engineering being the core skill, many peripheral activities can be performed directly as part of the design process. A good example of this is in the purchasing of component parts, in most organisations the designer determines what is required, communicates this information to a buyer who then proceeds to purchase the goods as instructed. In many instances however the purchaser finds problems in the supply or ambiguities in the information given, which requires more communication with the designer and so more time is spent passing information backwards and forwards. By comparison the 'total individual' would simply contact the supplier and place an order directly, dealing with any queries in one single communication.

An illustrative assessment of these two structure types is shown in Fig 5.1 and 5.2 for the entire manufacturing life-cycle. Although not precise, they do reasonably represent time utilisation as observed from a management position over many years.

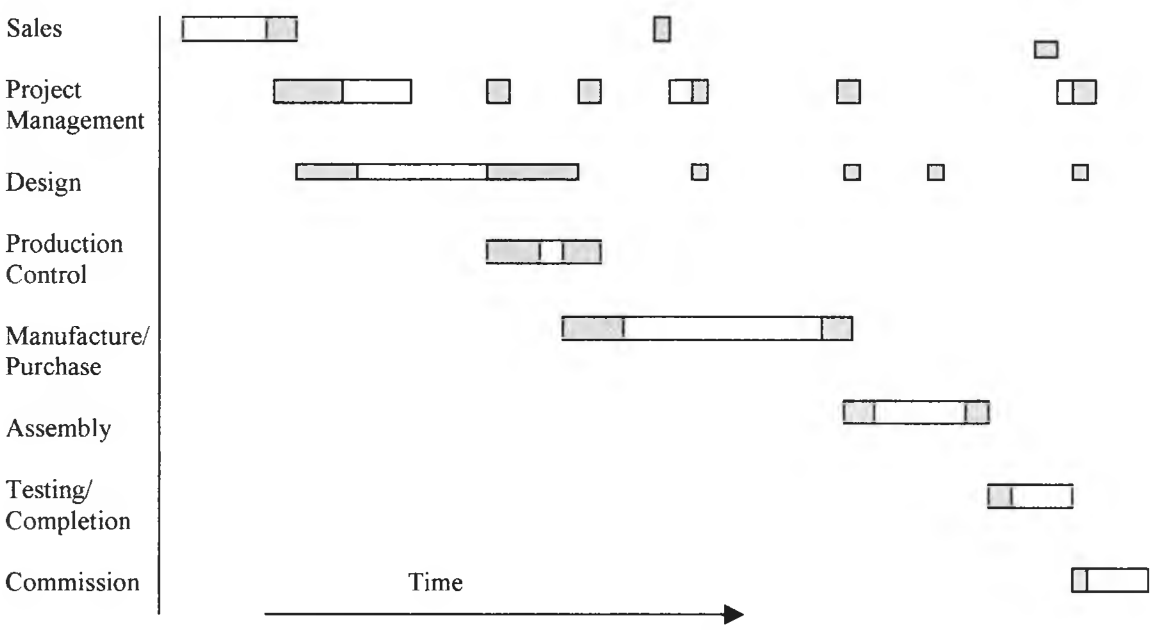


Fig 5.1 Time Utilisation Assessment - Departmental Structure

Where ▭ = Communication Time

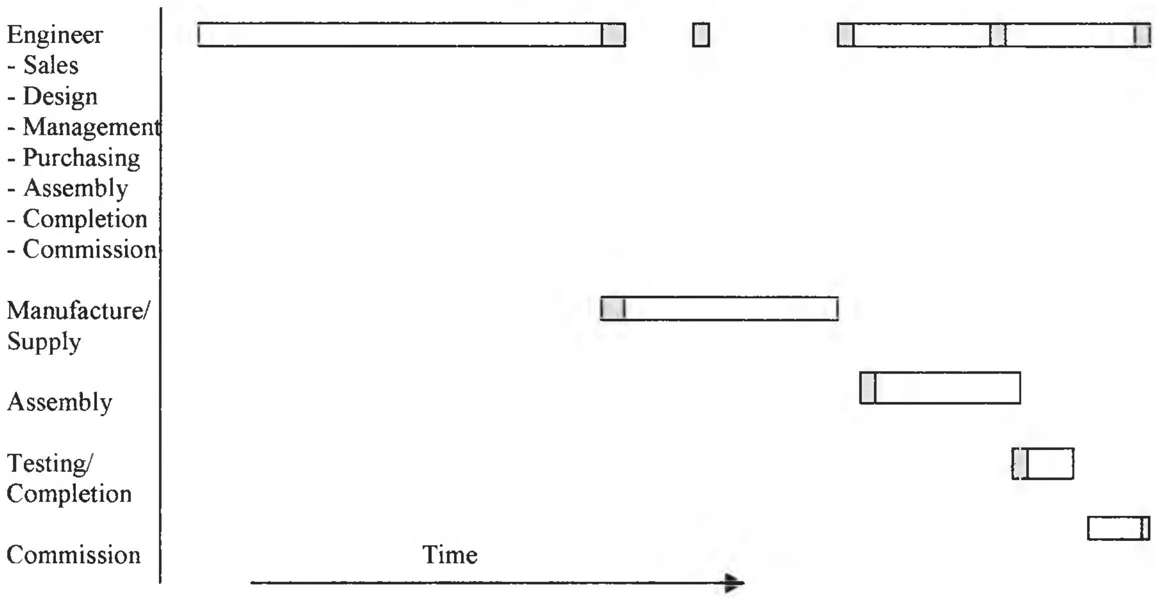


Fig 5.2 Time Utilisation Assessment - Small Organisation

Although the overall efficiency of the small organisation shown, is much higher in terms of 'Value added' time than that of the more conventional departmental type structure, the problem is finding individuals with sufficient all-round capability to deal with such a roll. The organisation of **Spm** represents a good example of this small company approach being utilised to maximum effect.

5.1.2 Cost in the Design Process

The basic sources and influences of product cost were introduced in **1.3.2**, a more detailed account of which was given in **2.2.** This further described methods of cost reduction, estimating and reviewed attempts at integrating 'design to cost' into a QFD framework.

In the satisfaction of Hypothesis # 3 **(1.5.1)** an effective marriage is sought between major cost drivers and elements within the QFD matrix. Comincini (1994) went some way to achieving this through the introduction of 'Correlation chains,' but lost the ability to take into account any interactions between the 'How' elements **(2.1.4 a)**. Previous work by Ding (1991) produced a cost model but was unsuccessful at applying it through a QFD framework **(2.2.4)**. The proposals made involved two separate approaches depending upon whether the product was to be entirely new, or an adaptation of an existing product, these are as follows.

Existing Product.

A. Design feature analysis
B. Possible design alternatives
C. Alternative production processes
D. Identification of cost drivers
E. Cost estimation
F. Trade-off on the cost model

New Product

A. Customer requirement analysis
B. Conceptual design
C. Design feature (characteristics)
D. Production planning
E. Identification of cost drivers
F. Cost estimation and cost model
G. Trade-off based on the cost model

When estimating possible product costs, particularly in the industry of 'One off' special purpose machines, the economics of trying to calculate accurate cost data would be prohibitive. This is due to the fact that a high level of the design would have to be carried out before a cost could be determined, an impractical situation where possibly less than 20% of enquiries from customers result in an order. What is therefore needed is a simple method, which focuses in on the main areas of cost, allowing estimates to be carried out with a reasonable degree of accuracy in a minimum of time. First identifying the major cost drivers is therefore a reasonable approach to take.

In applying the QFD matrices within the DFD methodology, it can be seen that the information generated at each of the five consecutive stages becomes progressively more detailed. This would lead to the conclusion that any cost data generated at the final stage would be the most accurate. However, as discovered in **chapter 3** and **Appendix A**, the DFD approach becomes very unwieldy and less effective after the first two stages. If every aspect of a product were to be carried forward through all stages, the volume of documentation would become prohibitive.

In support of Hypothesis # 3, a more specific statement can be made:

" Technical design functions (How's) are the major cost drivers"

The question now is where are these cost drivers and can they be practically evaluated? As suggested by Comincini (1994) it may be true to say that the top level design functions (stage 1 how's) are in fact the major cost drivers, however information at this stage is still in a fairly abstract and solution neutral form, not ideal for attaching financial values. Alternatively at stage 2, how's are in the form of viable system architectures, a point where cost data could be applied.

As part of a case study described in **2.5.2,** it was discovered that the stage 2 how's had to be grouped into subsystem for the analysis to have any meaning, furthermore relative importance's of characteristics within subsystems and the relative importance's of subsystems themselves could be calculated. With this new structure applying cost data directly to the DFD chart becomes possible.

Fig 5.3 illustrates the proposed chart layout, in this case using data from appendix **A** as an example. Cost data (where applicable) is added to each subsystem characteristic from either an existing database or by estimation, further normalisation of values onto a scale of 1-9 can then take place as for the technical evaluations. With target cost data added to the chart, costing issues can now be considered when making the appropriate selections.

As a cautionary note, apparent costs can sometimes be a very deceptive measure of true final costs, in many cases what has appeared to be a most cost-effective solution, in the end turns out to be the most expensive. This is where there is no substitute for good Engineering judgement, a skill that must not be missed no matter what the methodology.

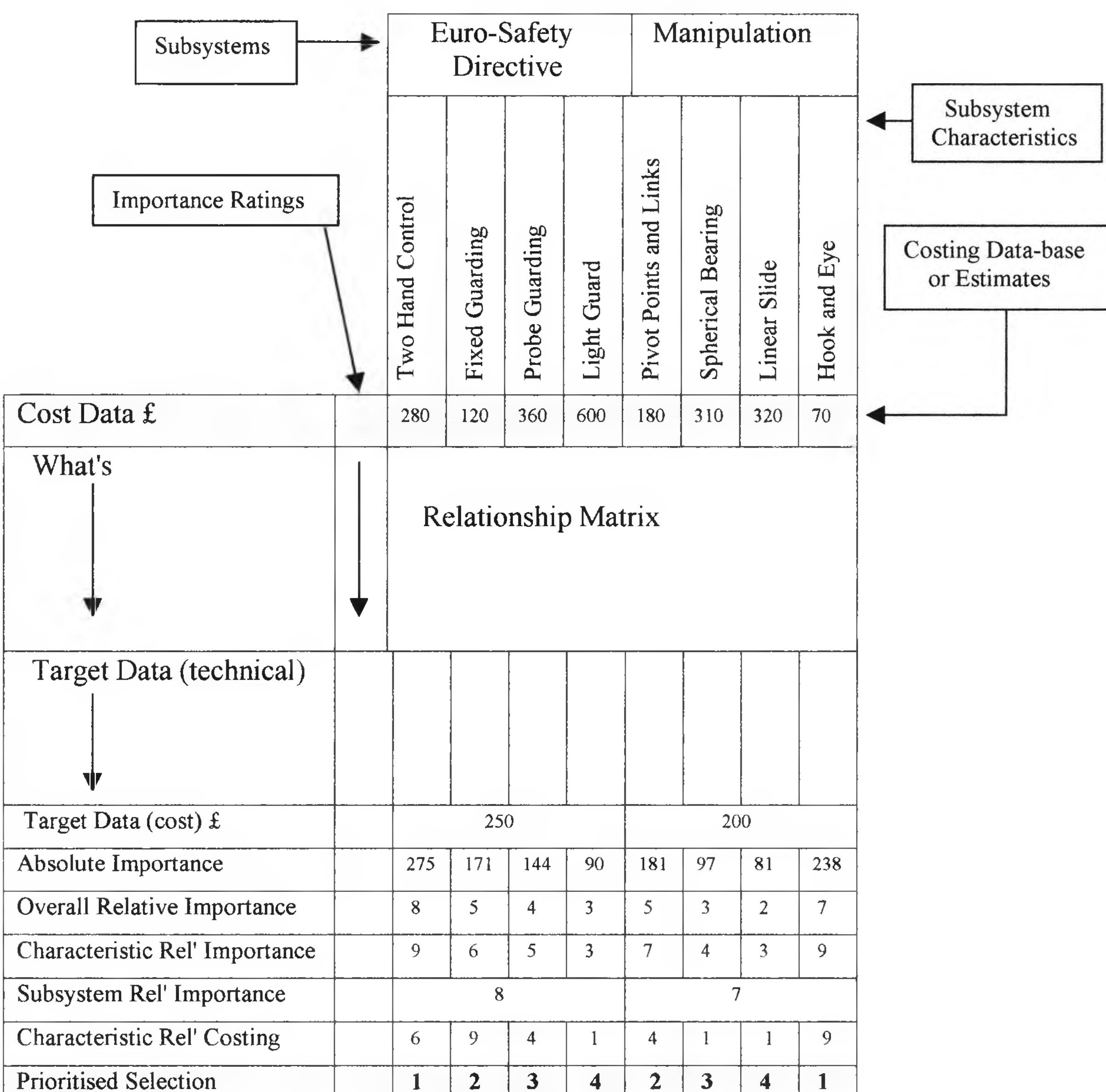


Fig 5.3 DFD/QFD Matrix with Costing Elements

5.1.3 Proposed Methodology

As a result of **5.1.1** and **5.1.2**, a marriage is sought between an efficient design approach and supporting 'tools' in the form of matrices, both suitable for a 'one off' machinery manufacturing environment.

It has been observed that small organisations benefit from reduced lines of communications, particularly in relation to operational efficiency. Furthermore cost elements linked with a proven DFD approach offer the potential to enhance performance through structured working. In any event it is vital that such an approach be simple and of direct benefit to those who use it.

Descriptive phases of model for 'one off' machinery projects:

1. *Customer Contact* - Project Engineer involved from day one, discussing what is needed and establish a rapport with the customer, this is essential as part of a long term working relationship. As discussed in **1.1.2** understanding the problem (customer requirements) is the most vital stage of the entire design process, extracting of all relevant data may be further assisted by the use of pre-defined questionnaire's, (see Appendix C).

2. *Proposal Design* - Based on information gained above, produce outline scheme to explain concepts of operation. Formal review or talk through proposal with at least one other designer, this is an important step as problems with the concept can automatically become obvious to the presenter if not to the recipient. The inclusion of external specialist knowledge may also be made at this stage.

3. *Proposal Refinement* - The expense of this stage may not be justified unless there is a strong possibility of eventual commercial success, assuming this point has been satisfied, a more detailed outline of equipment subsystems can be produced. Several alternative solutions to the same problem may emerge. In some cases it may be necessary to produce prototype rigs to prove some unknown aspect of performance.

4. *Potential Price Determination* - Cost data can either be estimated, or adapted from data base information. Historical data, if representative, is the most reliable source, it is therefore important that all cost information for actual projects be stored in a retrievable format. At this stage costing is still retained at a subsystem level.

5. *Design Selection* - Through a single stage QFD chart, technical selections can be made against customer requirements and cost data can be included in both the final selections and the establishment of a final price. A proposal and cost can now be presented to the customer.

6. *Design Completion* - As a live project, design effort can be directed at refining the proposed concept and developing parts to a detail level. The same person/team go on to expedite manufacture and the purchasing of standard components. This stage also includes control elements and software.

7. *Hardware Assembly* - Project Engineer remains directly involved with the equipment build, ensuring design is correctly translated and dealing with any problems as they occur.

8. *Test/debug and Commission* - As a 'one off' machine some elements of modification/development will occur, these must be dealt with immediately if project 'over-runs' are to be avoided.

During the above eight stages, a single project Engineer must either perform, or be responsible for all activities.

Fig 5.4 illustrates the project model.

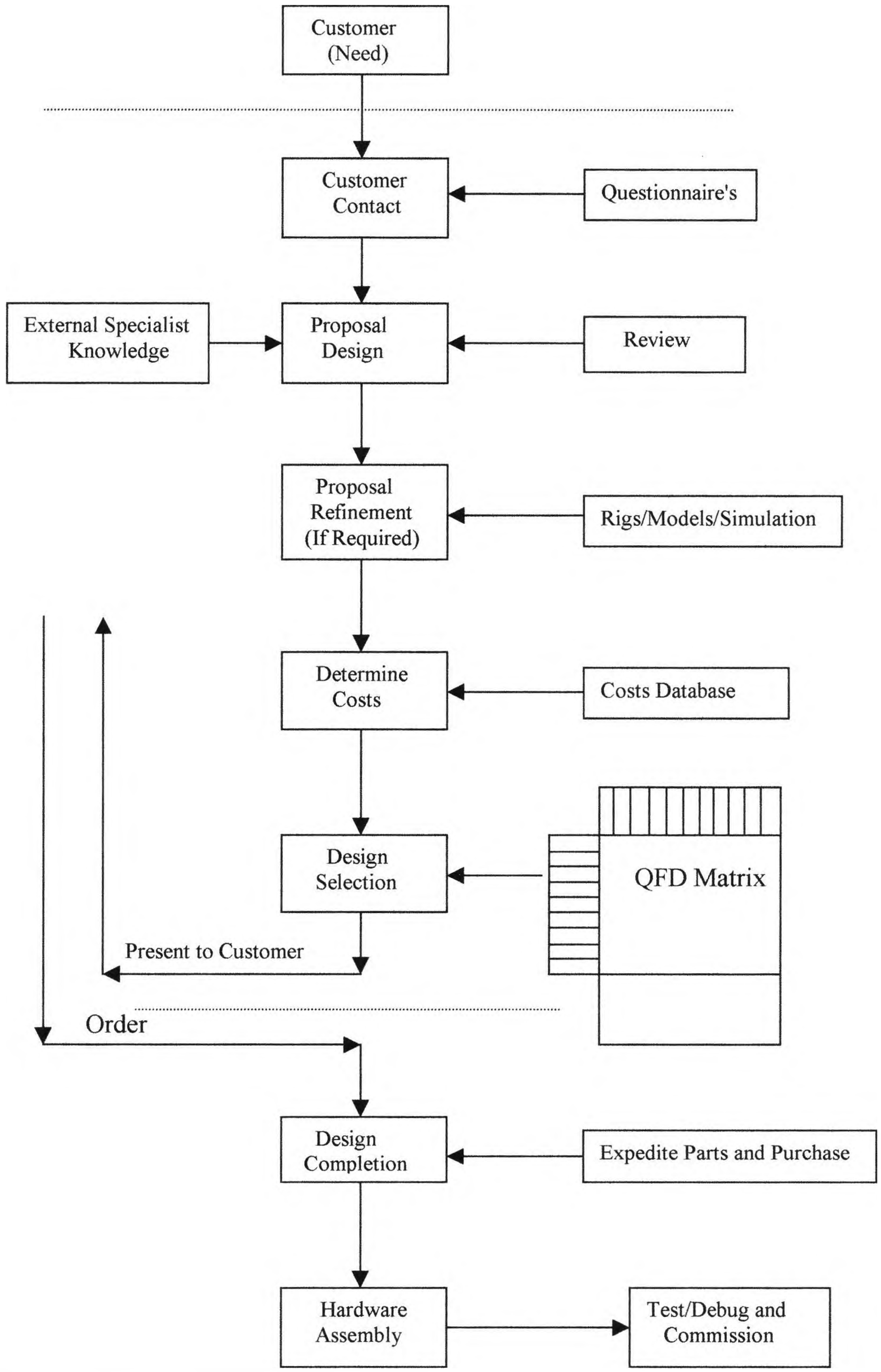


Fig 5.4 'One off' Machinery Project Model

5.2 Case Studies

Within the working environment described in 5.1.1, it is possible to apply and adapt (if necessary) the proposed methodology given in **5.1.3.**

5.2.1 Case Study 1: Visor Cutting Machine

A customer has a requirement to produce Visor 'rip-off's' for use with industrial safety wear, these consist of 112μm thick Polyester sheets, shaped to fit the visor which can be ripped off and disposed of when their surface becomes contaminated (fig 5.5). Two different profile shapes must be produced, both at the rate of 120 per minute, followed by collation into stacks of 10 or 50. The final operation is to package each collation and code it prior to discharging the completed product.

This represents a typical example of a small self-contained special purpose machine, where no specialist prior knowledge exists relating to this product and hence the designer is effectively starting with a blank sheet of paper.

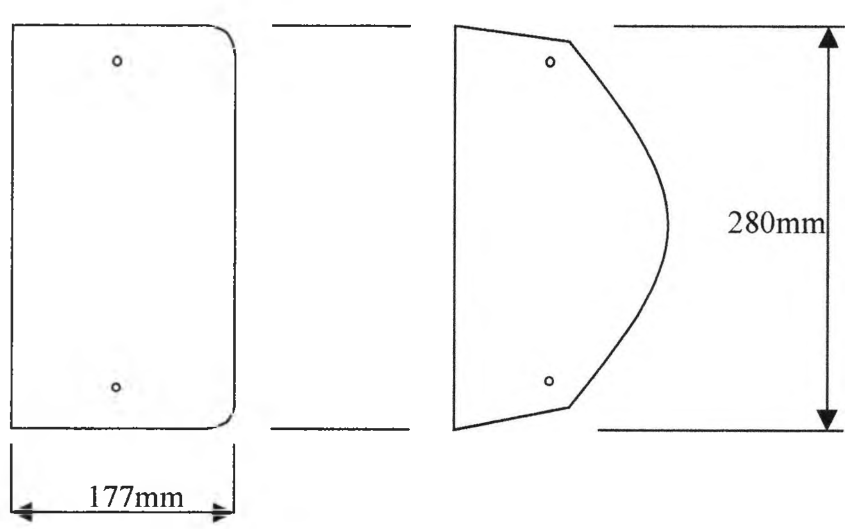


Fig 5.5 Visor 'Rip-off's'

Prior to being in a position to quote the customer a price for such a machine, it is first necessary to elicit fully all his requirements along with other information needed to make a commercial judgement of the situation. Appendix C shows a completed Questions/prompt sheet that aims to highlight the major issues, which must be addressed when meeting with the customer. Since customer contact is by the project Engineer, there is no need to translate gathered information into an Engineering format, as this will be done at source.

Concept generation was discussed in **1.1.5**, where the notion of *convergent* and *divergent* approaches was introduced. Furthermore in **1.1.2** Gasparski introduced his 'practical situation' (PS) in respect of Praxiology in Engineering design, suggesting that a none standard PS could be converted to a standard PS by the supplementing of external specialist knowledge. When dealing with a wide range of totally different requirements, as is typical in special purpose machinery design, it is impossible for any one person or organisation to be a specialist in all likely potential fields. Both locating and applying external expertise, therefore becomes another task for the designer.

With a requirement to cut sheet material at a rate of 120 components per minute, the first and obvious solution of a conventional reciprocating die and punch would have inherent problems. Controlling the feed of raw materials and the carrying out of punching either stationary or 'flying' allows little in the way of an elegant solution to be proposed. This led to the investigation into using continuous rotary die technology and subsequent discussions followed with a company specialising in this particular product. From an initial *divergent* search for ideas, a more *convergent* approach follows, where the core technology imported into the project largely influences its direction.

Developing an overall machine concept design, the sequential events of producing, collating and packaging the product, segregates the equipment into a number of individual operating assemblies. Fig 5.6 illustrates the basic form of the equipment proposed, clearly showing these component elements.

Since the high-risk element of this design is effectively delegated to a third party, there is no need to further refine the proposal or carry out any experimentation with prototype rigs. A price must therefore be determined incorporating a committed element from all external suppliers.

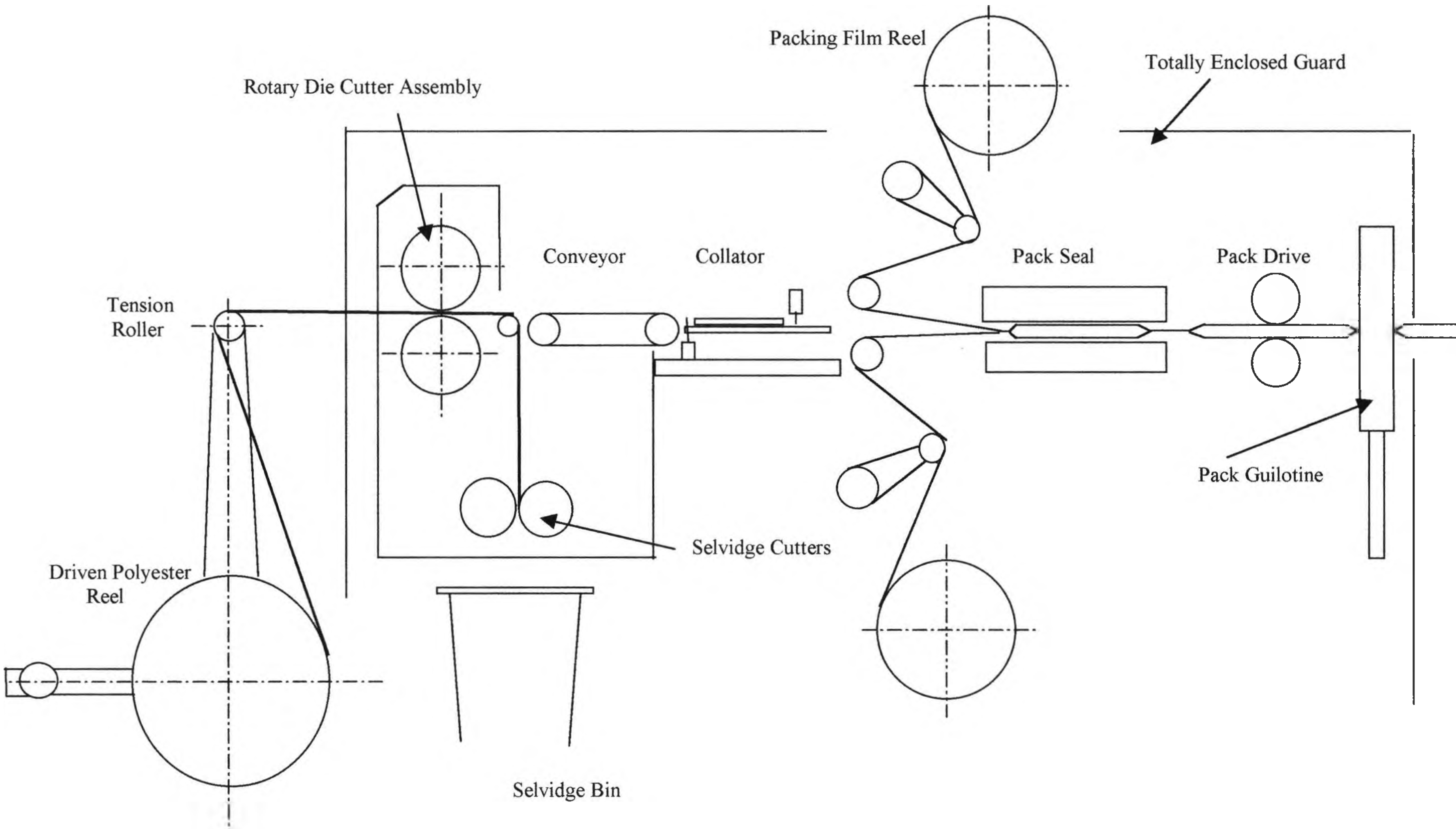


Fig 5.6 Visor Shields Production Machine

As a single overall concept for this project has emerged, there is no need to go through a design selection procedure and so, in this case, the intended use of a matrix is not possible. Elements of cost were either estimated or subject to external quotation, for some parts, particularly relating to the film feed area, a limited amount of historical data was available upon which new prices could be based.

After presentation of both proposal and price, the project became the subject of a live order. Managed and largely designed by the author, the machine was built completely within 14 weeks. Initial test operations showed the majority of machine elements worked perfectly, with the exception of one small feature of the rotary die system. Being a part bought from a specialist organisation, they were charged with the task of correcting this fault, unfortunately this took months of effort and created an unacceptable situation with the customer.

In this case the use of an 'expert' became the weak point in the project, when a specialist task is delegated to a third part, control of that element of the machine is also lost. Care must always be exercised when using specialised resource, particularly when the requirement is one that also extends beyond the prior experience of the expert's normal field. If this is the case, a new concept must be found or the potential project abandoned.

5.2.2 Case Study 2: Gas Exchange System for Bottled Product

An international brewing group, required a special purpose machine builder with whom they could work in partnership with, to develop a new machine concept for bottling designer beers. Having approached their normal equipment suppliers in Germany, the project was turned down on the basis of time scales and technical difficulty, hence the involvement of **Spm.**

When beer is bottled, an attempt is made to evacuate oxygen by means of 'dosing' with water or liquid nitrogen followed by immediate crowning. By comparison, the new requirements are to carryout several pressurisation's and releases of Nitrogen gas directly onto the bottle and to perform the crowning operation whilst retaining this pressure. In addition a plastic insert (widget) must also be placed inside the bottle.

Two phases of the project were to be performed:

1. Manufacture a pilot development rig, which would prove design concepts and the quality of finished product. This machine to have a low volume manufacturing capability of 15 bottles per minute in order to produce test market quantities. Design, develop and installed complete in 14 weeks.
2. Full scale production facility capable of producing 400 bottles per minute, to be designed, built and installed in 26 weeks.

Starting with the development of a pilot rig, the specification is not as clear cut as with the more typical example shown in **5.2.1.** Here both product and machinery develop together and the two organisations must operate as a collective team, working towards a common goal. Both items of specification and cost must be recorded as they develop, ensuring that the technical and commercial aims of both parties are achieved.

As a none expert company in the crowning of bottles, it again becomes necessary to seek expert advice, only this time not to the point of becoming entirely dependent on the performance of others, as was experienced in **5.2.1**. Due to the level of influence enjoyed by the customer, it was made possible to visit a crowning bottle specialist company for one day only, during which time the maximum of information had to be extracted. (Not such a simple task, since to get an informed answer, an informed question must first be asked). Gaining knowledge of a process rather than hardware hopefully permits the application of that knowledge in new and novel ways. The major design parameters extracted are shown in fig 5.7.

Having a framework of fixed parameters on which to build, solutions for the new requirements of gas exchanging and widget insertion can be proposed. Further more, working together with the customer and bottle manufacturer, it had been made possible to accommodate a high tolerance sealing diameter on the bottle neck, which could also be common across the full range of bottle sizes, fig 5.8. This additional step of rationalising requirements, in partnership with the customer, avoids solutions becoming compromised. By trying to accommodate only those requirements, which are truly necessary, a more robust final solution should be possible. In many ways this process stage represents the effects of the focusing and quantifying qualities of the DFD approach.

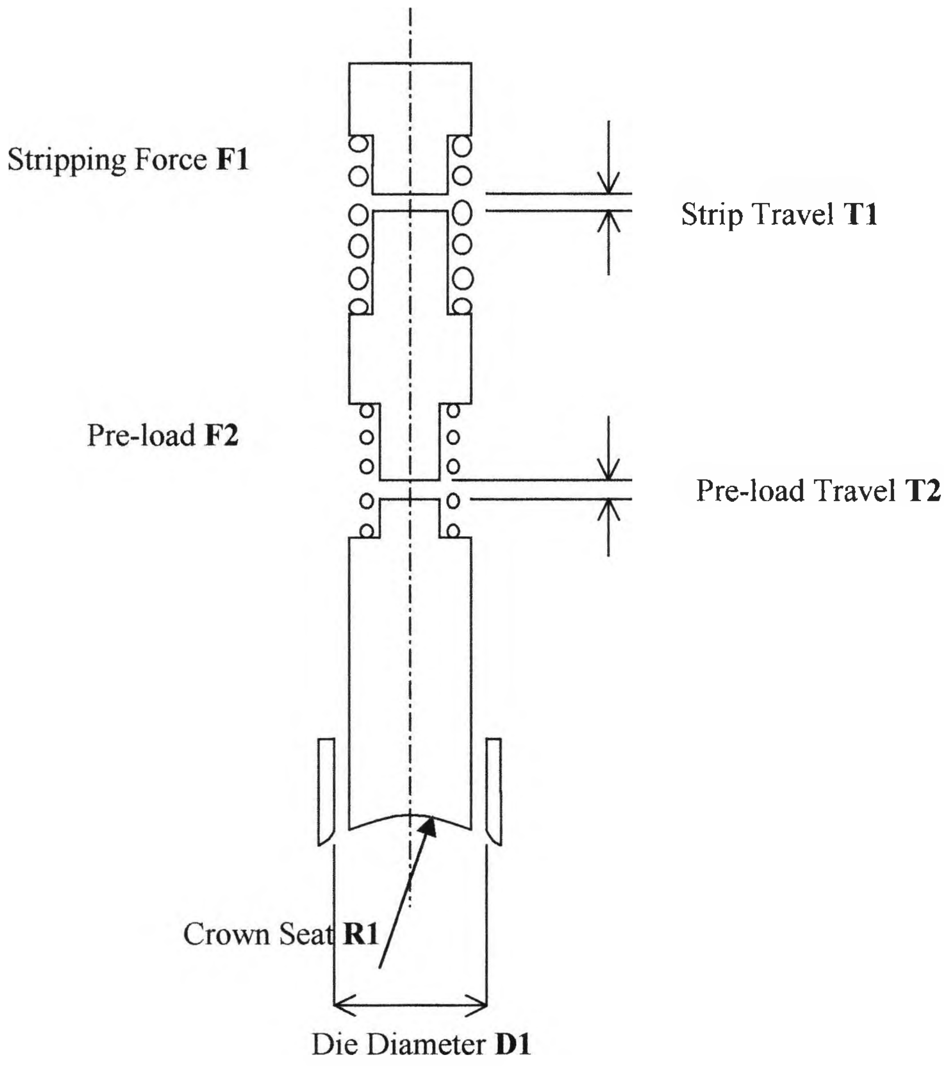


Fig 5.7 Crowning Technology Parameters

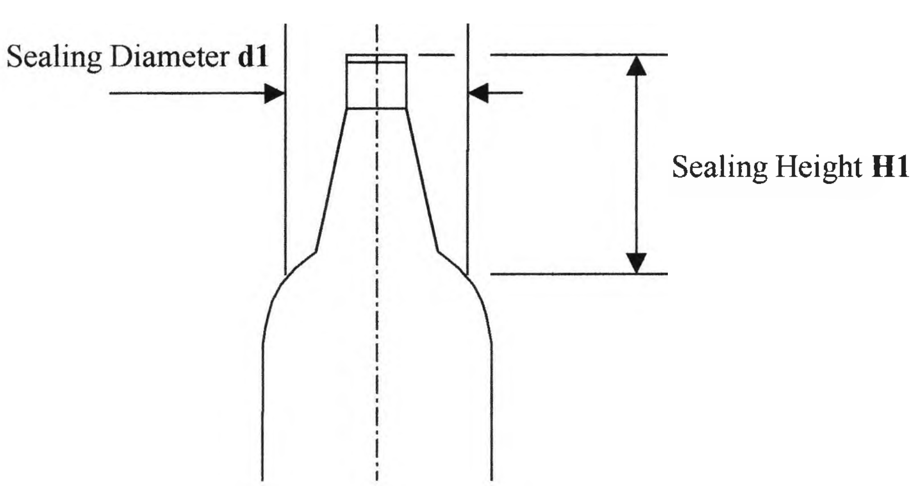


Fig 5.8 Bottle Sealing Dimensions

For both the pilot and main production facility, the main focus of activity is on the development of a gas exchange and crowning (GEC) head. As both systems will consist of a multi-head turret arrangement, this unit becomes a key component, produced in quantities of five for the pilot machine and possibly forty for the production facility. Building upon the established crowning technology previously discovered, a framework of possible design concepts can be proposed.

An Engineering interpretation of mechanical requirements for the GEC head is summarised below.

1. Easy placement of crown into head
2. Efficient gas sealing
3. Mechanically robust and stable components
4. Easily cleanable
5. Direct access of gas into bottle
6. Tolerant to bottle height variation

Combined with the rationalised product requirements shown in fig 5.8, a small range of design options became possible, as illustrated in fig 5.9.

When applying matrices to the selection process, as performed within the DFD methodology (**2.1.1**), the proposing of system architectures would be a second stage activity. Previous design functions with numerical ratings would be available from the first stage as a basis for second stage evaluations. Alternatively, since only the most important requirements are to be considered, a failure of any one of which would represent a total design failure, then all of the six requirements will be considered of equal importance. Cost elements may also be included through the mechanism proposed in **5.1.2**.

From the designs proposed in fig 5.9, subsystems and their respective characteristics were extracted and presented in table 5.1 accompanied by estimated cost values.

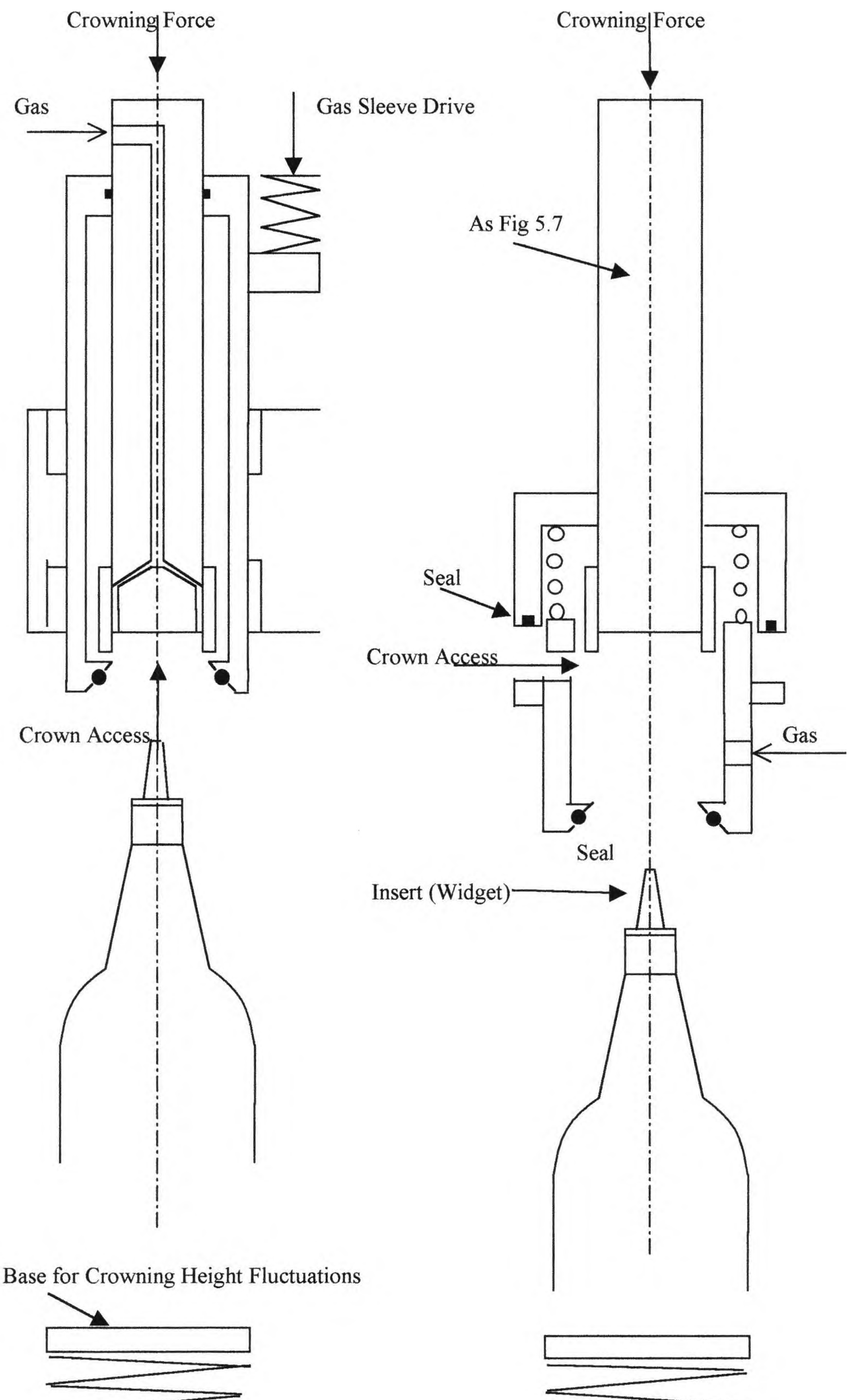


Fig 5.9 GEC Head Design Proposals

Subsystems and Characteristics	Cost £
Gas Exchange	
High Level	250
Low Level	150
Gas Sealing	
Single Point	120
Double Point	340
Crown Placement	
Vertical	200
Horizontal	100

Table 5.1 Subsystems and Characteristics

		Gas Exchange		Gas Sealing		Crown Placement	
		High Level	Low Level	Single Point	Double Point	Vertical	Horizontal
Cost Data £		250	150	120	340	200	100
Easy Placement of Crowns in Head	1			9	1	9	1
Efficient Gas Sealing	1		1	3			
Mechanically Robust and Stable Components	1	3	1	9		3	
Easy Cleaning	1	1		3		1	
Direct Access of Gas into Bottle	1		1				
Tolerant to Bottle Height Variations	1				1		
Absolute Importance		4	3	24	2	13	1
Characteristic Relative Importance		1	2	1	2	1	2
Characteristic Relative Cost		2	1	1	2	1	2
Prioritised Selection		1	2	1	2	1	2

Fig 5.10 Design Selection Matrix

Strength of relationships: 1 = Weak, 3 = Medium, 9 = Strong

Taking the top priority selections for the fundamental design issues analysed in fig 5.10; a design for the GEC head was finalised and built into a pilot production test machine as per the concept shown in fig 5.11.

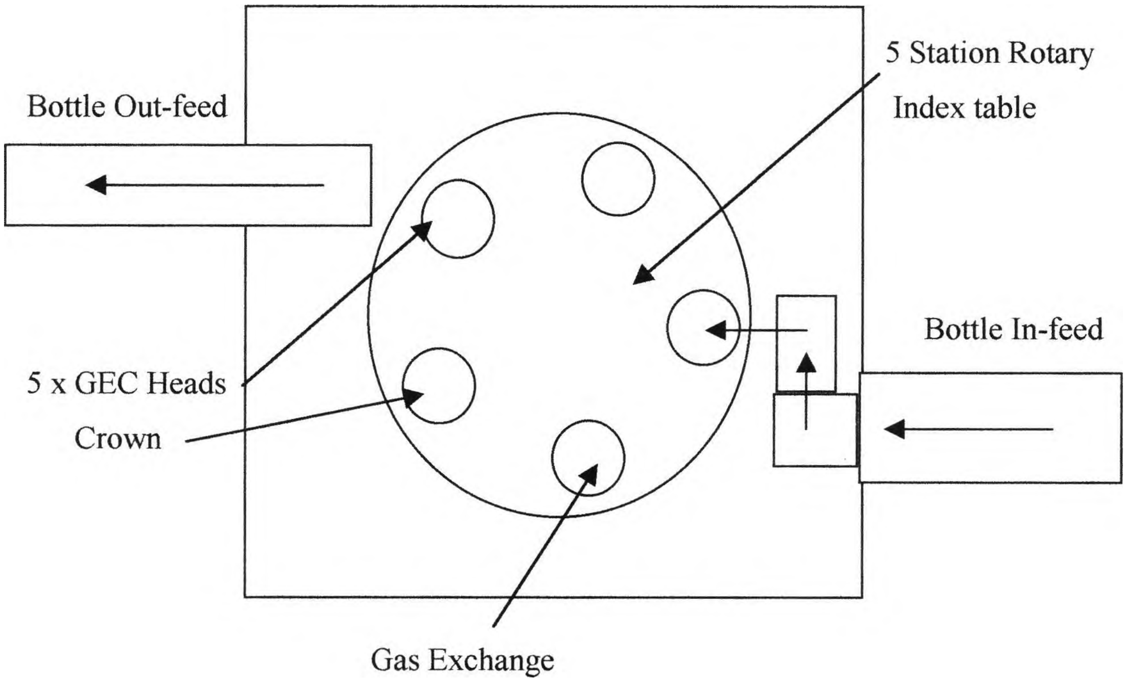


Fig 5.11 Pilot Production Test Machine (Plan View)

The total working system above was completed from a blank sheet of paper to operational in the customer's works in thirteen weeks (one week ahead of schedule). On the basis of initial production trials, an order was immediately placed to continue with a full production facility.

5.2.3 Conclusions from Case Studies

Following largely the model proposed in fig 5.4, two projects have been completed which demonstrate how a small company environment, allows completion of technically novel projects, within extremely short time frames. By the use of a 'total individual' approach, the wasted effort of continuous communication within the organisation is not required, resulting in a greater efficiency of productive effort.

Although the benefits of a small company structure are evident, the greatest problem they face is in the recruitment of Engineers of sufficient calibre to cope with such a broad range of tasks. Training of Engineers has declined steadily over many years, with few having worked through all levels of an organisation, not just as observers but as skilled practitioners. Without Engineers who are both capable and willing to perform a multitude of varied tasks, it would be impossible to operate such a small company structure economically.

Applying a matrix as part of the design selection procedure, in combination with cost data, has been carried out successfully, be it to a limited extent. As a largely 'one off' manufacturing environment, the design emphasis has to be more on functionality rather than optimisation. Unlike the example given **5.1.2**, where multiple manufacture justifies the cost of design refinement, organisations such as **Spm** must get the design right first time as a matter of survival. This particularly relates to the design concept, which if incorrect, cannot be put right by any amount of detail manipulation. The matrix used in **5.2.2** goes some way to addressing this problem, through a justified concept selection on the basis of customer satisfaction and cost.

Benefits afforded through the implementation of matrices, are in the traceable decision making process for the selection and evaluation of the best proposed solution option. Where cost data is involved, the process is of particular value in the estimation of future proposal costs where re-use of a proposed design is appropriate.

Both of the above case studies involved elements of external specialist knowledge, as accommodated in the project model shown in fig 5.4. The experiences gained however showed that in such a project environment, being totally dependent on any external partner could create a very dangerous situation. If the specialist fails to deliver, then the whole project is jeopardised. A better way of using such expertise was found to be in the gaining of knowledge only rather than hardware, allowing total control of the entire package to remain 'in-house'.

Chapter Six

Summary of Research Findings

Through a variety of products, processes and industries, formal design methods have been both explored and expanded upon within a working design environment. Aided by the implementation of matrices, commercially successful, customer orientated products have been developed, acting as vehicles for further developing the design process.

6.1 Process Development

6.1.1 Product/Process Improvement Methodology

Chapters 3 and 4 concentrated on the evolution of a product design methodology based entirely around a unique *self-pierce* riveting process. Although already in existence, a much greater understanding of process behaviour was derived, resulting in the development of a much-improved fastening system.

The methodology developed and used, can be best summarised with reference to fig 6.1. Fully understanding all customer requirements is diligently performed by means of a stage 1 analysis of the DFD process, combined with supporting concept models evaluated by a *cause and effect* analysis. Rather than follow the conventional DFD approach and propose potential solutions at the second stage, a focusing activity was performed which numerically evaluated generic regions of the process and presented them in a specification format. Translated as process features, alternative designs were proposed to satisfy the identified parameters.

In order to evaluate the overall fastener performance, an index value was derived which would allow the bringing together of several different dimensional characteristics within a single measure. This feature was termed the *Quality measure* and is described by equation **3.2**.

As a process identified to take place in a state of inherent conflict **(3.2.1)**, an evaluation method had to be derived which recognised such conflict. Equation **3.3** achieved this through combining conflict indices with the *Quality measure*. Supported by the *plasticity analysis* of potential fastener performance, a prioritised schedule for parameter selection was formulated.

Driven by the above, the most important product factors were built into a controlled range of experimental products, each with two levels of value setting, against which test results were obtained. To fully evaluate this data, a method was developed which brought together *main effects, energy effects* and *ANOVA*, within a single analysis structure.

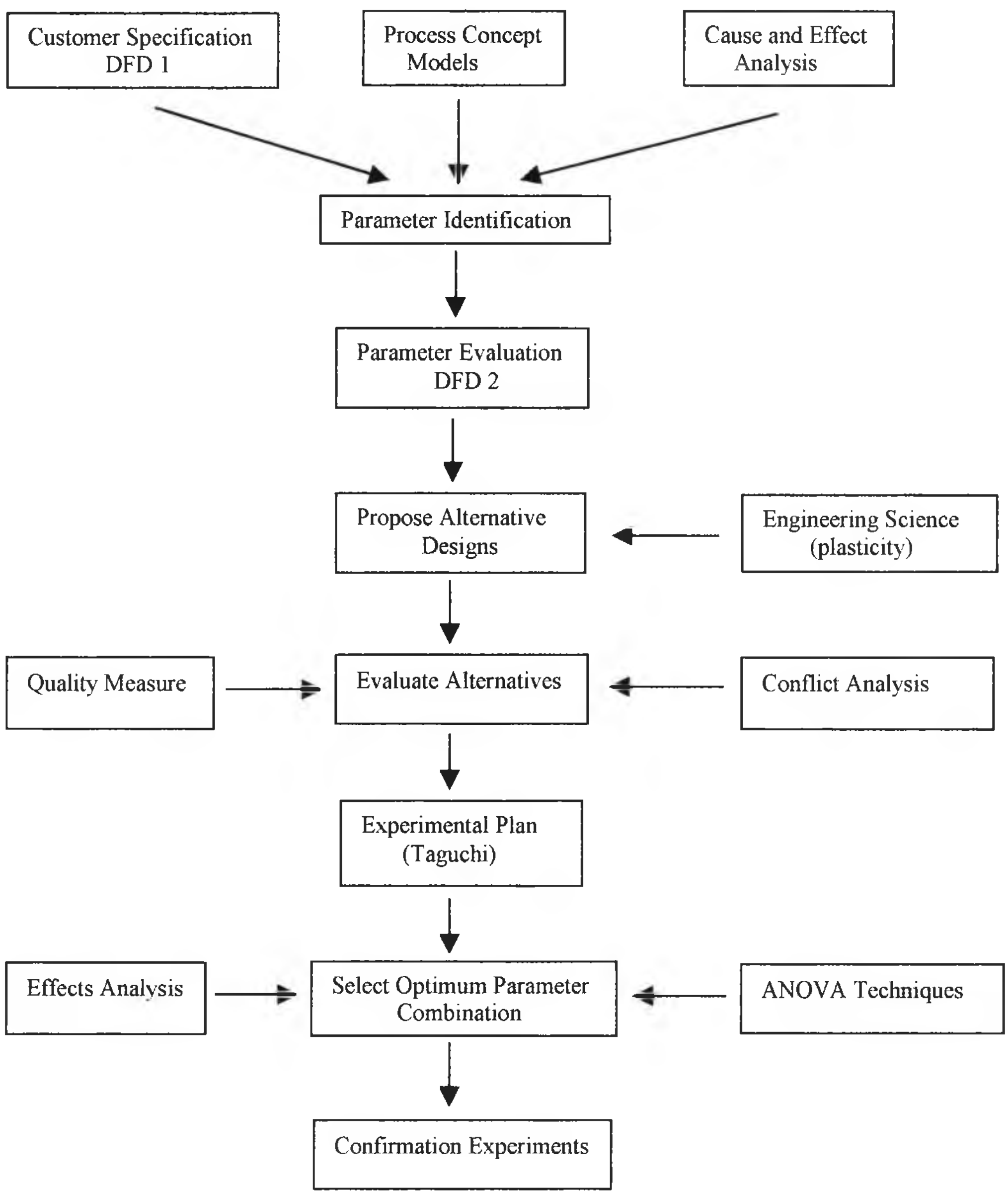


Fig 6.1 Product Improvement Methodology Model

By using the 'Correlation Roof' of the 'House of Quality', a simple identification of the important factors and their level settings could be derived to give the best product combination. Furthermore, guided by Engineering Science inputs in the form of 'Plasticity theory', (**3.3.1**) and parameter rationalisation in **4.1.2**, a much reduced range of parameters, and hence a more economical experimental programme could be conducted. Representing primary elements of the *Self-pierce* riveting process, the 'Roof' is decomposed into the two sections of Rivet and Anvil, allowing prioritisation within each respective group. As a further development of this matrix, interactions can continue to be accommodated by placing a second 'Correlation Roof' matrix above the factor level analysis, fig 6.2.

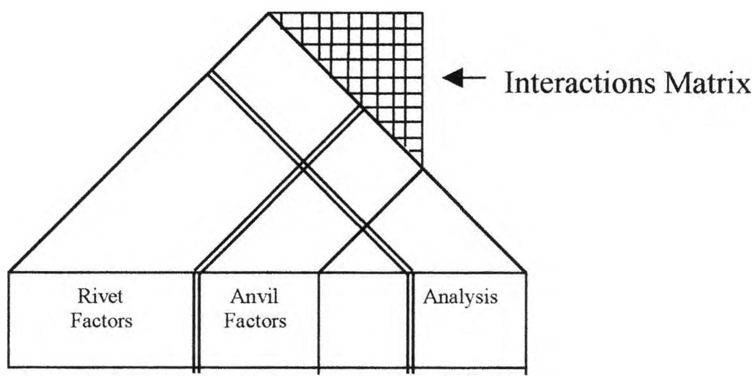


Fig 6.2 Correlation Roof Decomposition

This adaptation of the standard QFD chart resulted in the development of the 'Design selection matrix' fig 4.8, and represents a significant discovery in the harmonising of largely incompatible performance measures into a single selection matrix. Through the derivation of factor settings, Engineering Science influences are incorporated and through the experimental selection of optimum factor levels, a *Robust* product combination is achieved. In addition, a measure of process energy absorption influences product selection as a function of its minimisation. Verification experiments conducted in **4.4.1** proved both the superior performance of the re-designed product and the lower levels of process variance observed in comparison with joints produced using the original product.

From the model arrived at in fig 6.1, a distinct route of traceable steps can be followed to achieve an optimum product design. An illustration of the stages and information flows as they evolved are shown in fig 6.3. As can be seen, the mechanism provides an open cyclic structure, which permits re-iteration of the Design process where results fail to meet expectations.

Carrying the 'non dimensional' experimental results into the 'correlation roof', the 'Design selection matrix' represents a unique example of meaningful numbers, (representative of process performance) being placed into a QFD style matrix. In its conventional form, the 'Roof' of the QFD matrix would act as a means of identifying correlation's between function as either positive or negative. Whilst the relationship matrix would allow subjective assessments of interactions to be made. The 'Design selection matrix' does none of these, but what is achieved is a design selection based upon actual experimental results supported by both statistical and energy usage data.

This represents a significant departure from the conventional use of QFD matrices, particularly in relation to the 'Roof' section, where as stated by Cohen (1995) 'the potential benefits are great'.

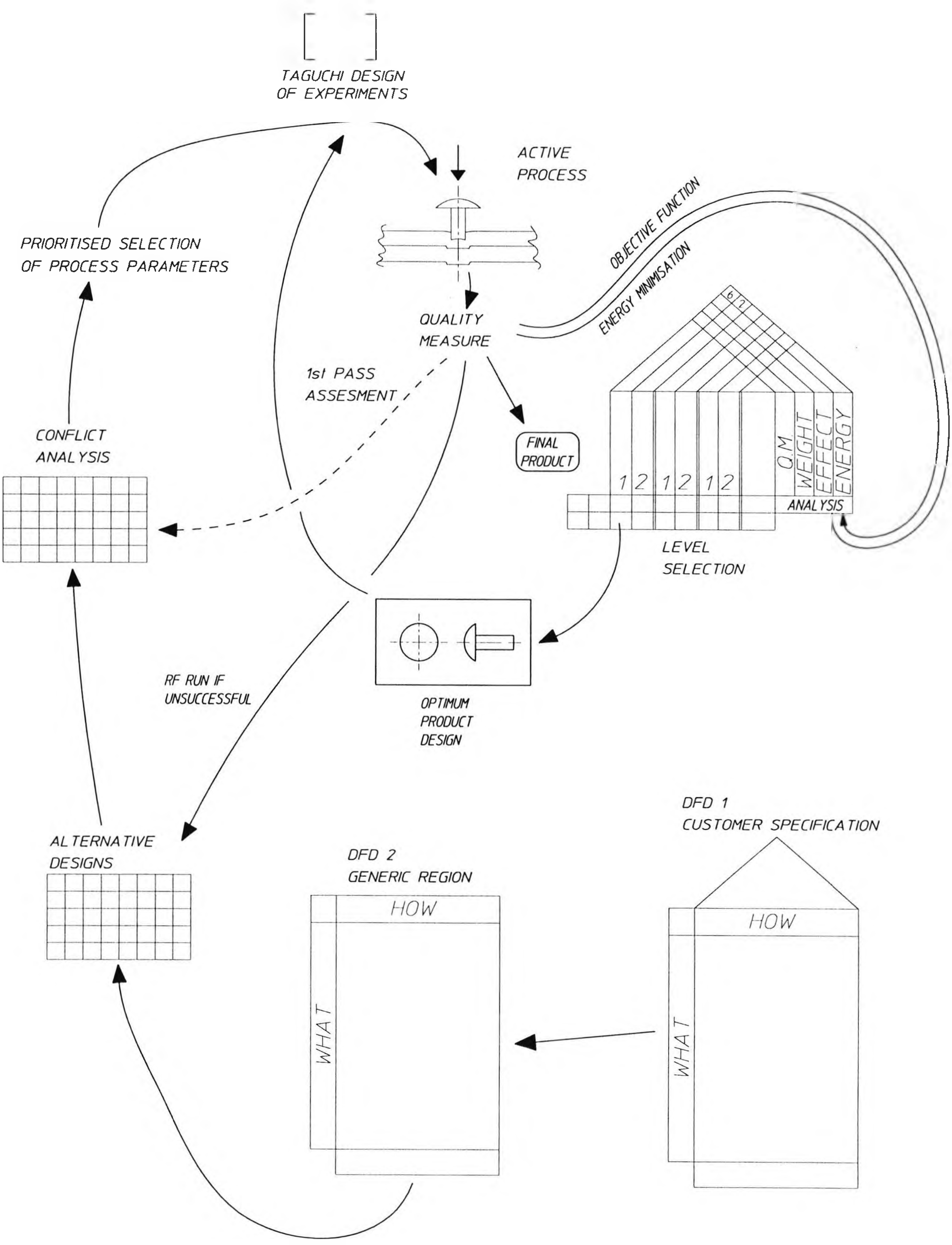


Fig 6.3 Product Optimisation Model for an Active Fastening Process

6.1.2 Improvements to the *Self-Pierce* Riveting Process

Descriptions of the *Self-Pierce* riveting process and discussions regarding its massive future potential were given in **1.4.1**. The resulting need to improve the current design of product, whilst simultaneously creating a greater understanding of process behaviour, was the basis for beginning this research.

Joint material indentation by the rivet was explored in **2.4.2**, resulting in the proving of the validity of 'load bounding' techniques as a means of calculating piercing loads in the plastic region. This discovery was carried forward and used to good effect in the exploration of alternative shapes for the rivet end geometry. By comparing calculated results against actual load v displacement curves, equation **(3.5)** was proven to represent a suitable over estimate of piercing loads for the alternative shape of rivets.

For the more complex clenching stage of the process, no such relatively simple analysis could be made. However, after studying a large amount of joint data, some important observations were made regarding the behaviour of different joint materials. For aluminium alloy it was noted that final clenching load was only marginally affected (8%) by changing joint thickness, where by contrast joints created in steel, saw the clenching load vary by up to 20% over the joint thickness range of 2 to 5mm. Where the majority of market growth for this product is seen to be in the fastening of aluminium alloy structures, this observation is of particular importance, especially in the sizing of machinery to carry out the process over a multitude of joint thickness.

Through the design of experiments, an adaptation of Taguchi's *Dynamic* approach **(2.3.2)** was made. In place of noise signals forming the outer array, a control signal in the form of joint thickness was applied, effectively becoming an *Imposed* noise. Through carrying out repetitions under each level of *Imposed* noise, the effects of random noise were accounted for in the analysis, **(4.1.1)**.

The design of rivet, which subsequently resulted from the above experimentation, was proven through prediction and verification to be a superior product to that previously manufactured. Rivets made from two different materials and hardened to different levels were used in the verification experiment, the result being that the harder grade rivet showed superior performance in terms of performance magnitude and its low variance of results between different settings of joint thickness, (*Imposed* noise).

It has been shown that through a new approach to product and experimental design, along with a new development of matrices in the selection of the optimum factor combination, that a much-improved product/process has been evolved.

6.2 Product Design

6.2.1 Cost Elements in Matrices

The subject of cost in design was introduced in **1.3.2,** where some of the realities of product cost in the commercial world were described. In **2.2.1** and **2.2.2,** sources of cost and methods of cost reduction were explored and, with reference to a vivid example, demonstrated the large potential savings in cost possible by the alternative use of standard purchased parts, in place of manufacturing.

The possibility of incorporating a 'design to cost' methodology within a QFD structure was researched in **2.2.4**. No examples of its effective application appeared to exist, with research into the subject, by others, only revealing the obvious notion, that variety in design is a major cost driver.

Cost as a function of time utilisation, in contrasting company environments, was explored in **5.1.1**. Much more efficiency of effort was observed in small companies, compared to their larger counterparts, where internal systems and communication between departmentalised disciplines, accounted for a high percentage of otherwise productive effort. From this it was concluded that the small company operated the most cost effective structure and had the ability to complete projects within relatively short deadlines.

Entering cost data into the QFD matrix was first attempted in **5.1.2**, where using data from a design project given in appendix A, cost values were effectively applied to the second stage chart. By the segregation of subsystems, each subsystem characteristic could be realistically evaluated by combining relative costs with relative importance's in the final prioritised selection of factors.

Being a product item designed for repetitive manufacture, the above example justified the carrying out of a detailed DFD analysis down to parts level. By contrast, a special purpose machinery design environment producing 'one off' pieces of equipment cannot justify such a level of effort to optimise the design. Hence applying a degree of 'over-design' is the norm under such circumstances. However in case study 2 **(5.2.2)** a simple form of selection matrix, including costing elements was successfully applied to a single 'special purpose' machine. Adding estimated costs to alternative subsystem characteristics, the final prioritised selection could be made in terms of satisfaction of requirements and potential cost.

6.2.2 Advantages in the Use of Matrices?

Matrices, particularly in a QFD/DFD format, have been used by industry for several years in supporting the design activity. The structure of such matrices was described in **1.2.2** and their development as part of the more comprehensive DFD design system was presented in **2.1.1**.

By far the largest recorded use of the QFD approach is in the automotive industry. Working on large scale design projects, destined for high volume manufacture, Engineers, some times working collectively in different parts of the world, require an effective mechanism to consolidate and evaluate their efforts. Retaining visibility of all customer requirements, the team approach to design is well served by the QFD mechanism. In such a mass production environment, the benefits gained from the system far outweigh the cost of its implementation.

Further developments to the QFD matrix methods have been proposed by Comincini (1994), in the form of 'correlation chains' and by Atherton (1997) in the form of the 'square matrix' method. The purpose of this work has been to expand the use of matrices as part of an overall design methodology, embracing issues of cost along with product *robustness* and Engineering science results.

Research conducted in chapters 3 and 4, successfully developed the design process along with the *self-pierce* riveting product, resulting in the evolution of the comprehensive 'design selection matrix'. Initially relating to a mass-produced product, by contrast, the work carried out in chapter 5 was concerned with 'one-off' special purpose machinery. Despite this low volume requirement, a comprehensive design process model was proposed (fig 5.4) which incorporated a matrix element, be it to a limited extent. Having to recover all design costs on a single product, prohibits the use of detailed analysis methods, therefore in this case, matrices are best applied only where a recorded justification of particularly crucial decisions is required.

Depending on the nature of the business, some initial 'one off' machines can find further sales at a later date, or alternatively, certain elements of a system may find re-use within different machine configurations. In either event, the QFD matrix can provide a useful platform for a system of parametric costing. As discussed in **6.2.1**, costs can be attached to sub-system characteristics at the second stage charts. It is thus feasible that these pre-costed elements can be integrated into the costing process of a totally new system.

In conclusion, although design matrices offer a mechanism by which all elements of customer requirements can be fully addressed, they are still most effective in large organisations dealing with mass-produced items. For a small organisation, the approach of the 'total individual' offers the best solution, working with the minimum amount of systems pressure, but guided by a simple procedural approach (fig 5.4).

Chapter Seven

Conclusions

Research has been conducted into the design process, particularly relating to the potential supporting role of matrices. Explored in two contrasting industries, all activities have been conducted within an actual design environment, being subjected to all the commercial pressures that are a reality of industrial life.

7.1 General Conclusions of the Research

7.1.1 Satisfaction of Working Hypothesis

In section **1.5.1**, three working hypothesis were put forward as part of the aims and objectives of this project. The following re-states these hypotheses along with the conclusions arrived by this research.

Hypothesis # 1

"Matrices can be utilised as an active tool for the creation of *robust* product Designs".

Through the development of the *self-pierce* riveting process, a viable product improvement model has been evolved which both builds upon and expands the current DFD methodology (fig 6.1). The standard matrix structure of QFD, in combination with process concept models, has permitted the evaluation of those parameters, which are of particular importance to process performance. Acting as a platform for proposing alternative designs, the subsequent evaluation process conducted through designed experiments, selects those parameters which are key to *robust* performance.

Only as a part of a suitable methodology, as that described above can matrices play an active part in the design of *robust* products.

Hypothesis # 2

"The roof of the House of Quality can be used to introduce Engineering Science results into the design selection procedure".

The correlation roof of the 'House of Quality', has been successfully adapted to form a new 'design selection' matrix (fig 4.8). Accommodating statistical, main effects and energy data, numerical representations of parameter effects have been combined in such a way as to give a highly comprehensive selection of factor levels. Although not directly representative of Engineering science results themselves, the numbers now placed into the correlation roof result directly from the experimentation process, and as such represent the physical performance of those parameters.

Further segregation of the 'correlation roof' was found possible, in this case into the elements of rivet and anvil, allowing separate and combined evaluation of parameters.

Hypothesis # 3

"Design Matrices can be utilised to identify major product cost drivers"

The above hypothesis was later translated as follows:

"Technical design functions (How's) are the major cost drivers"

Identified as only being relevant for the DFD second stage how's, cost data was effectively integrated into a matrix, initially relating to a repeat manufacture product item. By adding cost to each design function, as either an estimate, or drawn from a database, relative costing could be combined with relative importance in the calculation of subsystem characteristic priority.

Further attempts were made to integrate costs into a simplified matrix applied in a 'one-off' manufacturing environment. Although not as directly effective as in the previous case, cost data was still introduced into the selection process over a range of alternative concept ideas.

Once generated, cost data held within the matrix structure, could be drawn upon as part of a comprehensive and rapid costing method, used when tendering for systems re-using previous or similar design elements.

7.1.2 Satisfaction of Industrial Requirements

The main requirement for this research has been to develop a much-improved *self-pierce* riveting product, which exhibits features of performance and *robustness*, to meet the expectations of a large growth market.

Through the customer focused activities of the first stage DFD methodology, detailed specifications of all requirements were the initial basis for re-building the process. By focusing effort on those areas found to be of most important to fastener performance and supporting factor level selections with controlled experimentation, a product of far superior performance and robustness to that previously produced was developed. Further more, as a result of a plasticity analysis of rivet penetration and a study of joint formation data, a greater understanding of process behaviour has been achieved.

As a result of this work, *self-pierce* riveting has found commercial success with such companies as Ferrari (see **4.4.1**) General Motors and Ford.

7.2 Further Work

7.2.1 Development of Optimisation Model for Other Active Processes

Although developed around the *self-pierce* riveting process, the resulting design method and approach could equally be applied to other active processes. For example, press joining, blind riveting, parts forming or as a means of developing an entirely new process directly from customer requirements. All processes, which directly absorb energy as a function of their performance, would benefit from a development methodology capable of addressing such issues within the design process.

Having prepared the ground, this thesis lays down a clear structure upon which alternative processes/products could be developed. In the selection of alternatives, by the simple summation of experimental main effects over a range of imposed noise, a fast track method incorporating statistical data has been given. Further development of this approach into other areas of experimental analysis should be explored. By the subsequent simplification of the conventional statisticians approach, the use of controlled experimental analysis in every day Engineering environments, would become more attractive.

7.2.2 Further Development of *Self-Pierce* Fastening

As a constraint of the sponsoring organisation, the process development has related to *self-pierce* 'riveting' as opposed to the more generic approach of *self-pierce* 'fastening'. All organisations must however continue to move forward, if they are to continue to satisfy their customers ever increasing expectations. So on this basis, re-running the entire design approach, opened out to cover the wider perspective of 'fastening', is strongly recommended.

Chapter Eight

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Appendix A: Design of a *Self pierce* Riveting Gun

This chapter shows the actual use of the DFD methodology in the design of a small scale piece of equipment, and further attempts to evolve the process along lines more recognisable to the majority of practising designers. Carried out as part of a research programme conducted by Hill (1994), the design process itself is followed through in its entirety to the point where a finished and tested prototype is compared against objectives and past product performance.

Customer Requirements

Before evaluating what the Customer Requirements are, it is first necessary to determine exactly who the customers are. Within this methodology, the term 'Customer' is extended beyond just the equipment purchaser to embrace all groups of parties who will have an active contact with the product at any point during its 'Life Cycle'. The exact form of this life cycle will itself depend upon the products classification which embraces its Genesis, Origins, Endurance and Consumption. (see 1.3.1)

Considering the full product life cycle from a supplier user perspective, the following list of customers was produced.

1. Purchasing Organisation - Buyer of product
2. Equipment User - User of product
3. Maintenance Personnel - Maintainer of product
4. Technical Departments - Specifier of product for manufacture
5. Manufacturing Departments - Maker of product
6. Company - Financial gain from product
7. Legal and Standards - Full life cycle safety issues

In recognising the existence of these customers, along with the need to promote a team approach throughout the project duration, it was vital that all such customers were properly represented. Within the relatively small organisation of *Aylesbury Automation,* representation of all these parties was not practically possible, therefore a substitute team was formulated as follows.

A. Sales
B. Design Department
C. Managing Director
D. Production Department
E. Quality Department

To avoid the development of pre-conceived ideas, all information at this stage was gathered in a *solution neutral* form. Rather than hold a formal meeting or conduct a *Brain storming* session, it was felt that making direct formal requests for information, to be returned within a deadline, would provide more valuable information. To stimulate this process, prepared sheets were given out showing a breakdown off all customers, accompanied by a few suggested requirements alongside each one. All recipients were then free to add their own requirements in the same style but not restricted to their own customer classification. This resulted in a total of 50 usable requirements (What's)..

The next stage was to classify these 'whats' into Primary, Secondary and Tertiary requirements, the Tertiary requirements could then be treated as the customer requirements for design purposes.

Table A.1 shows an extract from the full listing and illustrates the breakdown of requirements within the Primary and secondary sub-categories.

No	Customer requirements	Primary Requirements	Secondary Requirements	Serial No	Tertiary Requirements
1.	Full rivet gauge range	1. Application	Riveting Range 1.1	1.1.1	Full rivet gauge range
2.	Handle all rivet head styles			1.1.2	Handle all rivet head styles
3.	Flexible parameter spec			1.1.3	Handle process range of material thickness
4.	Minimal cycle time		Operating Limits 1.2	1.2.1	Accessibility to rivet position
5.	Multi-directional operation			1.2.2	Operate in any attitude
6.	Auto/manual interfacing			1.2.3	Minimal cycle time
7.	Rivet max joint thickness		Interfacing 1.3	1.3.1	Manual cycle initiation
8.	Ease of Manoeuvrability			1.3.2	Master control interfacing
9.	utilise existing rivet feed technology				

Table A.1 Classified Requirements Extract

Quality Plan

Producing a quality plan provides a comprehensive means of adding a numerical measure of importance to each of the tertiary customer requirements, whilst also providing a mechanism for an effective bench marking process.

Following the method given by Jebb et. al (1993), a team approach was again of particular importance in order to formulate a true and correctly balanced assessment of inputs. Firstly a rating on a scale of 1 to 5 (1 = low, 5 = high) was given to each requirement from its relevant customer perspective, alongside which was also added a rating on the same scale for similar products in current manufacture. Competitor activity was also assessed on the same scale and rated accordingly, this gave a comparative relationship whilst also a datum for improvement against an active market place. For the plan itself, a quality target was first set as an achievable goal in relation to the broader market perception, from this an improvement plan was derived as a ratio of Quality target against current rating. Finally an assessment of sales advantage was made and added to the plan.

Calculation of absolute rating for each customer requirement could then be calculated as:

Absolute weight = Customer Rating x Improvement Plan x Sales Advantage

For ease of interpretation, the resulting figures from the above were normalised on a scale of 1 - 9, to give relative weights. Table A.2 shows an extract from the full Quality Plan which both maps, and records, the information process.

QUALITY PLAN								
Serial No	Tertiary Customer Requirements	Customer Rating	Current Rating	Plan			Weight	
				Quality Target	Improv'nt Plan	Sales Adv'tge	Absolute Weight	Relative Weight
1.1.1	Full rivet gauge range	5	4	5	1.25	1.2	7.5	4
1.1.2	Handle all rivet head styles	5	5	5	1	1.5	7.5	4
1.1.3	Handle process range of material thickness	4	3	5	1.67	1.2	8	4
1.2.1	Accessibility to rivet positions	5	3	5	1.67	1.5	12.5	6
1.2.2	Operate in any attitude	4	5	5	1	1.5	6	3
1.2.3	Minimum cycle time	4	3	5	1.67	1.5	10	5
1.3.1	Manual cycle initiation	5	3	5	1.67	1.2	10	5
1.3.2	Master control interfacing	4	4	5	1.25	1.2	6	3

Table A.2 Extract from Quality Plan

DFD Stage 1 - Requirements Analysis

Having established a fully quantified assessment of true customer requirements in the form of the quality plan, the next step is to generate the Design Functions.

A *Design Function* can be defined as the identifiable and actionable design requirement translated from an established customer requirement or constraint.

Applying this conversion to our previously generated customer requirements was again a team function. Each requirement was taken in turn, analysed and satisfied in a physical yet still solution neutral form. This part of the design procedure was found to be a little difficult to visualise and required a good deal of control to avoid wrongly applied Design functions becoming part of the data. Table A.3 shows an example of a single Tertiary Customer requirement, 'Efficient Rivet Control' translated into three Design functions.

Tertiary Customer Requirement	Design Function
Efficient Rivet Control	Efficient Rivet Restraint Rivet Captivation Efficient Rivet Transport

Table A.3 Design Function Generation

After all of the customer requirements had been deployed, a list of 54 design functions was produced.

Grouping of the Design functions under Primary, Secondary and Tertiary categories was next carried out. In order to apply some measurable quantity to these items, an assessment was also made as to the likely value of that quantity in the form of target information. Where a measurable Design function occurred, data was added in the form of a target value accompanied by upper and lower limits, confidence level of assessment, units and improvement direction. An example of this data recording is shown in Table A.4.

Having generated a comprehensive list of classified and quantified Design functions, it was then possible to evaluate this data for the eventual formulation of a prioritised product specification by using the DFD 1 chart as shown in the enclosures.

Customer requirements (What's) with their respective importance rating from the Quality plan, were listed down the charts left hand column and Design functions (How's) listed along the charts top row. The following two stages of analysis could then be carried out.

Starting with the interactions, using the roof of the chart, all of the Design functions were first analysed against each other in order to determine if any interactive relationships existed. Any such interaction could hence be labelled as follows:

1. Eliminate. 2. Combine. 3. Transfer. 4. Modify.

The second part of the DFD 1 chart provides a relationship matrix for the primary purpose of numerically rating each Design function. For each Customer requirement a positive relationship was sought with each Design function, the magnitude of that relationship being identified at its intersection as follows:

1. Weak 3. Medium 9. Strong

Having applied this data to the chart, the final evaluation to give Design function importance ratings could be carried out. This simply consisted of taking the column sums of the products of customer importance rating and relationship values, then normalising the values on a scale of 1 - 9 to give a simple comparative index. The full DFD stage 1 chart is given in the enclosures.

PRIMARY DESIGN FUNCTIONS	RIVETING HEAD ASSEMBLY									
SECONDARY DESIGN FUNCTIONS	FORCE GENERATION 1.3					CONSTRAINTS 2.1				
TERTIARY DESIGN FUNCTIONS	Variable force generation	Remote power source	Power to force conversion	Force-velocity characteristics	Low cost purchase	Unit cost	Tooling cost	Capital investment	Existing remote rivet feed	Economic batch size
SERIAL NUMBER	1.3.1	1.3.2	1.3.3	1.3.4	1.3.5	2.1.1	2.1.2	2.1.3	2.1.4	2.1.5
UNITS	kN	kw	kN	S	£	£	£	£		
TARGET VALUE	40	4	40	1.5	300	1.8k	250	15k		5
CONFIDENCE LEVEL	7	6	7	7	7	7	7	7		7
UPPER LIMIT	45	4	45	2	350	2k	300	20k		
LOWER LIMIT	35	3	35	1	250	1.5k	200	10k		5
IMPROVEMENT DIRECTION	0	-	0	-	-	-	-	-		0

Table A.4 Extract from Classified Design Functions Chart

From all the information available on the DFD 1 chart it was now possible to formulate the complete Stage 1 Requirements Specification.

Information was laid out in a concise and ordered manner, giving for each Design function all target data, where applicable, along with an explanation relating to interactions and other comments. The net result was a highly detailed and prioritised specification, acting both as a platform from which to move forward into the concept generation stage and also an effective record of its own origins. Table A.5 shows part of this specification.

DESIGN FUNCTION	RELATIVE IMP.	UNITS	TARGET VALUE	CONFIDENCE	UPPER LIMIT	LOWER LIMIT	TARGET DIRECTION	INTERACTIONS AND COMMENTS
2.1.1 UNIT COST	9	£	1800	7	2000	1500	-	Highest importance factor which indirectly interacts with most other functions as they can all affect cost. Direct interaction with 1.3.5-Low purchase, this gives us a means of controlling cost in some instances by buying in components at lower cost than can be manufactured in house
1.2.8 ROBUST DESIGN	7							High importance factor interacting with 2.1.12-Process robust parameters, demands experimentation with process parameters to establish which are most critical to system robustness

Table A.5 Extract from Stage 1 Specification

DFD Stage 2 - Conceptual Design

Having formulated a full and comprehensive specification for a 'Portable Self Pierce Riveting Tool', the next task was to take that information and generate overall solution concepts capable of satisfying that specification.

As a mechanism to help stimulate and present as many concept ideas as possible, a morphological chart was utilised as shown in table A.6. Firstly the stage 1 specification had to be examined to select those parameters which could be classified as tangibly realisable, i.e could be satisfied by direct physical solutions. In the left hand column of the matrix were added all of these selected items, with alongside each an expandable grid of solution spaces available for recording ideas generated by the Design team. In all 17 Design functions out of 58 were selected for concept generation.

Taking each parameter (Design function) in turn, concepts of overall potential solutions were proposed in the form of simple descriptive statements and placed horizontally across the chart. Since these solutions represented the simplest and lowest levels of concept information, they were directly carried over to become the subsystem characteristics, again being categorised under Secondary and Primary headings along with assessments of target values, table A.7.

Evaluation of the subsystems and subsystem characteristics could then be carried out by means of the DFD 2 chart.

Parameters	Possible Solutions					
1.1.1 Rivet Captivation	Standard Pocket	Finger Gripper	Collets	Sprung Ring	Sprung Flats	
1.1.2 Rivet Detection	Through-Beam Optic	Reflective Optic	Pneumatic Back-pressure	Laser Detector	Electrical Contact	Eletro-mag Flux

Table A.6 Morphological Chart

Stage 1 specification requirements along with their respective ratings were first loaded down the left-hand column of the chart, whilst the classified groupings of solutions were loaded along the top row. As with the previous stage, interactions were sought and identified accordingly, whilst the relationship matrix was again evaluated with appropriate numerical ratings. Calculation of both absolute and relative importance of subsystem characteristics was performed using the same procedure as for stage 1.

At this point it was felt that overall relative importance rating of subsystem characteristics did not give a realistic comparative measure, since the nature of each subsystem family was in itself entirely different. A further analysis was therefore carried out, to give subsystem characteristics a relative numerical rating within their own particular subsystems. Finally the subsystems themselves were rated relative to each other. The full DFD 2 chart is given in the enclosures.

Taking information from the DFD 2 chart permitted the creation of a descriptive specification of potential Design solutions.

Since each subsystem represented the more fundamental aspects of the design, it was decided to take their previously calculated relative importance ratings as the primary prioritising parameter. The subsystem characteristics, prioritised within each subsystem, hence became the second priority with overall relative importance being the third. After taking note of this data and the consequences of any interactions the stage 2 specification could be completed with the addition of any comments and target data.

PRIMARY ARCHITECTURE	MOBILE RIVET SETTING TOOL 3		
SECONDARY SUBSYSTEMS	RIVET DETECTION 3.5	FORCE GENERATOR 3.11	FORCE FEEDBACK 3.14
	Through beam optic Reflective optic Pneumatic back press' detect' Laser detector	Direct hydraulic cylinder Indirect hydraulic cylinder Direct pneu/hydraulic cylinder Indirect pneumatic cylinder Electrical solenoid	Pressure switch Pressure transducer Load cell Piezo-electric sensor
SERIAL NUMBER	3.5.1 3.5.2 3.5.3 3.5.4	3.11.1 3.11.2 3.11.3 3.11.4 3.11.5	3.14.1 3.14.2 3.14.3 3.14.4
UNITS	Spot Diameter	Kn	Pressure Force BAR kN
TARGET VALUE	1	40	0-250 0.45
CONFIDENCE LEVEL	6	7	6
UPPER LIMIT	1.5	45	0-260 0.50
LOWER LIMIT	0.5	35	0-240 0.40
IMPROVEMENT DIRECTION	0	0	0

Table A.7 Extract from Classified Concepts Chart

Table A.8 shows part of the specification for the single subsystem of 'Force Generator'; in this case since the subsystem is of the highest possible rating, both characteristic and overall relative importance have equal values.

SUB SYSTEMS	CHARACTERISTICS	CHAR RELATIVE IMP.	SUBSY. RELATIVE IMP.	OVERALL RELATIVE IMP.	COMMENTS AND INTERACTIONS	UNITS	TARGET VALUE	CONFIDENCE	UPPER LIMIT	LOWER LIMIT	TARGET DIRECTION
3.11 Force Generator	3.11.1 Direct Hydraulic Cylinder	9	9	9	Force applied directly down the centre line of therivet by means of a hydraulic cylinder - interacts with and absorbs 3.10.1 hydraulic fluid pressure and 3.12.1 direct cylinder - **High Importance Factor.**	kN	40	7	45	35	0
	3.11.3 Direct Pneumatic/ Hydraulic	6		6	Pneumatic pressure intensification system capable of generating a direct riveting force - interacts with and absorbs 3.10.2 pneumatic air pressure and 3.12.1 direct cylinder - **High Importance Factor.**	kN	40	7	45	35	0
	3.11.4 Indirect Pneumatic Cylinder	3		3	Force applied by means of a pneumatic cylinder acting through some means of magnification mechanism - interacts with and absorbs 3.12.2 toggle links and 3.12.3 - **High Importance Factor.**	kN	40	7	45	35	0
	3.11.2 Indirect Hydraulic Cylinder	3		3	Hydraulic cylinder applying force via additional mechanism - Low Importance Factor - **Hold on Record.**	kN	40	7	45	35	0
	3.11.5 Electrical Solenoid	1		1	Direct force applied by means of an electrical solenoid - **Hold on Record.**	kN	40	7	45	35	0

Table A.8 Stage 2 Specification Extract

DFD Stage 3 - Detail Design

The requirements for this stage of the project involved the derivation of component detail, to accommodate the best possible selection of parts combination.

At this point it became apparent, that the large number of subsystems and their respective characteristics represented an excessively large amount of alternative potential solutions for this scale of product. In order to selectively reduce down this large solution space, an intermediate stage of rationalisation within each subsystem was carried out.

Taking for example, the subsystem 'Force Generator 3.11', fig A.1, the three most promising characteristics identified in the stage 2 specification were laid out in detail, including all target data and any other relevant observations. A small relationship matrix was used to further evaluate the characteristics. Relevant Stage 1 Design functions were loaded down the left-hand column of the chart whilst the three subsystem characteristics were loaded along the top row. Carrying out the standard DFD relationship evaluation, checking how each characteristic measured up to the specific targets set, gave a more concise second evaluation of each characteristic. For this example characteristic 3.11.1 'Direct Hydraulic Cylinder', emerged as by far the only preferred option for further analysis.

This process of rationalisation was repeated for all other appropriate subsystems. Having now a detailed and largely quantified specification of the outline solutions, the actual process of detail designing could then proceed. The first stage was to take core specification parameters as the building blocks of the product. Having target data to hand allowed the adding of constraints, such as overall height, prior to designing, hence providing a physical definition for much of the product solution space. The selected solutions and target values continued to be fed into the design process, which, after several re-draws and reiterations the best possible design combinations of characteristics emerged. As a result of this several alternative schemes evolved with specific variation at the parts characteristic level.

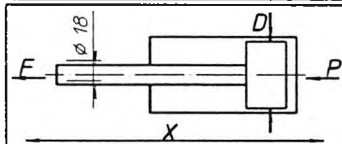
Continuing onto a detail level, proposal sketches of individual piece parts were made in order to visualise better the characteristics of variation from which selections would be made. Subgroups of specific component parts were created under which the variation of parts characteristics were held.

The stage 3 analysis provides the mechanism to ensure that the best possible selection of characteristics is made. From the design evolution stage, eleven subgroups of parts with their respective characteristics were loaded onto the top row of the DFD 3 chart. Down the left-hand column were loaded the Stage 2 Design solutions, in addition to which was also added a selection of relevant customer requirements. The purpose of this being, to tie back directly the parts level analysis to original customer data left behind at stage 1. The full DFD 3 chart is given in the enclosures. Subsequent evaluations of interactions and relationships were carried out as for the previous two stages, allowing the calculation of overall and subgroup specific weightings for the parts characteristics.

The stage 3 specification was drawn up for all parts characteristics with their respective ratings from the DFD 3 chart. Considering each part individually, taking into account importance ratings and any interactions, a detailed range of comments was made along with recommendations for further action. Examples of a specification for a single part is shown, table A.9. For the two candidate characteristics in this case, there was no strong overriding benefit for either solution, therefore the final conclusion was left open for prototype appraisal.

D.F.D.2 CHARACTERISTICS	FORCE GENERATOR 3.11

3.11.1 DIRECT HYDRAULIC CYLINDER INCORPERATING 3.10.1 3.12.1



D	AREA (m^2)	P(for 40KN)
50	0.00196	204
45	0.00159	251
40	0.00125	320

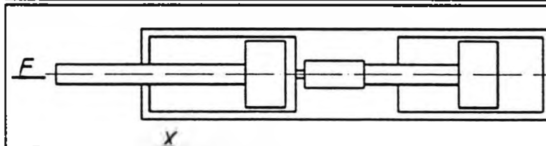
APPLICATION OF POSITIONAL FEEDBACK - MODERATE

WEIGHT = 5Kg
LENGTH = 170mm

NOTE: INVESTIGATE 50 AND 45 DIA BORES AS LOWER SWEPT VOLUME . BENIFITS MAY OUTWEIGH EXCEEDING PRESSURE TARGET .

EFFECTIVE TARGETS: F=40KN (+/-5) P=200bar (+/-40) MECHANISM WEIGHT=6Kg x=170mm(370 target-200 approx)

3.11.3 DIRECT PNEUMATIC/ HYDRAULIC CYLINDER INCORPERATING 3.10.2 3.12.1



F=4Kn WITH 5.5 bar

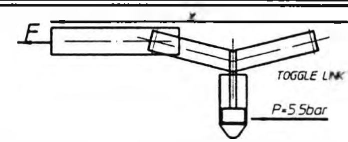
PRESSOTECHNIK TYPE 58

APPLICATION OF POSITIONAL FEEDBACK - DIFFICULT

WEIGHT =35Kg
LENGTH = 670mm

EFFECTIVE TARGETS: F=40KN (+/-5) MECHANISM WEIGHT=6Kg x=170mm(370 target-200 approx)

3.11.4 INDIRECT PNEUMATIC CYLINDER INCORPERATING 3.12.2 3.12.3



APPLICATION OF POSITIONAL FEEDBACK - DIFFICULT
ANY 'F' ACHIEVABLE DEPENDING ON LINK PROPORTIONS
FOR F=40Kn WITH 70mm TRAVEL
LENGTH = 250mm

EFFECTIVE TARGETS: F=40KN (+/-5) MECHANISM WEIGHT=6Kg x=170mm(370 target-200 approx)

DIRECT INFLUENCE DESIGN CHARACTERISTICS	TARGETS MODIFIED	RATING	3.11.1	3.11.3	3.11.4
1.3.3 POWER TO FORCE CONVERSION	40Kn	3	9	3	3
1.3.4 FORCE-VELOCITY CHARACTERISTICS	1.5m	3	1	9	9
1.2.4 (MACHCANISM) OVERAL WEIGHT	6Kg	2	9		1
1.8.4 OVERALL HEIGHT (MECHANISM)	170mm	2	9		1
1.4.1 POSITIONAL FEEDBACK (APPLICATION)		3	9		
ABSOLUTE IMPRTANCE			53	36	40
ABSOLUTE IMPRTANCE			9	3	3

1-WEAK BENEFICIAL RELATIONSHIP
3-MEDIUM BENEFICIAL RELATIONSHIP
9-STRONG BENEFICIAL RELATIONSHIP

ACTION -CONTINUE DESIGN WITH 3.11.1 (DIRECT HYDRAULIC CYLINDER) AS PRIMARY FORCE GENERATOR CHARACTERISTIC

Fig A1 Subsystem Rationalisation

PART	CHARACTERISTICS	CHAR. RELATIVE ORDER	OVERALL REL. IMP.	COMMENTS AND INTERACTIONS	REC' ACTION
4.1 VRVT Type	4.1.1 Internal Flange	1	9	Gives slight size advantage in terms of overall length of assembly due to flying lead type connections. Transducer end needs encasement for protection. Interaction with all part variable dictated by this transducer type.	Use either type for initial prototype.
	4.1.2 External Flange	2	8	Appears more robust fitting and sealing system but small length penalty. Encasement of end possibly not vital but desirable. Interaction with all part variables dictated by this transducer type.	

Table A.9 Extract from Stage 3 Specification

Final Design Selection

Due to the earlier stage 2 rationalisation process, only a single combination of subsystem characteristics were permitted through to stage 3, this left the final product selection to be made entirely at the parts characteristic level.

In keeping with the team approach, it was always essential that some form of review process be performed periodically throughout the course of the design process. Since a great deal of the latter stage design activity had been carried out on an individual basis, a team review was particularly important before committing any parts to manufacture.

The Customer representative team as used in the initial 'Requirements analysis' stage, was again called upon to take part in a formal review. Design configurations and parts were considered in some detail, but no significant changes were found to be necessary, other than some minor points of detail. As discussed in **2.1.1**, facilities are provided within the methodology for calling upon various design methods and tools within the prescriptive design model. For this particular project, the conducting of an FMEA (Failure Mode and Effect Analysis) as a test for potential weaknesses in the design, was implemented. FMEA's are discussed in section **1.2.3.**

Integrating the inputs generated by the project review, FMEA's and the in depth DFD analysis, it was then possible to begin the process of producing actual production part drawings. Parts characteristics being taken through to the prototype build stage, were rationalised to give two levels of variation, resulting in the need to manufacture parts for the building of two representative prototype units. Following the normal prescribed DFD route would have resulted in both a materials selection stage 4, and a production processes stage 5, being carried out. However due to product size, the extent of prior product knowledge, and the intended use of subcontract manufacture, there was no apparent need for these other stages, hence it was decided to end the process after stage 3. As with all design processes, decisions have to be made as to the most economic course of action to be taken. In this case it was felt that the potential gains of extended paperwork analysis would not be reflected in the product improvement.

After manufacture, all parts were assembled, during which time a formalised log was maintained to record any design errors, or improvements felt necessary for incorporation in the final product design. A full test programme was set and completed covering the analysis of efficiency, performance and durability of the prototypes. It was after this process of tests and trials that the final product combination of parts characteristics could be confidently made.

<u>Results Analysis</u>

The objective of this project was to replace an existing product, with one of a new design, created specifically to satisfy the maximum possible number of customer needs. A comprehensive measure of success would hence be derived by both a direct comparison with the original product, and also with the customer requirements derived at the DFD 1 stage.

Table A.10 shows the main attributes of a comparison between old and new products, which illustrates the superiority of the new design particularly in the two important areas of weight and cost. Against the original target values set at the Quality Plan stage, performances achieved in the majority of cases were either equal or superior, as illustrated in table A.11.

Finally, fig A.2 shows a photographic comparison between the old and new designs, which illustrates fully the large saving in product size and weight achieved.

Parameter	Original Product	New Design
Weight	35 Kg	14.5 Kg
Process Monitoring	No	Yes
Joint Pre-clamping	No	Yes
Cost (approx)	£3K	£1.6K

Table A.10 Old to New Comparison

Design Function	Target	Actual
Overall Weight	20 Kg	14.5 Kg
Reach (Throat depth)	100mm	100mm
Cost	£1.8K	£1.6K
Access Gap	40mm	41mm
Overall Height	370mm	415mm

Table A.11 Actual to Target Comparison

Summary

Although time consuming, some of the main benefits of using the DFD methodology were the recorded commitments of all team members and the detailed analysis which resulted in the precise definition of true customer requirements. From this clearly defined platform, the process of following a structured design approach resulted in the efficient generation of novel product subsystems.

Since no information is destroyed, only held on record, a clear path can be traced back to justify exactly why certain decisions were made and the criterion which led to that conclusion. This approach therefore fits comfortably within the requirements for product design as laid down by BS5750/7000.

In conclusion, for this product, the DFD process has proved itself to be both a powerful and usable design tool, particularly over its first two stages. For different types and sizes of product within different organisational structures, the approach would however require modification to suit, particularly when considering the potential explosion of information which may occur if not adequately controlled. In all cases, a computer-based system would greatly aid in the handling and storage of data.

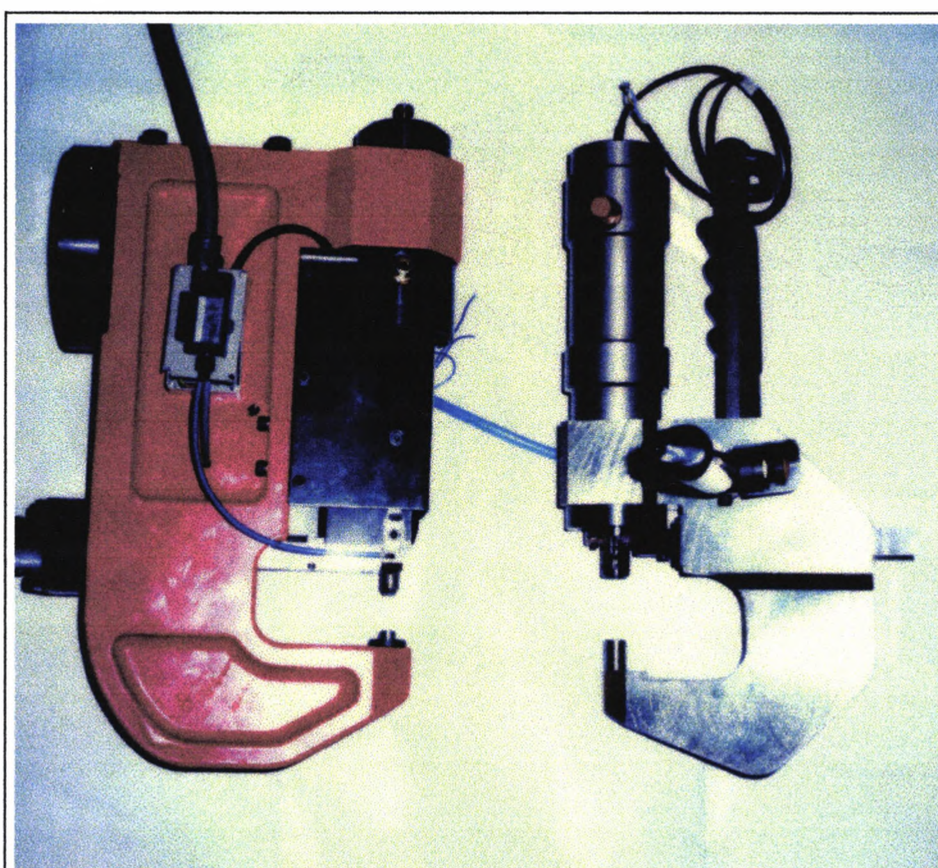


Fig A.2 Old V New

Appendix B: DFD Charts and Tables

Customer Requirements Questionnaires

As a means of extracting 'True' customer requirements, a questionnaire was formulated for distribution to all identified customers. Segregated into customer groupings, the form begins with several suggested requirements to help stimulate the mental process and demonstrate the 'none solution specific' form of answers required. Each customer is asked to contribute to every customer grouping, after which an order of importance must be added.

The following gives an example of a completed questionnaire:

Initial suggestions in **bold.**

Customer	No	Customer Requirement	Priority
Purchasing organisation (process specifier)	**1**	**Short delivery time**	13
	2	**Consistent parts quality**	3
	3	**Quantifiable joint performance**	1
	4	Repeatable joint performance	2
	5	low cost per joint	4
	6	No environmental problems	15
	7	Rapid operation	6
	8	Corrosion resistance	14
	9	Low residual distortion	10
	10	Close component clamping	7
	11	Long tool life	11
	12	Tolerant to pre-coated materials & Mastiks	12
	13	Joint thickness variability tolerant	9
	14	Joint material properties variability tolerant	8
	15	Max strength per fastener	5
	16	Re-cycleable with host	16

Customer	No	Customer Requirements	Priority
Purchasing organisation/individual (end product user)	18	**Never needs to know its there**	1
	19	Maximum strength	2
	20	Crash repairable	3
Process user	21	**Easy to apply**	1
	22	Perform reliably	2
	23	Clean operation	3
Quality assurance	24	**Known standard of performance**	1
	25	Repeatable standard of performance	2
	26	Statistical capability data	4
	27	Joint inspection capability	3
Manufacturer (fastener system)	28	**Easy to make fastener**	1
	29	Maximum tool life	3
	30	Easily defined setting tools	4
	31	Minimum number of processes	2
Supplying organisation(AAB&TR)	32	**Lowest cost for maximum profit**	1
	33	Competitive market price	3
	34	Technical market advantage	2
	35	High volume production	5
	36	Minimum number of variants	4
Legal/Professional organisations	37	**Parts manufacture to ISO9000**	1
	38	QS9000 approval	2

Classified Customer Requirements

Primary	Secondary	Tertiary
1. Joint Creation	1.1 Performance	1.1.1 Tight component clamping
		1.1.2 Minimal residual stress
		1.1.3 Joint thickness tolerant
		1.1.4 Joint properties tolerant
		1.1.5 Maximum strength
	1.2 Application	1.2.1 Easy to carry out
		1.2.2 Operate reliably
		1.2.3 Rapid process
		1.2.4 Join pre-coated materials
		1.2.5 Usable with mastik/adhesive
		1.2.6 No environmental problems
		1.2.7 Long tool life
	1.3 Acquisition	1.3.1 Rapid deliver on demand
		1.3.2 Low cost per joint
	1.4 Quality	1.4.1 Known performance std
		1.4.2 Repeatable performance
		1.4.3 Statistically capable
Parts Creation	2.1 Manufacture	2.1.1 Easy to make
		2.1.2 Minimum stage to process
		2.1.3 Maximum tool life
		2.1.4 High volume manufacture

Primary	Secondary	Tertiary
		2.1.5 Minimal variants
	2.2 Quality	2.2.1 ISO 9000
		2.2.2 Controllable parameters
	2.3 Organisation	2.3.1 Lowest cost for max profit
		2.3.2 Competitively priceable
		2.3.3 Technological advantage
3. Host Performance	3.1 Usage	3.1.1 Corrosion resistance
		3.1.2 Maximum strength
		3.1.3 Crash repairable
		3.1.4 Trouble free
	3.2 Disposal	3.2.1 Re-cycleable

Quality Plan

Serial No	Tertiary Customer Requirements	Customer Rating	AAB&TR	Plan			Weight	
				Quality Target	Improvement Plan	Sales Advantage	Absolute Weight	Relative Weight
1.1.1	Tight component clamping	5	3	5	1.67	1.5	12.5	6
1.1.2	Minimal residual distortion	5	3	5	1.67	1.5	12.5	6
1.1.3	Joint thickness tolerance	3	3	3	1.00	1.2	3.6	2
1.1.4	Joint properties tolerant	3	3	4	1.33	1.2	4.8	2
1.1.5	Maximum strength per joint	5	4	5	1.25	1.5	9.4	5
1.2.1	Easy to carry out	4	2	4	2.00	1.2	9.6	5
1.2.2	Operate reliably	4	3	5	1.67	1.5	10	5
1.2.3	Rapid process	4	4	4	1.00	1.5	6	3
1.2.4	Join pre-coated materials	4	4	4	1.00	1.5	6	3
1.2.5	Usable with mastik/adhesive	4	4	4	1.00	1.5	6	3
1.2.6	No environmental problems	3	4	4	1.00	1.2	3.6	2
1.2.7	Long tool life	3	4	4	1.00	1.0	3	1
1.3.1	Rapid delivery on demand	4	2	5	2.5	1.2	12	6
1.3.2	Low cost per joint	4	4	5	1.25	1.2	6	3
1.4.1	Known performance standard	4	2	5	2.5	1.5	15	7
1.4.2	Repeatable performance	5	3	5	1.67	1.5	12.5	6
1.4.3	Statistical capability standards	4	2	4	2.00	1.5	12	6

Serial No	Tertiary Customer Requirements	Customer Rating	AAB&TR	Plan			Weight	
				Quality Target	Improvement Plan	Sales Advantage	Absolute Weight	Relative Weight
2.1.1	Easy to make	4	4	4	1.00	1.0	4	2
2.1.2	Minimum stages of process	4	3	4	1.33	1.0	5.4	3
2.1.3	Maximum tool life	4	2	4	2.00	1.0	8	4
2.1.4	High volume manufacture	3	2	4	2.00	1.0	6	3
2.1.5	Minimal variants	4	2	4	2.00	1.0	8	4
2.2.1	ISO 9000	4	3	5	1.67	1.5	10	5
2.2.2	Controllable parameters	5	3	5	1.67	1.2	10	5
2.3.1	Lowest cost for maximum profit	5	2	5	2.5	1.0	12.5	6
2.3.2	Competitively priceable	5	3	5	1.67	1.5	12.5	6
2.3.3	Technological advantage	5	2	5	2.5	1.5	18.8	9
3.1.1	Corrosion resistance	5	3	5	1.67	1.5	12.5	6
3.1.2	Maximum strength	5	4	5	1.25	1.5	9.3	4
3.1.3	Crash repairable	4	4	4	1.00	1.2	4.8	2
3.1.4	Trouble free	4	4	5	1.25	1.5	7.5	4
3.2.1	Re-cycleable	3	4	4	1.00	1.2	3.6	2

Design Functions

For each tertiary customer requirement, a means of achieving it was proposed in a none solution specific format. This process continued until all requirements were fully *deployed.*

No	Design Functions
1	Efficient material piercing
2	Minimal material displacement
3	Efficient shank flair tendency
4	Maximum shank flair
5	Minimal surface friction
6	Robust rivet parameters
7	Robust anvil parameters
8	High velocity formation
9	Cold fastening process
10	No pierce through joint
11	Avoid rivet material treatment
12	Avoid rivet surface treatment
13	Stainless fastener material
14	Large batch manufacturing
15	Predictable joint performance
16	Consistent joint formation
17	Consistent rivet formation
18	Robust to material fluctuations
19	Rivet, anvil, material robust relationship
20	Removable rivet
21	Galvanic avoidance
22	Minimum force to form joint
23	Measurable parameters of rivet
24	Measurable parameters of joint

Classified Design Functions

Primary	Secondary	Tertiary
1. Self Pierce Riveting Process	1.1 Joint Formation	1.1.1 Efficient piercing
		1.1.2 Minimal metal displacement
		1.1.3 Shank flair tendency
		1.1.4 Cold fastening process
		1.1.5 High velocity formation
		1.1.6 No pierce through
		1.1.7 Consistent joint formation
		1.1.8 Minimal surface friction
		1.1.9 Minimal force to form
	1.2 Fastener Formation	1.2.1 Measurable rivet parameters
		1.2.2 Consistent rivet formation
		1.2.3 Consistent rivet properties
		1.2.4 Large batch manufacture
		1.2.5 Minimise material treatment
		1.2.6 Minimise surface treatments
		1.2.7 Stainless material
	1.3 Joint Performance	1.3.1 Predictable joint performance
		1.3.2 Maximum shank flair
		1.3.3 Removable rivet
		1.3.4 Galvanic avoidance
		1.3.5 Measurable joint parameters
	1.4 Robustness	1.4.1 Robust rivet parameters
		1.4.2 Robust anvil parameters
		1.4.3 Robust to material fluctuations
		1.4.4 Robust joint parameter relations

DFD1 Process Specification

Design Functions	Weight	Comments and Interactions
1.4.1 Robust rivet parameters 1.4.3 Robust to material fluctuations 1.4.4 Robust joint parameter relationships	9	Highest importance factors - Confirms known weakness of process generally being lacking in overall robustness, this includes the effects of rivet parameters in terms of shape, size and properties, also the effects of the fluctuations of size and properties of the material into which the joint is being formed. In addition the effects of each parameter on each other needs to have a robust relationship. Application of *robust design* to the process is to be a key feature of this project. All functions of robustness have a positive interaction relationship and as such should be considered together as a single requirement, 1.1.7 consistent joint formation becomes a function of robustness and so becomes absorbed by it.
1.4.2 Robust anvil parameters	8	Shape and proportions of anvil setting tool known to be critical for good joint performance, to be combined with and included in the further analysis of the above functions.
1.3.1 Predictable joint performance	8	High importance factor - The ability to predict to a high level of certainty the likely performance of a joint under proposed conditions of joint material properties and proportions. This will become a function of general overall process robustness (with which it interacts) and a fully documented source of existing joint test data.
1.1.7 Consistent joint formation	7	High importance factor - Repeatability of joint performance under normal fluctuation of process variables. Becomes absorbed into other functions of robustness.

Design Function	Weight	Comments and Interactions
1.1.1 Efficient piercing	7	High importance factor - The efficiency with which the rivet is able to pierce its way through the upper layers of the joint material. Several interactions occur with other functions, 1.1.2 minimal metal displacement, 1.1.8 minimal surface friction, 1.1.7 consistent joint formation and 1.1.9 minimal force to form, all have positive benefits from efficient piercing. Negative interactions also occur with 1.1.3 shank flair tendency and 1.1.6 no pierce through. Since a conflict exists between functions, compromises will have to be sought in order that those functions of the highest importance receive the higher priority for satisfaction by the design process
1.1.3 Shank flair tendency	5	High importance factor - The tendency which the rivet shank has to flare out during the final stages of joint formation and so of key importance to final joint strength. A negative interaction occurs with 1.1.1 shank flair tendency as a conflict exists between the rivet shank requiring to be hard enough to retain shape, and hence pierce efficiently through the upper joint layers, whilst also being malleable enough to flair out in the lower layer. A positive interaction inevitably occurs with 1.3.2 maximum shank flair.
1.2.2 Consistent rivet formation	5	Medium importance factor - The ability of the rivet to be produced to a consistent standard of shape and dimensions. Positive interaction and combination with 1.2.3 consistent rivet properties.
1.2.3 Consistent rivet properties	5	Medium importance factor - Rivet properties of hardness, malleability, surface conditions etc to be producible to consistent established values. Positive interaction and combination with 1.2.2 constant rivet formation
1.3.2 Maximum shank flair	5	High importance factor - To achieve as large a flair on the shank end as possible, which is vital to the final joint strength. Positive interaction with 1.1.3 shank flare tendency.

Design Function	Weight	Comments and Interactions
1.1.2 Minimal metal displacement	4	Medium importance factor - To have the minimum amount of joint material displaced during formation. Positive interaction with 1.1.2 efficient piercing.
1.2.1 Measurable rivet parameters	4	Medium importance factor - To have important parameters of the rivet to be easily measurable in a production environment.
1.2.4 Large batch manufacture	4	Medium importance factor - To produce the rivets in large volume batches in order to derive maximum financial benefit.
1.1.6 No pierce through	3	Medium importance factor - The end of the rivet shank not to pierce completely through the lower joint material. Negative interaction with 1.1.1 efficient piercing, since the more tendency the rivet has to pierce then the greater will be its inclination to break through the lower material level, give priority to highest rated factor.
1.2.5 Minimise material treatments	3	Low importance factor - Eliminate post formation processes of increasing rivet hardness where possible.
1.2.6 Minimise surface treatments	3	Low importance factor - Reduce the need for applying corrosion resistant surfaces to the rivet. Positive interaction with 1.2.7 stainless materials, which where practical to use eliminates this need.
1.2.7 Stainless materials	3	Low importance factor - Form rivets from a stainless material type. Positive interaction with 1.2.6 minimise surface treatments.
1.3.5 Measurable joint parameters	3	Medium importance factor - Parameters that can be practically measured to give an indication of joint quality, either during or after joint formation. (in process quality monitoring being developed as a separate project).

Design Functions	Weight	Comments and Interactions
1.1.8 Minimal surface friction	2	Low importance factor - Keep friction between rivet shank and material being pierced to a minimum, has a positive interaction with 1.1.9 minimal force to form, and has a positive influence on 1.1.1 efficient piercing and 1.1.2 minimal metal displacement.
1.1.9 Minimal force to form	2	Low importance factor - Partial function of 1.1.8 above and positive interaction with 1.1.1 efficient piercing.
1.3.4 Galvanic avoidance	2	Low importance factor - Mechanism by which galvanic corrosion can be avoided, benefits from 1.2.7 stainless material.
1.1.5 High velocity formation	1	Low importance factor - High velocity of rivet during joint formation
1.3.3 Removable rivet	1	Low importance factor - Rivet capable of being removed from joint for repair or rebuild.

DFD2 Process Specification

Process Features	Weight	Comments and Interactions
2.1.2 Poke Features	9	Highest importance factor - Relates to the shape and form of the hole (poke) produced in the end of the rivet shank. Preliminary experiments with different forms have confirmed the highly influential nature of this feature in achieving joint requirements. In proposing alternatives it will however be necessary to design around the cold forming process and hence the limits of its capability.
2.1.5 Material Properties (fastener)	8	High importance factor - Relates to both the raw material properties in pre and post headed conditions, plus its final state after any heat treatment processing. Carries through the same conflict found at the DFD1 stage, where the need for sufficient hardness to pierce has to be compromised with its malleability to allow flaring.
2.1.3 Poke Proportions	6	High importance factor - Very much a function of 2.1.2 with which it must developed in unison.
2.4.1 Material Properties (joint material)	6	High importance factor - Process has been found to be highly influenced by joint component material properties. This becomes a constraint on the process since it is directly specified by the customer; it must however be fully explored over a selected range of potential material types.
2.2.1 Anvil Profile Features	5	High importance factor - Shape of internal form of anvil which directly influences the flaring action of the rivet and the amount of force required to carry out the process.
2.2.2 Anvil Profile Proportions	4	High importance factor - Will be a function of 2.2.1 and hence developed in unison with.
2.1.6 Surface Properties	4	Medium importance factor - Characteristic of final material surface or plating applied. Effects found to date relate largely to the frictional properties and subsequent *drag through* of material during the piercing stage.
2.3.1 Pre-clamp	4	High importance factor - Provided by the setting machinery and found to be an essential element in achieving a distortion free joint.
2.1.1 Shank Properties	3	Medium importance factor - Relates to shank diameter and length, which in turn are proportioned as a function of joint material thickness and hardness.

2.4.2 Thickness Range (joint material)	2	The achievable range of total joint thickness which will be proportional to the material hardness.
2.1.4 Head Features	1	Shape and proportions of rivet head to give either a flush finish or a specific external appearance. Additional under-head features have also been found to effect joint tightness.
2.2.3 Delivery Attitude	1	Ensuring end of rivet shank is driven perpendicular into the work surface. This is a function of both delivery system and squareness (cut-off) of the rivet shank.
2.3.2 Delivery Velocity	1	Speed at which rivet is driven into material whilst forming joint.

Appendix C:

Customer Questions Prompt Sheet

Company Details: *The Visor Company*
Unit24
Bridge Rd
Suffolk *Tel (01869)22345*

Contact Details: *Mr Smith - Project Manager*
Mr Jones - Production Director

Requirements

Product Type: Description

Polyester Visor Rip-off's to be cut to two different shapes and counted into stacks of either 10 or 50 on demand. Material will be provided in 400mm diameter reels, which must be easily loaded into the machine. Each stack to be packaged in pre-printed polypropylene film by a heat sealing process with finished packs being discharged out of the end of the machine. Packaging film will be supplied on two 200mm diameter reels , which must also be accommodated within the machine.

Drawings? *Yes* *000347585 and 38438454*

Variants: *Two*

Materials: *Polyester for the Visor and Polypropylene for the packaging*

Properties: *Visor material is very hard and tough, packaging material is very prone to stretching but can be heat sealed.*

Samples? *Yes* **Existing Product?** *No but similar*

Production Rate: *120 per minute* **Target Efficiency:** *90%*

Instalation

Available Space: *6m x12m*

Services: *15amp single-phase supply plus service air*

Interfacing with other Equipment: *Not Required*

Safety Standards: International *European machinery directive*

Company *None*

Other Requirements: *Changeable code printing required for marking each finished pack automatically within the machine.*

Justification

Pay Back Policy: *18 Months*

Potential Savings: *£X per year*

Budget: *£XXX*

Estimated Likelihood of Success *70%*

Delivery

Target Dates: *12 Weeks from placement of order*

Warranty Period: *12 Months*

Payment Terms: *30% 50% 20%*

Other Notes

It is important that surface of rip off's has no marks of any kind made during manufacturing process

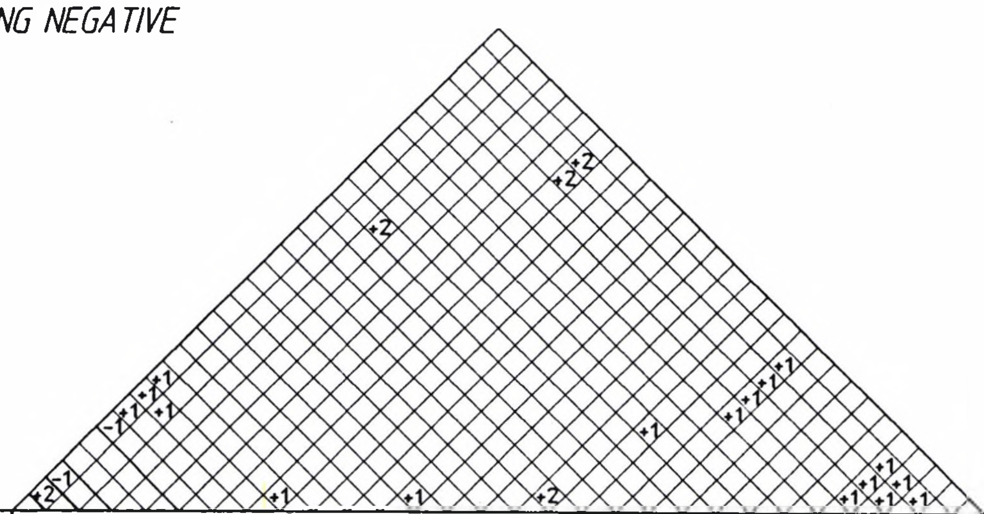
DFD 1

INTERACTIONS

+2 STRONG POSITIVE
+1 POSITIVE
-1 NEGATIVE
-2 STRONG NEGATIVE

RELATIONSHIPS

1 - WEAK RELATIONSHIP
3 - MEDIUM RELATIONSHIP
9 - STRONG RELATIONSHIP
BLANK - NO POSITIVE RELATIONSHIP



				1 SELF PIERCE RIVETING PROCESS																												
		DESIGN REQUIREMENTS		1.1 JOINT FORMATION										1.2 FASTENER FORMATION								1.3 JOINT PERFORMANCE						1.4 ROBUSTNESS				
		CUSTOMER REQUIREMENTS		1.1.1 EFFICIENT PIERCING	1.1.2 MINIMAL METAL DISPLACEMENT	1.1.3 SHANK FLAIR TENDANCY	1.1.4 COLD FASTENING PROCESS	1.1.5 HIGH VELOCITY FORMATION	1.1.6 NO PIERCE THROUGH	1.1.7 CONSISTENT JOINT FORMATION	1.1.8 MINIMAL SURFACE FRICTION	1.1.9 MINIMAL FORCE TO FORM		1.2.1 MEASURABLE RIVET PARAMETERS	1.2.2 CONSISTENT RIVET FORMATION	1.2.3 CONSISTENT RIVET PROPERTIES	1.2.4 LARGE BATCH MANUFACTURE	1.2.5 MINIMISE MATERIAL TREATMENTS	1.2.6 MINIMISE SURFACE TREATMENTS	1.2.7 STAINLESS MATERIALS		1.3.1 PREDICTABLE JOINT PERFORMANCE	1.3.2 MAXIMUM SHANK FLAIR	1.3.3 REMOVABLE RIVET	1.3.4 GALVANIC AVOIDANCE	1.3.5 MEASURABLE JOINT PARAMETERS		1.4.1 ROBUST RIVET PARAMETERS	1.4.2 ROBUST ANVIL PARAMETERS	1.4.3 ROBUST TO MATERIAL FLUCTUATION	1.4.4 ROBUST JOINT PARAMETER RELATIONSHIPS	
			IMPORTANCE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
1. JOINT CREATION	1.1 PERFORMANCE	1.1.1 TIGHT COMPONENT CLAMPING	6	9	9	9		1		3	9	3		1	1							1	3					3	3	3	3	
		1.1.2 MINIMAL RESIDUAL DISTORTION	6	9	9	3		1		1	3	3		1	1							1	1					1	1	1	1	
		1.1.3 JOINT THICKNESS TOLERANT	2	1		1	1			3	1	1											1					3	3	9	9	
		1.1.4 JOINT PROPERTIES TOLERANT	2	3	1	1	3			3	3	1										9	3					9	3	9	3	
		1.1.5 MAXIMUM STRENGTH PER JOINT	5	3	1	9	1		1					1	1							3	9					9	9	9	9	
	1.2 APPLICATION	1.2.1 EASY TO CARRY OUT	5	1	1		9	1																								
		1.2.2 OPERATE RELIABLY	5	3		3	1			1		1			3	3																
		1.2.3 RAPID PROCESS	3				3	9																								
		1.2.4 JOIN PRECOATED MATERIALS	3				9		3			1													1							
		1.2.5 USABLE WITH MASTIC/ADHESIVE	3	1			9																									
		1.2.6 NO ENVIRONMENTAL PROBLEMS	2				9																									
		1.2.7 LONG TOOL LIFE	1	3	1	1						9						1					1						1			
	1.3 ACQUISITION (FASTENER)	1.3.1 RAPID DELIVERY ON DEMAND	6														1	3	3	3												
		1.3.2 LOW COST PER JOINT	3				1							1	1		3	3	3	1								1	1	1	1	
	1.4 QUALITY	1.4.1 KNOWN PERFORMANCE STANDARD	7	1		1				3				3	3	3						9						3	3	3	3	
		1.4.2 REPEATABLE PERFORMANCE	6	3	1	1	1			9	1	1		1	9	9		1	1			9						9	9	9	9	
		1.4.3 STATISTICAL CAPABILTY STANDARDS	6				1			1				3	1	1						3				9						
2. PARTS CREATION (CONSUMABLES)	2.1 MANUFACTURE	2.1.1 EASY TO MAKE	2											1	9	3	9	9	9	3								1				
		2.1.2 MINIMUM STAGES OF PROCESS	3															9	9	3												
		2.1.3 MAXIMUM TOOL LIFE	4																													
		2.1.4 HIGH VOLUME MANUFACTURE	3				1							1	3	3	9	3	3									3				
		2.1.5 MINIMAL VARIANTS	4			1									1			1	1									9	1	9	9	
	2.2 QUALITY	2.2.1 ISO 9000	5							1				9	1	1						3						1	1	1	1	
		2.2.2 CONTROLLABLE PARAMETERS	5	1										9	1	1						1						3	3	3	3	
	2.3 ORGANISATION	2.3.1 LOWEST COST FOR MAXIMUM PROFIT	6											1	1	3	9	3	3	1								1				
		2.3.2 COMPETITIVELY PRICEABLE	6														9	3	3	1								1				
		2.3.3 TECHNOLOGICAL ADVANTAGE	9	3	3	3			9	9	1	3		1	3	3						9	9			9		9	9	9	9	
3. HOST PERFORMANCE	3.1 USAGE	3.1.1 CORROSION RESISTANCE	6						3											9					9							
		3.1.2 MAXIMUM STRENGTH	4	1						3					1								9							3	1	
		3.1.3 CRASH REPAIRABLE	2				1																	9								
		3.1.4 TROUBLE FREE	4	1						9					1	1				1		3	1		3			1	1	1	3	
	3.2 DISPOSAL	3.2.1 RE-CYCLEABLE	2				1																									
		UNITS						M/S															D									
		TARGET VALUE						.25															1.5									
		CONFIDENCE						7															8									
		UPPER LIMIT						.5															1.7									
		LOWER LIMIT						.1															1.3									
		TARGET DIRECT						+															+									
		ABSOLUTE IMP		222	154	181	166	44	113	256	95	90		158	198	187	168	128	127	106		298	209	18	69	135		364	310	369	369	
		RELATIVE IMP		7	4	5	4	1	3	7	2	2		4	5	5	4	3	3	3		8	5	1	2	3		9	8	9	9	

DFD 2

RELATIONSHIPS

1 - WEAK RELATIONSHIP
3 - MEDIUM RELATIONSHIP
9 - STRONG RELATIONSHIP
BLANK - NO POSITIVE RELATIONSHIP

CORRELATION BETWEEN PROCESS FEATURES TO BECOME PART OF EXPERIMENTAL PROCESS.

DFD 1 PROCESS SPECIFICATION				2. PROCESS FEATURES																				
				2.1 FASTENER							2.2 TOOLING				2.3 MACHINERY			2.4 JOINT MATERIAL						
				2.1.1 SHANK PROPORTIONS	2.1.2 POKE FEATURES	2.1.3 POKE PROPORTIONS	2.1.4 HEAD FEATURES	2.1.5 MATERIAL PROPERTIES	2.1.6 SURFACE PROPERTIES		2.2.1 ANVIL PROFILE FEATURES	2.2.2 ANVIL PROFILE PROPORTIONS	2.2.3 DELIVERY ATTITUDE		2.3.1 PRE-CLAMP	2.3.2 DELIVERY VELOCITY		2.4.1 MATERIAL PROPERTIES	2.4.2 THICKNESS RANGE					
			IMPORTANCE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1. SELF PIERCE RIVETING PROCESS	1.1 JOINT FORMATION	1.1.1 EFFICIENT PIERCING	7	1	9	3		1	9		1	3	1			1		9	3					
		1.1.2 MINIMAL METAL DISPLACEMENT	4	9	1	3		1	1		3	9			9			1	3					
		1.1.3 SHANK FLARE TENDENCY	5	3	9	9		9			9	3				1		3	3					
		1.1.4 COLD FASTENING PROCESS	4																					
		1.1.5 HIGH VELOCITY FORMATION	1													9								
		1.1.6 NO PIERCE THROUGH	3	9	9	9		3	1		3	3	1					3	3					
		1.1.7 CONSISTANT JOINT FORMATION	7		9	9		3			3	3			9			9	3					
		1.1.8 MINIMAL SURFACE FRICTION	2						3							3		9	1					
		1.1.9 MINIMAL FORCE TO FORM	2	3	9	9	9	3	9		3	3	1			1		9	9					
	1.2 FASTENER FORMATION	1.2.1 MEASURABLE RIVET PARAMETERS	4		1	1	1																	
		1.2.2 CONSISTENT RIVET FORMATION	5		3	3	3	9																
		1.2.3 CONSISTENT RIVET PROPERTIES	5					9	9															
		1.2.4 LARGE BATCH MANUFACTURE	4	3	9	3	3	3	1															
		1.2.5 MINIMISE MATERIAL TREATMENTS	3					3																
		1.2.6 MINIMISE SURFACE TREATMENTS	3						3															
		1.2.7 STAINLESS MATERIALS	3					9	9															
	1.3 JOINT PERFORMANCE	1.3.1 PREDICTABLE JOINT PERFORMANCE	8		3	1		3	1		3	1	1		3			3	1					
		1.3.2 MAXIMUM SHANK FLARE	5	3	9	9																		
		1.3.3 REMOVABLE RIVET	1	1			1	9											3					
		1.3.4 GALVANIC AVOIDANCE	2					9																
		1.3.5 MEASURABLE JOINT PROPERTIES	3	1	1						9	9												
	1.4 ROBUSTNESS	1.4.1 ROBUST RIVET PARAMETERS	9	1	9	3		9	1						1									
		1.4.1 ROBUST ANVIL PARAMETERS	8								9	3												
		1.4.3 ROBUST TO MATERIAL FLUCTUATIONS	9	1	9	3		3	1		3	1			9	1		9	1					
		1.4.4 ROBUST JOINT PARAMETER RELATIONS	9	3	3	3		3	1		3	3			3			3	1					
		TARGET VALUE																						
		CONFIDENCE																						
		UPPER LIMIT																						
		LOWER LIMIT																						
		TARGET DIRECT																						
		ABSOLUTE IMP		167	490	309	50	416	226		277	203	20		240	38		322	127					
		RELATIVE IMP		3	9	6	1	8	4		5	4	1		4	1		6	2					