



DAVID W KIRK

MECHANICAL DESIGN SUPPORT IN THE ASSEMBLY ENVIRONMENT

THE CIM INSTITUTE
PHD

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THE CIM INSTITUTE

PHD THESIS

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DAVID W KIRK

MECHANICAL DESIGN SUPPORT IN THE ASSEMBLY ENVIRONMENT

SUPERVISOR: PROFESSOR PETER J SACKETT

SEPTEMBER 1991

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"Genius is one percent inspiration and ninety-nine per cent perspiration."

Thomas Alva Edison, 1847-1931, *Life* Ch.24 1932.

SUMMARY

This thesis proposes a workable application philosophy for state of the art tools operating at the Design/Manufacturing interface. It promotes an organisational approach in developing a framework for a strategic Design For Assembly policy.

The definition of Engineering Design is explored. A proposed definition reveals a hierarchial structure. Existing generic design methodologies and specific Design For Assembly techniques are investigated and evaluated against a specific research environment.

The research method considers the design/manufacturing interface as a whole. A communication model investigates a mechanism for ratifying design changes. Process control theory explains the control of this mechanism.

The research has drawn upon the experience of two collaborators and several case studies are presented. The application domain is complex electro-mechanical products manufactured in a competitive mid volume environment.

AUTHOR PROFILE

The author joined Professor Sackett's Research Group at The CIM Institute in October 1987 as an SERC funded and industrially supported student. His work has contributed a design methodology to the Product Definition Process section of the Institute's Business and Manufacturing Integration research programme.

His affinity for Engineering started when he won the North East regional final of The Young Engineer For Britain competition in 1981. He progressed through "O" and "A" levels to take up a place on the BSc Mechanical Engineering Degree at Newcastle Upon Tyne Polytechnic, graduating with First Class Honours in 1987. The four year thin sandwich course taught practical and theoretical aspects of Engineering. Three formal industrial placements gave shopfloor experience at NEI Parson, steam turbine manufactures, and Thorn EMI Heating, manufacturers of domestics heaters. A final period at Dominick Hunter Filters, design and manufacturers of compressed air and process filtration equipment, involved him in the development of a filter calibration standard. Further work experience has been gained in a British Gas research station and as a marketing assistant at NEI Clarke Chapman. He is presently employed as a Manufacturing Engineer at Domino Amjet Limited. The Company design, manufacture and service commercial inkjet printers, primarily used for batch coding foodstuffs. He is responsible for ensuring that new products are efficiently transferred from Research and Development into Manufacturing. This has given him a wide experience of the technical and logistical problems of developing a new product in tight time scales whilst ensuring the introduction causes minimal disruption to existing operations.

PAPERS WRITTEN IN CONJUNCTION WITH THIS THESIS

SACKETT, P.J.

KIRK, D.W.

Integrated design support strategy. European CATIA users Association 1989 Conference. Watford, UK.

KIRK, D.W.

SACKETT, P.J.

A structured approach for concurrent engineering. Proceedings of the International Conference on Concurrent and Electronic Design Automation, p335-339. 26-28 March 1991. Bournemouth International Conference Centre, UK.

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SACKETT, P.J.

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A definition of engineering design.

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The structure of a design/manufacturing interface.

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- * My parents for their emotional and practical support as I started my career in Engineering.
- * Last, and most important, my wife Julie, for her love and support throughout the many different phases encountered in researching and writing this thesis. It is to her I owe the greatest debt.

THESIS STRUCTURE

CHAPTER ONE INTRODUCTION

An introduction to philosophy and it's role in solving problems is discussed. The general research theme is then introduced and put in the context of an ongoing research programme. The research methodology is discussed. The chapter concludes with the objectives of the thesis.

CHAPTER TWO ENGINEERING DESIGN

Chapter Two addresses engineering design and the status of formal research in Design Science. A discussion considers its importance at a national and company level. A proposed definition reveals a hierarchy of different interpretations. This framework is used to explain the technical and commercial demands of the author's research environment. Methods to Integrate the design and manufacturing functions are discussed.

CHAPTER THREE SYSTEM DEFINITION

The methods for Design For Assembly have traditionally had a Manufacturing bias. Design biased research provides limited comment. The results of these two approaches are compared in detail to those of the author's Integrated approach. A major deficiency of the Integrated approach is the lack of an application philosophy. The chapter concludes with the need to develop this philosophy. The theme of Integration will be continued; the design/manufacture interface will be modelled as a seamless whole.

CHAPTER FOUR CONCEPTUAL MODELS

The application philosophy tackles the problems of controlling the interface and the modes of communication present. The control characteristic is developed from Process Control Theory. The communication model goes beyond the technicalities of communications to understanding the consequences of the message being carried. This focuses upon the verification of manufacturing requested design changes. A range of decisions is found to exist. The extremes must be approached and solved in different ways.

CHAPTER FIVE TEST AND VERIFICATION

The results of the conceptual models are examined in design terms. The range of decisions found in the communication model are classified and tested with different design problems. The overall application philosophy is tested in two applications. The first compares it against the application philosophy of a classic Design For Assembly technique. A second example considers how it can be used to organise the concurrent running of design and manufacturing activities.

CHAPTER SIX CONCLUSION AND DISCUSSION

Chapter six closes the loop on the thesis, comparing results to the objectives set. Suggestion for further work are proposed.

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CHAPTER ONE INTRODUCTION

1.1 PHILOSOPHY

Picture three people, a customer, an Engineer and a mechanic each describing a motor car. The customer may talk about its many features, especially its luggage capacity. The Engineer may recount in exacting detail the way the engine works. The mechanic may comment upon the ease of changing worn out parts. Each description is influenced by the owner's background and future intentions. The customer might be planning to use the car on a long expedition, carrying heavy equipment. The Engineer might be developing an engine that uses water as fuel, and is trying to sell the idea. The mechanic might be identifying car servicing difficulties to a potential buyer. Each person has a different viewpoint on the same subject; they each have a different philosophy.

As a pursuit, Philosophy is the rational investigation of being, knowledge and right conduct[1]. To distinguish this from Science,

"...the systematic study of nature and behaviour of material and physical universe based on observation, experiment and measurement"[1]

Ayer proposes[2] that it is Science's job to explain the world, and philosophers' to clear conceptual obstacles from their path. This notion sees Science as a sound method to discover such facts as "A causes B". Philosophy must discover the logic behind the relationship; it is concerned with the language to make the world intelligible.

The result of this is a core belief onto which an intellectual framework can be built. Then, testing in different environments, rules, axioms and boundaries of operation can be formulated. This process of testing is as much about failure as conformance; it is only from finding fault with a theory, can a boundary of operation be plotted. This represents the boundary of acceptable knowledge in that environment. As time progresses, new ideas emerge to test this accepted picture. Such experiences, Anomalous Experiences [3], are proposed as a mechanism in which new parameters, requirements or operating procedures test existing ideas, so leading the way to new ground and new knowledge. The new picture is itself, subject to the same processes, eventually to conceding to new ideas.

1.2 THE CIM INSTITUTE RESEARCH PROGRAMME

The opening of world markets has disturbed the steady state operation of industry. To survive this transition phase, British companies must face head on the challenge of foreign companies in home markets and extend into new, overseas markets. There is a need for companies to compete[4][5]. This phase is raising company profiles from just fulfilling a need, to satisfying the Customer. Increasing emphasis is on the quality of products supplied, the cost to manufacture them and the time taken to supply the customer.

With competition producing an ever widening range of products, a dissatisfied customer can easily change supplier. The customer now demands the highest quality products. Quality is no longer the preserve of the shopfloor. Quality must form part of a company's strategic operating plan, driven by senior management. Total Quality Management insists that quality products come only from quality companies. Quality companies strive to find the cause of their problems. They go beyond the product, where the effects often emerge, to study every operation needed to produce the product. For example, the policy of Zero Defect ensures that problems do not occur, as opposed to will not occur. If a manufacturing process produces excessive scrap, the need for it must be designed out of the product or the process revised.

Product costing must reflect the financial demands of the company, investors and the ability of the customer to pay. Shareholders demand a return on the money they invest; typically, the higher the risk, the higher the expected return. To do this, an aggressive policy must be continuously reducing the product's manufactured cost and

increasing selling margin.

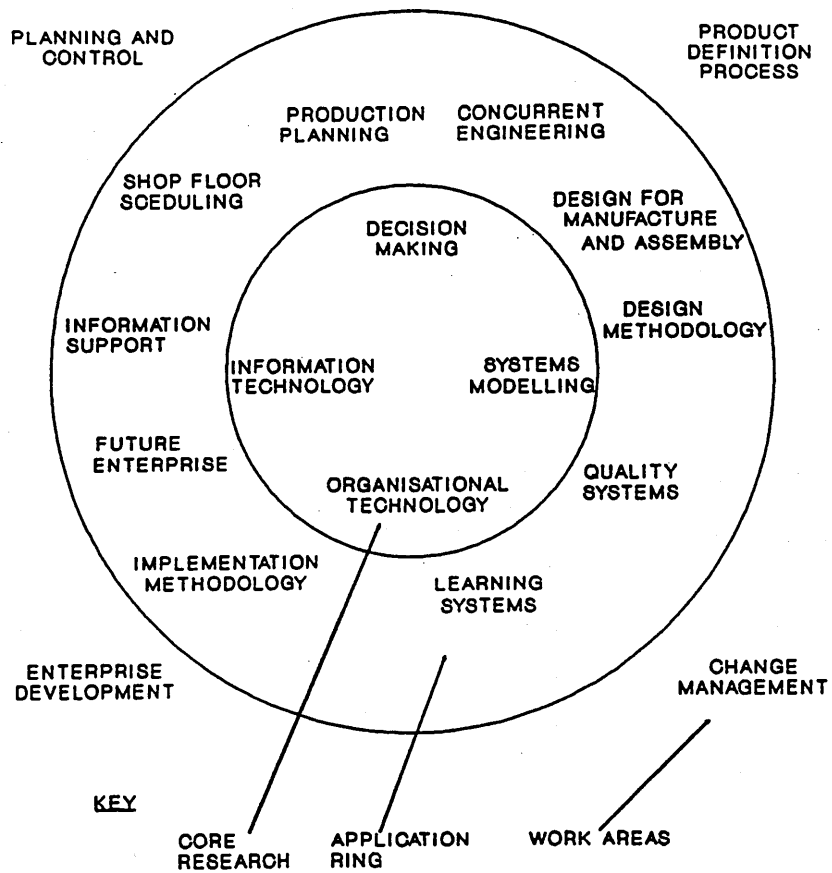
Time to market is emerging as a prime asset for being competitive. Efforts must reduce the time taken to satisfy the customer with existing products and the time to develop and introduce new products. Being able to react quickly to the change in customer demands and the competition is a prerequisite for a competitive company. This has been graphically illustrated in the motor industry[6].

Industry must meet the challenge, implementing the often radical changes, whilst still operating. Few businesses can afford the clean break to close down, reorganise, and reopen as a revitalised, modern, competitive manufacturing enterprise. Changes must be phased, pulling forward the gains of new ideas without fully compromising the operation of the old.

The research programme at The CIM Institute is helping industry to understand how it presently operates, the impact of being competitive and how best to react to the changes necessary. Figure 1 illustrates the current work programme.

The philosophy of Business and Manufacturing Integration reflects the operational needs of becoming more competitive. It proposes that a business should be organised and run around the processes, the Business Processes, needed to operate. Research is studying the Change management necessary to migrate from an uncompetitive state into a new competitive enterprise. A model of this transient activity would be an important planning tool for companies embarking on such a project. A second initiative is researching methods to support the development of these new enterprises.

THE CIM INSTITUTE RESEARCH BUSINESS AND MANUFACTURING INTEGRATION



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Figure 1 The CIM Institute Research Programme.

Information Technology is seen as a powerful tool in supporting this development; Computer Integrated Manufacturing. Indeed, such systems are shown not to recognise the traditional functional boundaries, so challenging the traditional approaches ability to manage such advanced systems.

Such increased complexity of operation demands new operating methods. Planning and Control of the manufacturing process must recognise the global scale of the problem. This becomes paramount as companies set up remote design and manufacturing sites.

The Product Definition Process tackles the issue of linking all the resources needed to define a product into a single process. This has particular significance in the context of electronic transfer of data in an inter-enterprise structured environment. Figure 2 illustrates how different functions of a business all have a key part to play in designing a product. Sales and marketing must predict the size of the anticipated market and help determine the timescales of development; finance must ensure that anticipated revenue returns the gross investment necessary to produce the product. The relationship between design and manufacture is of most interest to the Research team. To be competitive, a design must both work and be cost effective to produce[7].

To save time, a move must be made away from traditional approach of getting a design to work and then submitting it to a period of production engineering. This post design audit is also considered to compromise quality. The established research programme has produced methods to ensure that the limitations of manufacturing facilities are positively enforced during the mainstream design activity. This constant reinforcement helps rectify problems as they

occur, removing the need for a post design audit. Time and money is saved and an increase in the overall quality of the product is expected. The author's work has contributed the necessary design methodology to effectively implement such a policy.

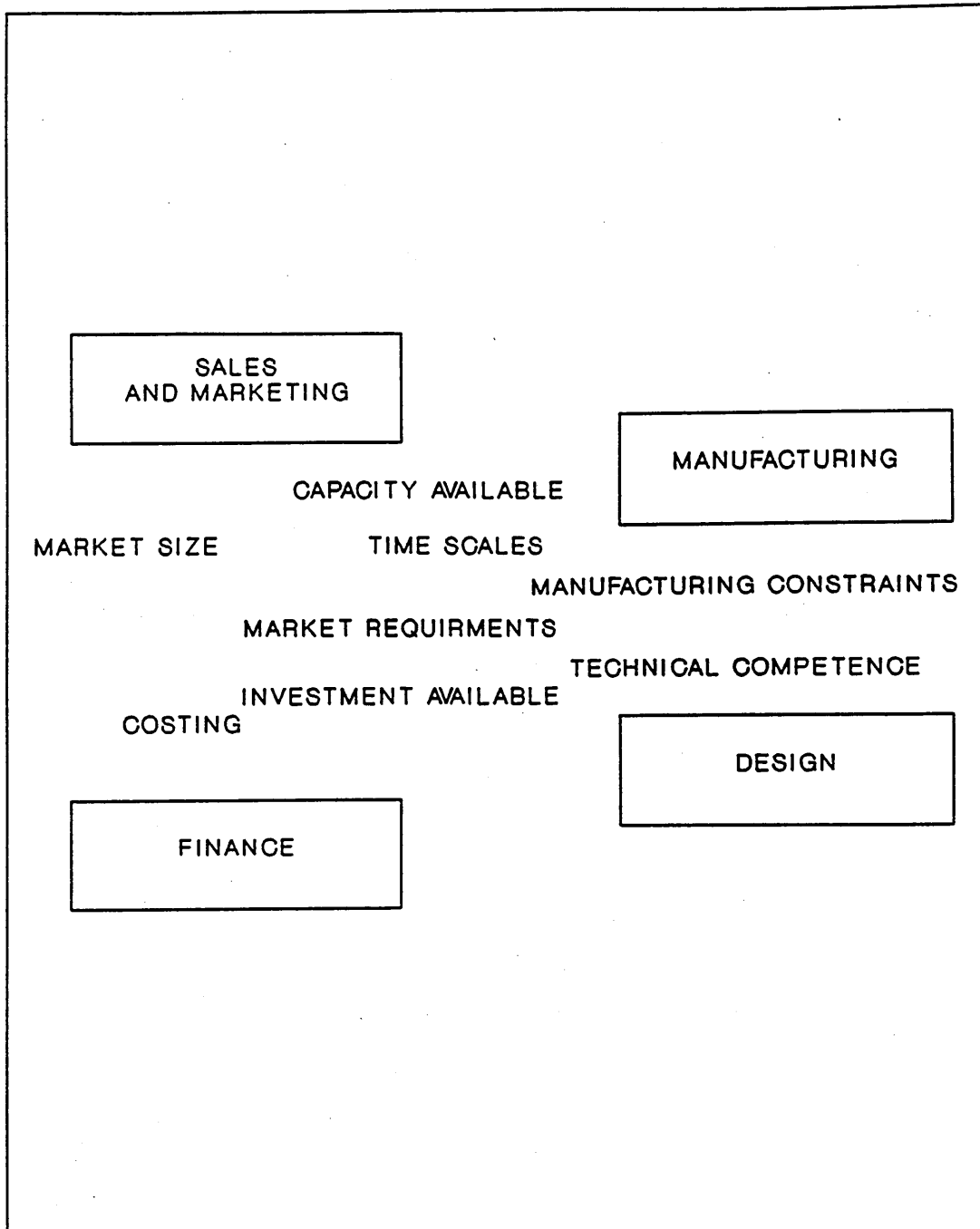


Figure 2 Product Definition Process

1.3 PROBLEM

The gains to be accrued from ensuring that a product is easy to assemble and manufacture has made for a viable research topic. The study of Design For Assembly and Manufacture is an attempt to formalise methods to promote these gains.

Automated assembly techniques have found favour with high volume manufacturers. Economies of scale help justify the capital investment required and drive efficiency programmes. A typical product in this environment is small, solid and easy to handle. A typical Design For Assembly method would recommend design improvements by scoring a finished design against such criteria as ease of feeding and gripping. A high score would indicate a design weakness. A period of analysis and redesign must then be undertaken. This is a post design audit. Such late changes to a design will compromise quality and increase time scales. Additionally, such methods are restricted to the narrow range of components found in such an automated assembly environment.

To broaden the appeal of Design For Assembly, the restrictions of the application method and range of products suitable must be addressed. Methods must be developed that do not compromise the designers main goal to design a product that works. Design analysis must be combined with the offering of positive advice on how to improve a design. This must form a natural part of the design process and be applicable to a wider range of products - both intended for automated and manual assembly.

The Design For Assembly research at The CIM Institute is developing techniques that work with the designer, offering positive advice on how to improve the design as the work

progresses. The work has undertaken problems found in the mid volume manufacturing sector. A much more complex product was encountered. A greater range of types and sizes of piece parts had to be designed. Commercial pressure to further reduce development timescales has reinforced the need for techniques that work with the designer during the mainstream design activity.

The results can be demonstrated with two computer based design analysis packages, that work with the designer, sharing information available from a Computer Aided Design system, offering positive advice on how to improve the design against set criteria. The first program helps the designer reduce the total number and range of parts being designed and ensuring that any parts requiring insertion operation have adequate lead in features. The second program provides on-line help when selecting a set of grippers for a product. The designer can simulate the gripping operation using the Computer Aided Design system. From an initial range of grippers selected, an optimisation algorithm can select the minimum number of grippers required or the most cost effective set.

The work has concentrated on the technicalities of the selected environment and so lacks a formal place in accepted design theory. An application theory was required. The authors goal was develop an appropriate Design Methodology into which a range of design tools could be placed.

1.4 METHODOLOGY

To develop this application theory, an investigation was proposed in the complex, real world environment described. To ensure informed results, it was necessary to select the most appropriate method to collect and analyse the data required.

1.4.1 DATA COLLECTION

The problem domain is in the mainstream operation of a manufacturing enterprise; it demands practical, usable solutions. Prospective collaborators needed to match the target industrial sector in complex electro-mechanical products, be small to medium size, and have aggressive manufacturing policies driven by the market place. The research programme has progressed through two suitable collaborators. The author's research period, three years, moved the overall programme into the second collaborator. The work progressed through three phases.

An initial period, one year, was dedicated to pure research predominately at The CIM Institute. During this phase, essential ground work covered formal design theory, contemporary manufacturing management and related information technology issues. To support this, the Academic Programme promoted an extensive itinerary of company visits, exhibitions and training courses, including;

MARS ELECTRONICS

KTM

MAP COMMUNICATION PROTOCOL
COURSE

TOTAL QUALITY MANAGEMENT
COURSE

EDWARDS HIGH VACUUM

TAGUCHI INTRODUCTION

IBM HURSLEY

CADCAM EXHIBITION (88)

IBM WARWICK, CIM CENTRE

DESIGN EXHIBITION (88)

PLESSEY AEROSPACE

It was during the conclusion of this phase that new ideas began to crystallise. The second phase, lasting six months, developed as the second collaborator joined the programme. A hectic period was spent adjusting to the specific demands of the sponsor, whilst establishing the research intent within the new environment. The final phase saw further development and testing of ideas, both against the demands of the selected environment and that of different writers. A part of this was the transition of ideas into the mainstream working environment.

1.4.2 DATA ANALYSIS

The work is based in a world where it is difficult to isolate involvement and adjudicate contribution. No one function of the enterprise is more important than another; each plays a vital role in its success. To produce meaningful results from the data collected, the most appropriate method must be used. Two approaches were considered; Classical Scientific or a more holistic Systems approach. The selection matched the central premise to the characteristics of the problem environment.

A scientific approach, as taught throughout the author's general science education, was examined first. This method would require the "problem" to be reduced to its simplest, prime units. An experiment could then record the effect on the body of varying only one unit at a time. The central premise being that the properties of the body is the exact

sum of the properties of the prime units. This approach assumes that the "problem" can be neatly cleaved into such isolated units.

It can be argued[8] that some bodies have a level of complexity so great, that it is meaningless to try and reduce them to such unit variables. Such complexity is indeed characterised by properties that only emerge as of a direct result of combining "units". To attempt to isolate different units may inadvertently deprive the experiment of the effect of such unknown properties; they do not exist without the interaction. Systems Thinking is an attempt to develop meaningful descriptions of such bodies.

The author's work is in such a complex environment; a requirement to modify a designer's original idea may only arise once it is subject to manufacturing scrutiny. The systems approach is considered the most suitable technique for analysing the processes required to move a product concept from the design to manufacturing.

The method adopted organises this complexity into a hierarchy. Each level is more complex than the one below, and can be characterised by its emergent properties; these are the result of the system and are meaningless at different levels. To operate as a whole, an effective means of Communication and Control is needed. Effective communication methods must be found to encode, transmit and decode information. Efforts must be directed at both ensuring technical excellence and that the correct meaning is transferred[9]. Control is required to promote a stable achievement of set objectives.

1.5 OBJECTIVES

General and specific objectives were set for the research programme and the thesis. The stimulus for starting the programme were;

- * Understand the forces impacting Design and Manufacturing activities in contemporary manufacturing companies.
- * Investigate the contribution Engineering Design can make to this drive for success.
- * Contribute to the Product Definition Process research initiative at The CIM Institute.

The following specific objectives relate to the brief given on joining the research team and developed through the early phases of the work.

- * Propose a Design Methodology framework to support design decision making in the context of the Institute's Design For Assembly research programme.
- * Test the proposed framework in a specific industrial target environment.
- * Consider the general applicability of the approach to the industrial environment and its relationship to existing Design theory.

CHAPTER TWO ENGINEERING DESIGN

Common to many manufacturing businesses is the life cycle their products pass through. Figure 3 illustrates a typical product life cycle.

Engineering design accounts for the range of activities required to describe a solution to problems posed. The solution can then be manufactured, installed, used and decommissioned. This final phase has long been ignored by both suppliers and consumers. The present high profile being enjoyed by Green, environmental politics is re-aligning both the views of the supplier and the customer. Efforts are now being directed at ensuring that products can be recycled or re-used. The range of problems being tackled spans from the recycling of domestic waste to attempts to re-use car components; The BMW motor car company claim to be designing components into their cars that can be re-used.

Design starts the product life cycle. Without some form of design, a product cannot be made, installed, used or decommissioned; the product would not exist.

A general view of Engineering Design is presented. The importance of it is considered at a national and company level. A definition is proposed that reflects both what it is, how it works and who is involved. A survey of Engineering Design research is presented. The approach classifies the different initiatives against a generic design process. This illustrates the diverse range of research programmes found and what problems they are trying to solve. The impact of computers in the design process is described using real life examples.

Using this framework, the author describes the working

environment, and problems posed, at the collaborating companies. This will clear the way for a new research initiative.

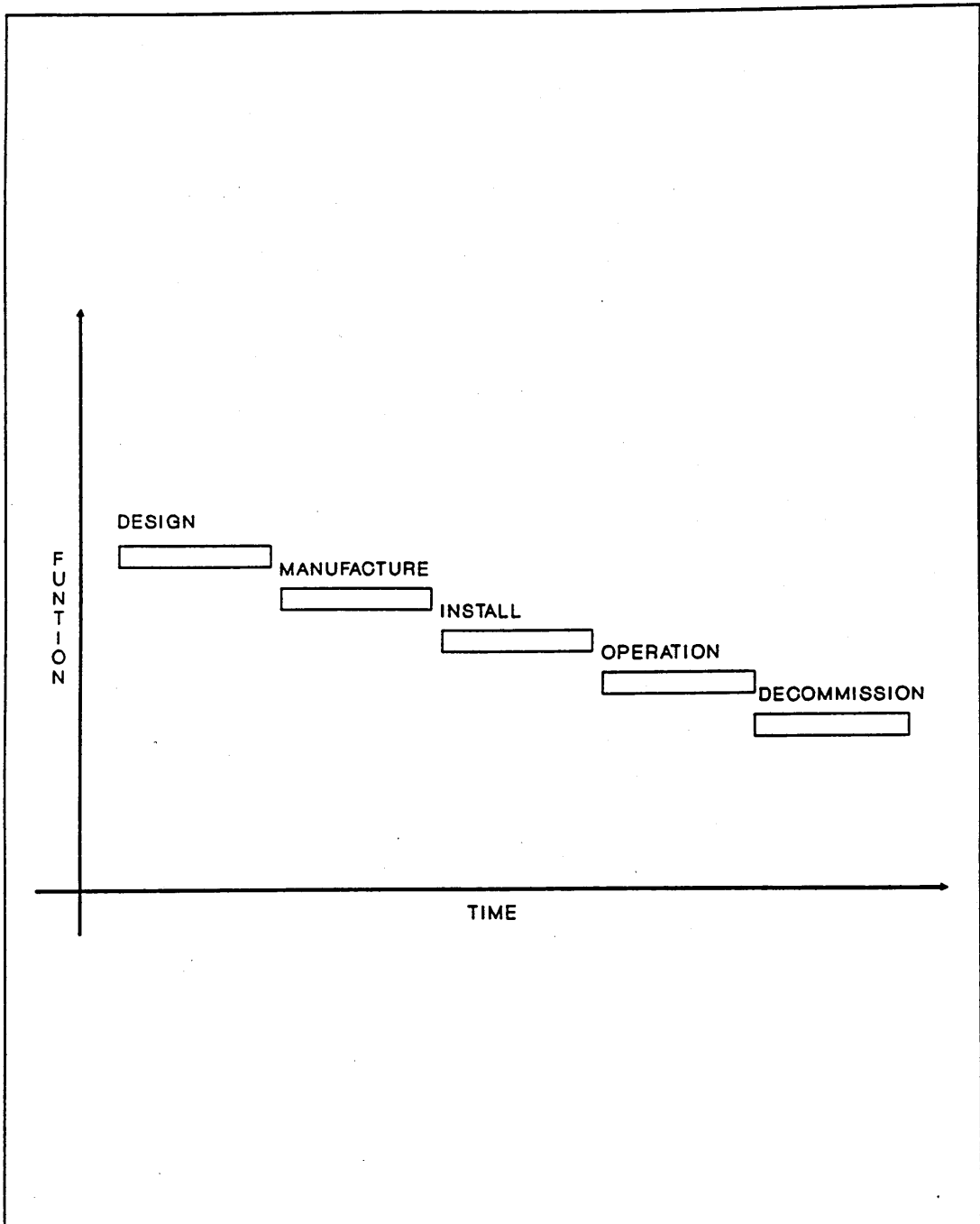


Figure 3 Product life cycle

2.1 IMPORTANCE

It is the responsibility of a designer to solve problems posed in such a manner that the solutions can be efficiently reproduced, installed and decommissioned. They have a clear responsibility to these proceeding activities. They also have a responsibility to the community which is involved with the product; the loss of 1500 lives aboard The Titanic in April 1912 prompted a rethink on the design of ship bulkheads[10]. Extracts from government sponsored reports are used to illustrate the political importance. Results of specific design research argues the need to consider the requirements of "downstream" activities during the design process.

2.1.1 POLITICAL

The need to commission a committee to consider the standing of mechanical engineering design at home, and in relation to practices overseas[11] sustains the importance attached to Engineering Design. The report recognised that success then, up to 1962, was built on post war euphoria as Britain played a key role in the rebuilding of Europe. The committee recognised the myopic view prevalent at the time that it was a sellers' market, so new product development was not required. Companies that adopted this philosophy saw no need to develop discrete design departments. It was then difficult to develop the teams and attitudes required once it was realised that new products were needed. In the same context the committee sounded a clear warning that British industry would not be able to compete on final cost with its low direct cost competitors if it were to use the same machinery and manufacturing methods as them.

A much deeper and more serious indictment was emerging concerning the role of the designer within the organisation. The results of applying an active campaign of minimal product development left its mark in both technical and social placing of the designer. In terms of technical ability the main complaint was levelled against their detail design ability with the deficiencies manifesting themselves in costly re-designs during the prototype phase and subsequent in service failures. Their social standing was also low, partly as a result of their lack of involvement with the product, "... design is often regarded as a background activity as compared to sales or manufacture".

The conclusions found the need to re-establish design at the front of the product life cycle and improve the training and working conditions of designers. Further reports[12] [13] pursued these points, drawing similar conclusions. Reiterating this in 1982, Dr Lickley[14], reported the need to establish design as the core of engineering education and manufacturing business. He encouraged the use of advanced Doctoral research programmes to study Engineering Design and advanced engineering techniques. He stressed the need for systematic design methodologies, but without encouraging esoteric solutions. More recently [15] integrating design into the mainstream operation of a business using advanced manufacturing technology has been proposed as an effective means of making a business more competitive. Those companies that neglect its products and manufacturing technology will ultimately fail, or fall victim to one of its more enlighten competitors [16].

2.1.2 COMPANY

The results of a design activity are a set of descriptions, from which copies can be made. The traditional language to convey these descriptions is a drawing. The way in which the designer encodes his intent using drawings can have a marked effect on the subsequent viability of the final design. Many production problems can be traced back to the design stage[17]. The effect on product costing and the selection of automated assembly techniques is used to illustrate the point further.

Research has studied the impact a designer's actions can have upon a product's cost. One study[18] found that 80% of the cost of 2000 components was determined during the design process.

A further study[19] estimated the cost of change once a product in production. In isolation a simple change, such as the size of a bolt, may appear trivial and inexpensive. Consideration must however be given to the wider issues. For example, if the new bolt is of a non standard size, a price premium may be incurred or existing assembly hardware may have to be modified to accept the new bolt. In addition to these product related issues, an operating procedure will be needed to administer and control the change activity. It is therefore conceivable that a £1 engineering change can easily cost £1000 to implement.

The decision to use automated assembly techniques will cause a major rethink in the design policy adopted; not only must the design fulfil the functional requirements of the design brief, it must also be suitable for the assembly hardware selected. A study[20] of ten products found that nearly 60% of all parts required a design change to

facilitate automatic assembly.

A similar study[21], focusing on the manufacturing process, trialed the automatic assembly of a product consisting of 150 piece parts. After six months effort only 40 parts, of which 25 where socket screws, could be readily automatically assembled. A total of eight grippers and three robots were required. It is therefore clear that the Engineering Design process has a clear commitment to ensuring that the requirements of "downstream" activities are dutifully considered.

2.2 DEFINITION

Asimov[22] captures the essence of engineering design as being;

"...a purposeful activity directed towards the goal of fulfilling human needs, particularly those that can be met by technological factors of our culture."

The emphasis derived from the words purposeful, fulfilling.. human and technological, allows the distinction between engineering design and other tasks using the word design to be drawn, for example artistic design. Whilst a sculpture may use engineering techniques, and the results may be satisfying a human need, the final results is not specifically met and bound by technological factors.

To help understand the many different engineering design applications, the author considered WHAT are the fundamental operating procedures, WHERE are they applied and WHO is involved. The result adopts established decision

making theory as the fundamental operating procedure. Three main levels of operations are found, involving three different operators. The role of different operators has been developed from a working experience and clearly illustrates a hierarchy of the different interpretation and contribution found in a single design environment.

The result characterises Engineering Design as a decision making process, operating in three possible environments at three different levels.

2.2.1 DECISION MAKING

Engineering Design transforms the description of a requirement into a description of an object to satisfy that requirement. Studies of the transformation process are concerned with the process of mapping from the Functional to the Attribute Space[23] and the subsequent embodiment in formal logic[24]. This process moves towards the solution not in one step, but a series of iterations, each one selecting and then refining on previous actions[25] until a solution with the most desirable characteristics is achieved.

Design is a decision making activity[26] [27].

This has been reinforced by studies of the designer at work[28].

The formal study of decision making classifies decisions according to the completeness and certainty of the facts required to take that decision. Five categories are typically described [29].

If all the facts are known and are certain to occur, a

decision under certainty can be taken. When the level of certainty can only be calculated with a probability, a risk must be taken. For example, when justifying capital investment on plant equipment, the probability of in service failure must be balanced against initial purchase price. If the probability cannot be calculated, the risk turns to uncertainty. For example, if the reliability figures were calculated in a specific operating environment, it would be uncertain how the product would operate in a different environment. This situation is further complicated if only partial information is available on which to base the decision.

These categories assume the independence of the decision maker from the decision environment; they only adjudicate on facts presented. Consider a complex environment where the decision environment actually changes as the decisions are taken. A state of conflict occurs; the decision maker becomes involved with a rational opponent.

The path followed as decisions are taken is often drawn as a tree structure, Figure 4. The node represents the point in time when a decision must be taken. The lines leading to further nodes represent the alternatives available at that time. Taking a decision involves selecting the most appropriate route forward. This selection must consider both the merits of the alternatives ahead, and their compatibility with decisions already taken. The decision making process is finished when no further alternatives can be found. The operator must have the ability to backtrack to previous nodes to check the validity of decisions taken. This is important if a conclusion is reached but it is felt that a satisfactory result has not been achieved. The re-evaluation process may then select an other alternative which may lead to a satisfactory finish.

The overall process is time dependent. It is not possible to say that range of alternatives is a closed set, never to change or be bettered. For example, before the invention of aeroplanes, our fore fathers knew of no other means of crossing a large expanse of water except in a boat. Now we can select from a range of water level carriers such as boats and hovercrafts and airborne carriers such as planes and helicopters. The criteria on which selection are based has also changed. Our fore fathers had no need to cross a rough sea in order to board an oil rig.

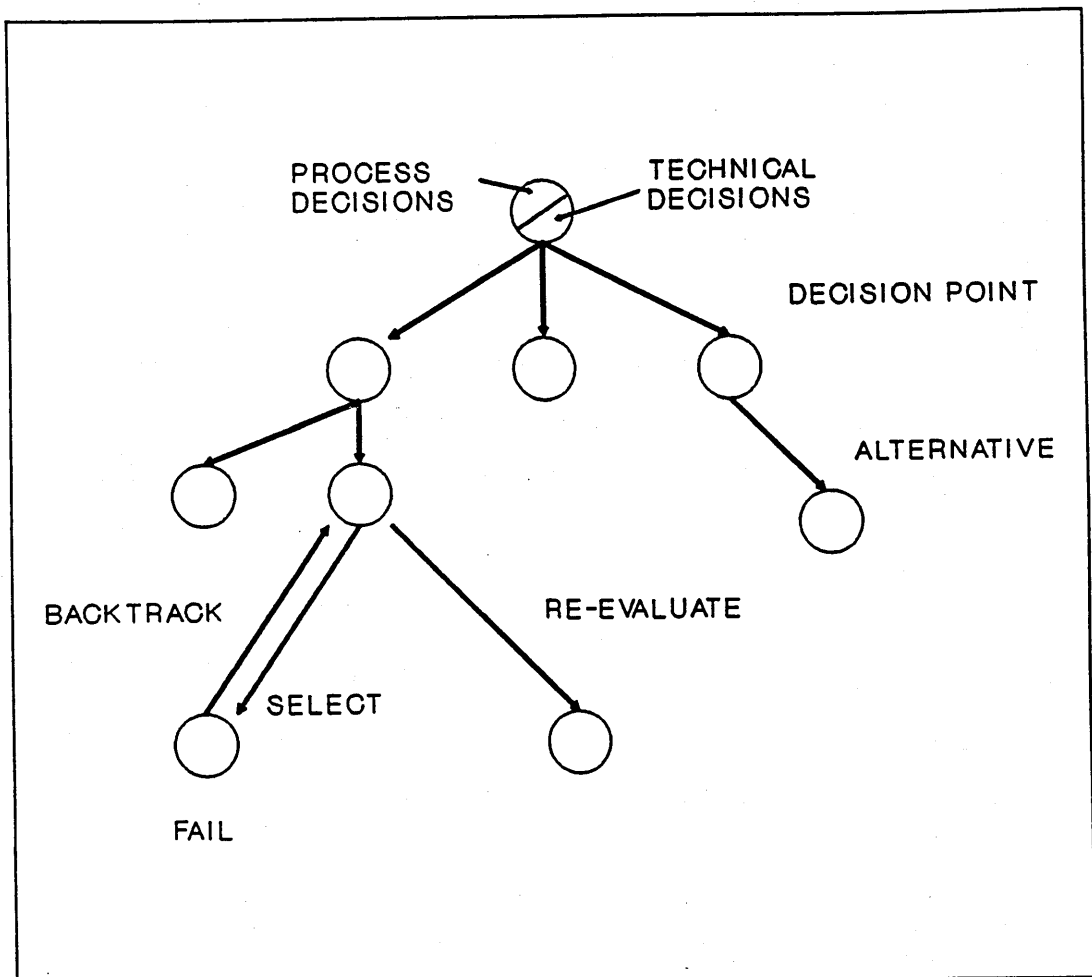


Figure 4 Decision making tree

Using this structure, it has been proposed that engineering design progresses and is controlled by two main elements[30]: Process and Technical. Technical decisions are used to select the most technically acceptable route. Their inputs span a broad range including principles of science and engineering, design limitations, risk of success and resources available. Process decisions are a level above this. They plan and control the technical process. Such decisions may decide when to analyse and with what techniques.

2.2.2 ENVIRONMENT

Having established the basic mechanism of design, decision making, the next stage considers the different environments that it may occur in. Three principal classes have been identified [31].

Configuration represents a situation where the problem is accurately defined and a well established technique is in place to develop solutions. It represents an intellectually manageable task which is far from trivial. Many industries operate within this mode; the distributor of, for example, industrial pumps, will match a motor to a pump head to meet individual customer needs. Each system needs designing, and each one may be different. The engineer can select standard components and generate numerous alternatives. The problem is well defined, and the solution space, the components and techniques required, are also exactly defined; technical skill is paramount to ensure correct specification.

In defining the second environment, consider the pump example again. Faced with an enquiry to pump a noxious, non standard fluid, the supplier would have to resort to a development programme before offering a service with

confidence. During this period the system would have to be reassessed to account for the new fluid. This process is not aimed at redesigning, more the adaption, the evolution, of the product to meet its new surroundings.

If this process of evolution proved inconclusive and the standard pump could not be adapted, the customer may have to resort to a new design phase, from which a new innovative product would emerge.

2.2.3 INTERPRETATION

To understand who is involved in an Engineer Design process, the author spent a significant period of research time actively involved in an engineering design process. Formalising this experience presents the opportunity to understand the range of skills required and the individual operators interpretation of what engineering design is.

The result is illustrated as a three tier hierarchy, Figure 5. The hierarchy does not reflect a time dependant process where one activity cannot start until the previous has finished. It is more a frozen picture of what is happening continually throughout the course of a design project. The hierarchy was formed by classifying the range of activities found in the observed process according to the data handled. The top level contains those tasks required to accurately define the exact design problem. The middle level then subdivides the problem into the individual functional requirements each requiring an engineering solution. The third level generates detailed engineering descriptions to satisfy those requirements.

The perception of what engineering design is, then reflects each operator's involvement with formulating the engineering solutions to the problems posed.

An Engineering Design activity commences with the need to solve a perceived problem with engineering principles. The top level of the hierarchy reflects the tasks required to accurately translate the perceived need into a clear and concise definition of what the finished product must do to satisfy the need; the problem to be solved. The success of the design process will depend on how well the finished design conforms to this original statement.

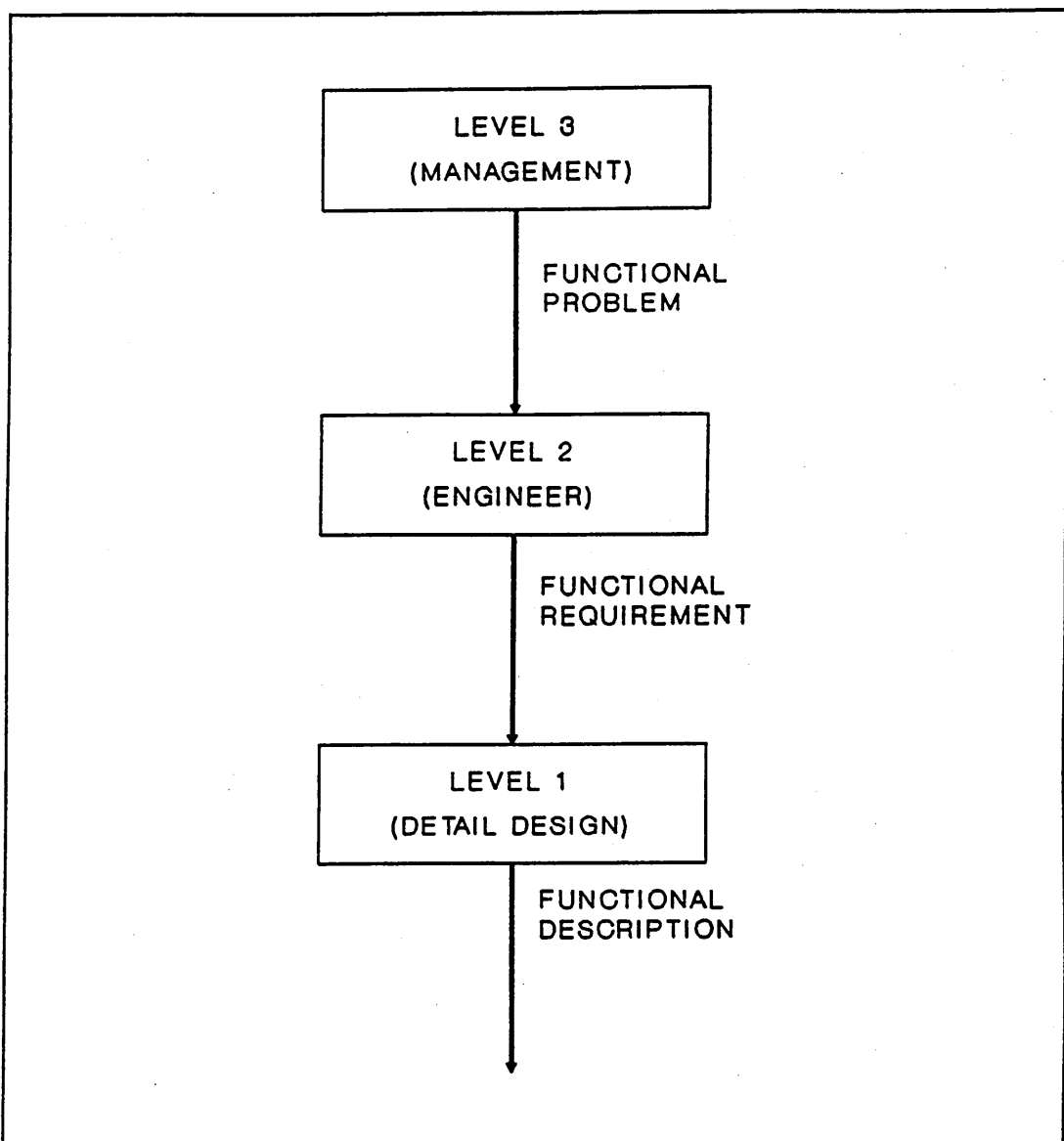


Figure 5 Design hierarchy

For example a functional problem of an inkjet printer may include such details as the speed of printing and the substrate to be printed on. The perception of what engineering design is at this level is very broad. The operator is concerned with developing the intent of the product and the performance envelop in which it must operate. A balance must be found between the commercial requirements for the design and the possible engineering principles required. For example, the decision to enter a product into a mass market must be supported with the necessary capital investment for the appropriate manufacturing techniques. An assessment must be made of the company's capacity and competence to support the complete life cycle of the product. Design forms but one of several important activities needed to realise a successful solution.

The middle layer must take the statements of intent and develop the functional requirements of the product necessary to satisfy them. For example, the specification of a high printing speed and a porous substrate could dictate the need for a fast drying ink. The chemicals used in such inks are typically corrosive, so limiting the range of materials and manufacturing processes available to the designer and the manufacturing department. The operator must begin to focus specific engineering knowledge at solving the design problem. The view adopted must go beyond the local problem domain to include the world view. This must include how the product will be distributed, installed, used, serviced and eventually decommissioned. Only with this clear understanding of the cause and effects of proposed solution can an effective design be realised.

The lowest level is responsible for translating the functional requirements into a concise set of detailed engineering descriptions from which the finished product

can be reproduced. Typically drawings, the package must contain all the information needed to meet the needs of all the subsequent activities such as manufacture and service. At this level, engineering design is perceived to be a very precise engineering task. A vast amount of engineering knowledge is condensed into each drawing necessary to describe the solution.

Attempts to identify each level with accepted job title must be specific to each environment. In the author's experience, the top level is a management function, the middle the responsibility of engineers and the third the design draughtsman. However, real world problems demand flexibility and a certain amount of vertical integration. For example a project leader must support engineering tasks, whilst an engineer may be required to produce detail drawings.

2.3 DESIGN PROCESS

Design Science is concerned with the study of the complete life cycle of designing a product. Included in this is consideration of proceeding activities required to document, manufacture, market and maintain the product. All are directly effected by decisions taken during the design process.

Compared to the natural sciences, the study of the activity of designing is very young, having evolved over the last 150 years[32]. The growth has centred around the need to solve specific problems in specific industries. This adhoc approach has resulted in fragmented and localised theories. Three main directions are found.

From a strategy point of view, designing is an information flow task. A requirement is translated from an intent into

an engineering description from which a product can be realised. The structure and method used to guide this information flow process is referred to as the Design Process.

As a primary means to achieve a solution, the Design Process cannot fully support the design team in their task. Different industries have specific technical requirements that must be met to ensure a consistent technical solution is described; their Technical System

The Working Means is responsible for developing practical tools from these research initiatives.

2.3.1 TECHNICAL SYSTEM

Technical System research is directed at understanding the exacting requirements to produce technically consistent designs. This is achieved using scientific principles to gain a complete understanding of the purpose, organisation and modes of operations. This will lead to a unified way of classifying and describing solutions. These aspects should be formulated into general laws, similar to those found in the natural sciences [33].

This work is primarily interested in success criteria specific to individual companies and product types. Typical work considers the link between the designers intention and the subsequent use of dedicated automated assembly techniques [34]. Progressing beyond such "Good/Bad" design guide[35], research is now concerned with establishing technical links between different industries and apparently different product types [36].

2.3.2 DESIGN PROCESS

A) MODEL

At present there is no single agreed model of the design process. A wide range of researchers agree the principal phases required

[37][38][39][40][41][42][43].

Their differences lie in the detail of implementation. This is strongly influenced by their own research stimulus and experiences. Figure 6 illustrates an amalgamation of these key principles into a recognisable Design Process. It shows four key stages found in a design activity; define the problem, conceptual, embodiment and detail design. The operation and importance of each stage is explained. This taxonomy is then used to classify existing Design Process research from which the potential for new work will emerge.

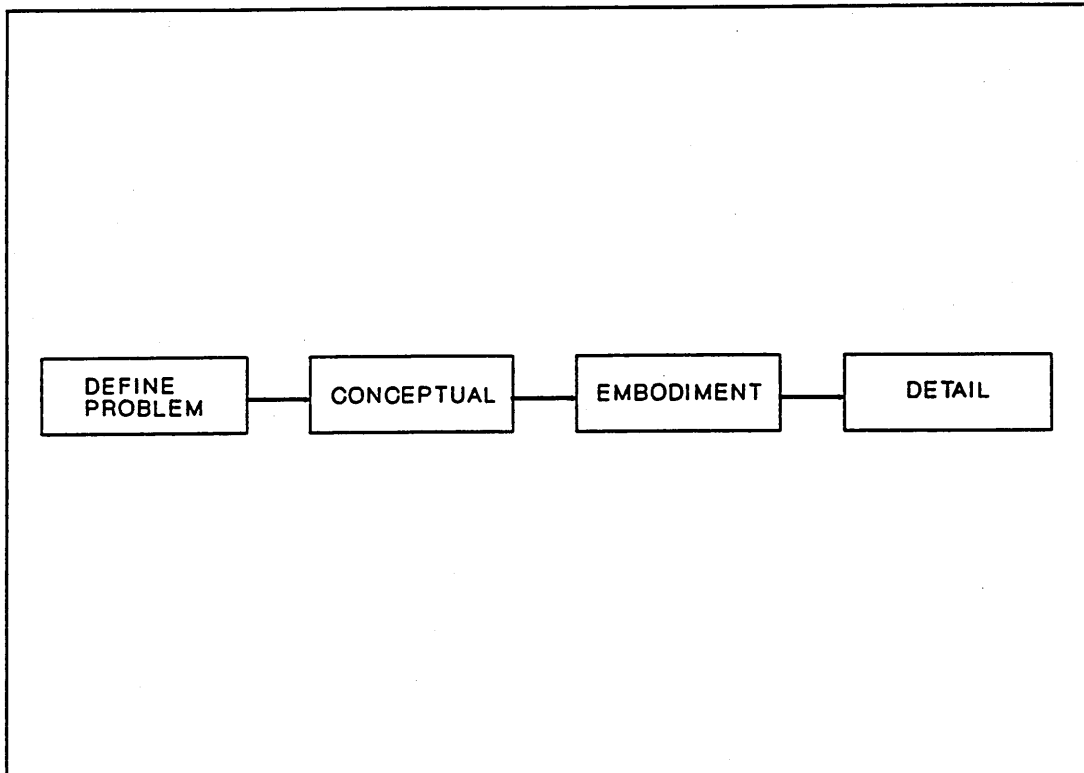


Figure 6 Design process

DEFINE PROBLEM

Before a line is drawn or a prototype made, the problem posed must be understood, defined and accurately documented. This document must convey the exacting requirements of the finished design. It must detail how it should work, where it should work, and often where it will not work; its performance envelope. It must go beyond functional features and questions the type of society in which the product will see service. The economic climate, the geographical climate and the operator's beliefs and philosophies.

For example, a man with a diesel tractor may plough a field quicker than a man and a horse, but used in areas remote from fuel or trained service technicians, its gain is soon marginalised. This is especially so if the farmer could not afford the initial purchase price. Local geography is important. The tendency for nylon to absorb water makes it unsuitable for use in a very humid environment. The beliefs of the intended market place must be considered. The Chinese associate death and mourning with the colours white and blue; an uncomfortable combination for domestic appliances.

This stage produces the product specification against which its development will be monitored and its successes in the market place assured.

CONCEPTUAL DESIGN

Engineered solutions must now be found to satisfy the set objectives. The conceptual design stage must search the range of possible solutions, evaluating and comparing different ideas. Calculations must check the feasibility of

central concepts. Decisions must be made on whether to adopt and develop new ideas or upgrade existing technology. Minimal attention is given to the form or detail of each idea; the goal is to generate many different routes to achieve the same goal. This list is reduced to the most suitable options by critical analysis against the initial objectives. This must include evaluating the capacity and competence of the entire organisation to develop, manufacture and then support the selected concepts.

EMBODIMENT DESIGN

This stage is used to layout the different concepts as a whole. The characteristics of the design begin to emerge. Checks are made to ensure that all the concepts selected are compatible. Work must now consider how the different ideas will interact and how they should be linked.

Attention must be paid to the mechanism and circuits required. Questions of ease of manufacture, long term reliability, commercial availability must now be answered. The design begins to obtain the form and dimension ignored during the conceptual stage. Major differences may require a change of concepts. Minor differences can be resolved during the detail design stage. The system is established and it's operation checked.

DETAIL DESIGN

Detail design must now take this layout and produce exact and precise technical descriptions of all the components required to make the design work. In doing this, the designer begins to influence a wide range of seemingly unrelated situations. The shape designed may be unappealing to the customer. Materials and tolerances required may be beyond the manufacturing process available. New processes may not be commercially suitable to the business

environment. His actions must be directed and controlled so as to minimise the effect of such conflict

The result is a package of drawings that describe how each individual component should be made and fitted together and a list of all the material required to build the product, the Bill Of Material.

B) CLASSIFICATION OF RESEARCH

Based on this model, four main themes can be found in contemporary design research;

- * GENERATE ALTERNATIVES
- * SELECTING SOLUTIONS
- * ENSURING CONSISTENT TECHNICAL DESIGN
- * CONTROL OF THE PROCESS

GENERATING ALTERNATIVES

This process of laying out a design is used to test how different design concepts will work together. This process must be supported with as many different design alternatives as possible. To produce successful results, a designer must be creative and innovative [40]. An innovative designer may take an existing product or process and adapt it to yield new gain. Svensson [41] and Asimow [22] present classic texts promoting creativity. Their work suggests that formal, structured methods must be found and taught to help designers explore their vast personal database of experience.

Figure 7 [41] explores this notion. Attitude and knowledge are listed as the prime assets required to organise an effective memory store. Once established, methods must be found to effectively search it for solutions to problems

posed. Declaring a problem or attempting a solution before all the facts are known is considered to reduce the area of operation; vital clues may be missed or the effects and not the cause of the problem may be found. Methods are then declared to help promote an effective search of the database and problem domain.

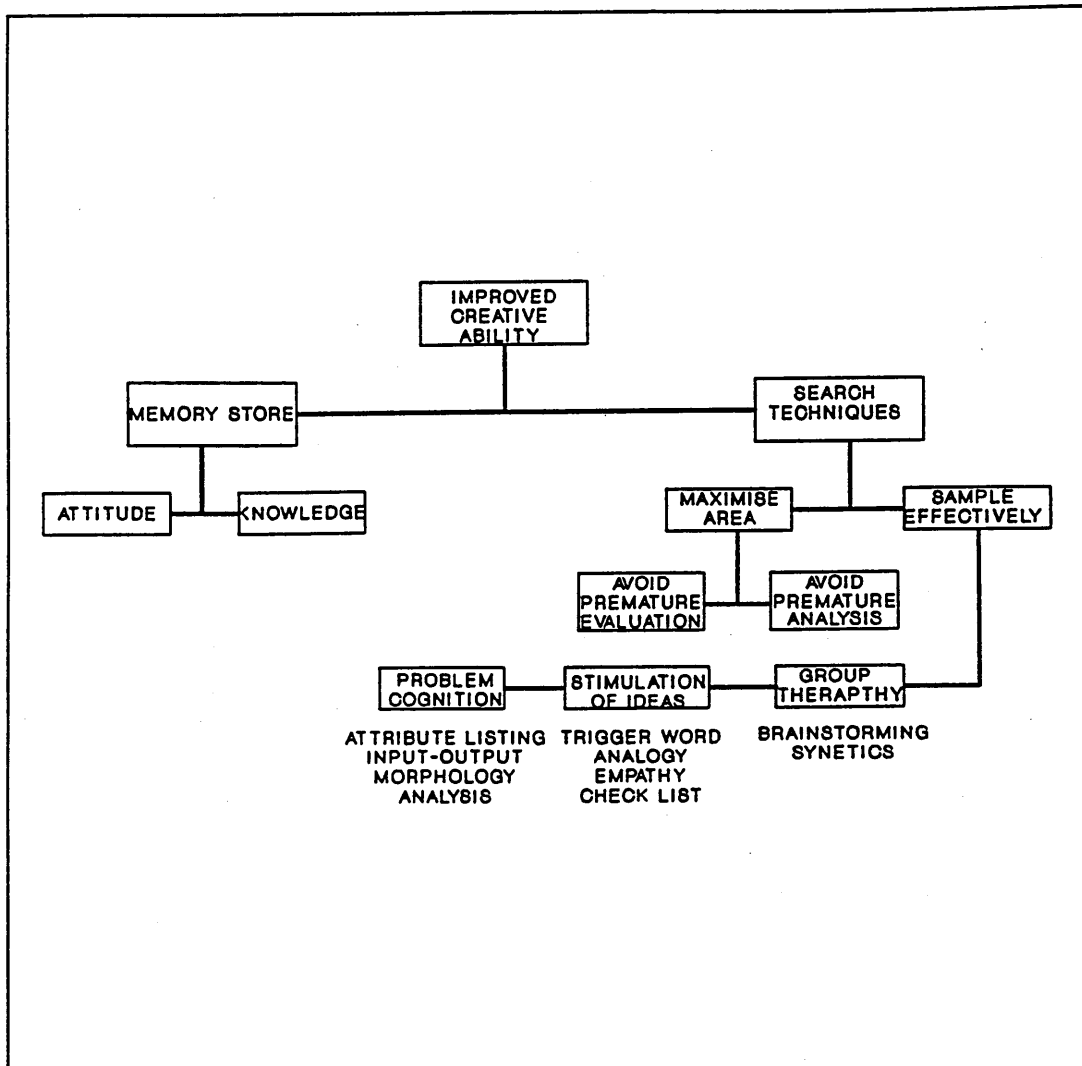


Figure 7 Classification of creative thinking

SELECTING SOLUTIONS

The final design must be selected from the range of concepts generated. The very fact that alternatives exist indicates that different concepts concentrate on different

aspects of the design problem. An acceptance band for each feature must be established against which the different ideas can be compared. The resulting design should then inherit the best features of each alternative.

Figure 8 [39] illustrates such an approach. The different options are laid out in a matrix. The designer can see what alternatives exist and how they work. This approach must be supported with a design process that breaks the design into single, quantifiable sections.

Applicator Strip	A ₁ stationary	A ₂ translation	A ₃ oscillation	A ₄ rotation	A ₅ rot. + transl.	A ₆ rot. + oscill.	A ₇ oscill. + transl.
B ₁ stationary							
B ₂ translation							
B ₃ oscillation							
B ₄ rotation							
B ₅ rot. + transl.							
B ₆ rot. + oscill.							
B ₇ oscill. + transl.							

Figure 8 Selecting alternative designs

ENSURING CONSISTENT TECHNICAL DESIGN

The demands of specific industries have led to an emphasis being placed upon the formal support of localised requirements; for example the demands of manufacturing processes. Such approaches have tended to produce handbooks of good design practises. Matousek [43] concentrates on the stages of establishing the working principles of the design, then the materials and manufacturing processes required, followed by the stages of form design. This approach makes the designer consider the material and manufacturing processes before assigning the final form of the design. A similar approach addresses the problems of designing for automated assembly [44].

CONTROL

Advances in general control theory have proved invaluable in the design of quality products. Modern servo motors systems, such as gun turrets or satellite tracking station, would simply not work without the application of controllers. Numerous complex procedures required to keep a helicopter in flight can now be handled by computer control, leaving the pilot free to concentrate on other tasks[45][46]. Whilst the results of design embody advanced control mechanisms, the process used to design them has been largely neglected.

The design process needs control to ensure that the right solutions are designed as quickly, and as effectively as possible. Adopting principles of closed loop control offers the potential of having a process that is tolerant to variations in operation and environment, can compensate for unknown external disturbances, force the outputs to follow prescribe inputs and the ability to modify the systems dynamics.

Ellinger [42] describes a closed loop system with two stages of amplifications corresponding to different phases in the design process. Asimow [22] describes a critical feedback apparatus to measure advantage and detect shortcomings. He says that this only comes into operation when a solution is judged inadequate. A more advanced theory describes the design as a dynamic process that is continuously generating information until sufficient information is available to proceed, a Learning System[47]. Two different environments are found. A Passive Environment offers information only on demand. An Active Environment reacts to this information exchange process becoming directly involved in the search for solutions. No recorded work known to the author takes seriously the potential of process control theory as a design management strategy.

2.3.3 WORKING MEANS

The maturing of computing resources has provided a significant stimulus to the development of tools to help the designer. Significant numbers of researchers are striving to support both the graphical tasks of design, drawing the solution, and the numerous textural activities also required - support of the decision making processes.

A) DRAWING

A concise history of Computer Aided Design (CAD) systems [48] reveals that much of their development is due to the advances in applied mathematics, rather than the demands of the engineering design community.

The mathematical techniques used to store and display the drawings have progressed in stages, partly in line with the availability of computing resources. The first system

available in the Sixties, could only handle simple two dimensional geometry - points, straight lines and simple curves.

The next stage, a decade later, extended the model to include the third "Z" dimension. Early systems stored information as points in space. The drawings are displayed as "wire frame" models, linking the space points with lines. To improve presentation the hidden lines and faces could be removed; problems with ambiguous views resulted.

During this time, the development of 2-D and wire frame modellers progressed in parallel. Their influence extended as methods were found to program computer controlled machine tools direct from the data held in the CAD database[49]. The mechanical and thermal behaviour of designs can be analysed using Finite Element Analysis [50] without having to resort to costly prototype and test programmes.

The ambiguity of wire frame modellers was removed with the development of Solid Modellers; they hold a geometrically unique model of each feature designed. Such systems would allow a designer to interrogate a model, checking for interference between components, their weight, volume and centres of gravity. Some modellers will link kinematic relationships into the model, allowing the designer the opportunity to simulate actual working operations. Current research themes include the method of storing and extracting designed features in the database [51]. These promise to revolutionise such tasks as production process planning [52].

B) TEXTURAL

Drawings exist to communicate design ideas. A significant amount of reasoning with non numerical data is required to generate the designs. Many of these textural tasks have been tackled by researchers using Artificial Intelligence techniques. The key to these systems is their ability to encapsulate and then manipulate textural information and apply a proportion of reasoning and intelligence [53] [54][55].

A common method of applying Artificial Intelligence techniques is through Expert Systems [56]. Numerous examples have been applied in industry[57][58], ranging from knowledge stores/teacher[59] to systems able to configure known components into solutions [60][61].

In general, the different techniques centre around a hierarchy of design "specialists", each one solving a particular set of problems and then passing the information down to the next "specialist". The top level modules control global considerations, whilst lower levels handle specific design tasks. This top down approach progresses from the general to the specific embodying the best working practices of systems design. In handling failure, the general approach is to reassess the value of the decisions made by the previous specialist. A classical example adopting this approach[62] demonstrates the principles when designing a table. The system presents a top level design specialist, "SmallTableDesigner", and two sub level specialist, "TopDesigner" and "SupportDesigner". Working with constraints of material and dimensions the system can arrive at a suitable design matching the shape of the top to the support design.

2.4 RESEARCH ENVIRONMENT

The author's work forms part of an ongoing research programme at The CIM Institute. His work has moved the programme into a new collaborator.

The first collaborator designed, manufactured and distributed specialised industrial pumps into a world market. The market place is mid volume. To maintain market share, the emphasis is on the timely introduction of new, cost effective products. To reduce costs and lead time, considerable investment was made in automated assembly techniques. These factors made it imperative that for all new products to meet their cost, quality and lead time target, they must be designed for assembly from the outset. No time was available for such production engineering once development was finished.

Detailed research found contemporary techniques lacking. Most originated from a single source, all concentrating on simple, small, mass produced designs. These techniques could not handle the range of components found; such as screws, gaskets and large castings. They could not be applied as the design progressed; they all relied on a period of post design audit during which the design is scored against set criteria.

The resulting research[63] [64] divided the problem between two aspects of the Technical System; ensuring that a sound design methodology was used and that the results complied with the requirements of the automated assembly facility. The design methodology concentrates on ensuring that a rational set of standard components are used, only the minimum number of additional components are specified and all parts needing insertion meet set criteria. The requirements of the assembly hardware is mapped against the

effect designed features have on the success of layout, presentation and gripping of components in the assembly cell.

The results are embodied in prototype computer based systems that work along side the designer, suggesting positive advice on how to improve the design. The work satisfies the Technical System. A lack of application/control theory hinders its further development.

The author's goal is to develop this strategy, and to broaden the research environment, a second collaborator to the programme was introduced. This company, located in Cambridge, conformed to the specification defined in 1.4.1.

The Company designs, manufactures and services commercial ink jet printers. The equipment is primarily used for the coding and marking of domestic consumable goods. A UK owned Public Limited Company, it distributes into a world market from two manufacturing sites. One in the UK, corporate headquarters and the base for the research, and one in North America. See Appendix A.

The products are a complex mix of electric, electronic and mechanical engineering. Manufactured in mid volumes, the operation is restricted to assembly only; all piece parts are bought in. Manual labour is the only effective means of assembling the present product range. Considerable reductions in manufacturing lead time and the value of work in progress has been achieved by a combination of Just In Time and Material Requirements Planning.

The market place now demands the rapid introduction of new features, combined with a reduction in lead times and cost with increased quality.

The Company was formed just 11 years ago, and so has few ingrained traditional attitudes on how to design, introduce and manufacture new products. A concurrent approach is being developed to combine the manufacturing and development resources.

The Technical System is strongly biased towards the empirical features required to make a printer work. This experience has been built up over the years; the young, and open organisational structure ensures it is rapidly available to the design process.

A problem exists supplementing this Technical System with the requirements of the manufacturing process. The manual labour workforce can handle all of the small, complex components used. However, to improve production planning and material flow, so contributing to the reduction in manufacturing lead times, it was found necessary to reflect the cell layout of the shop floor in the product's design.

This aspect of the Technical System is manually implemented by the Manufacturing Engineering group.

There is no formal policy of control.

To contribute a solution to both environments, the author proposes a system that encompasses the whole design/manufacturing interface. Chapter three will explore this system. It will compare it's operation and goals against the more traditional Design or Manufacturing biased approaches tested in his environment.

CHAPTER THREE SYSTEM DEFINITION

A critical period exists during the life of every product when the designer's ideas must be tested against new criteria; namely the costs, timescales and probability of achieving quality results[65]. This tests the designer's ideal of achieving functionality against a manufacturing ideal to make it quickly, effectively and to the highest quality standards. This traditionally occurs as the designer's ideas are offered for manufacturing approval.

Methods have been produced to help this process. They often originate in, and concentrate on the detailed criteria of a specific industry. Two such sets of work are typical in their approach. Common to both is the desire to trap and sort any problems before incurring the costs associated with manufacturing. Problems in DESIGN have attracted attention from design biased research. Problems in MANUFACTURE have attracted the attention of manufacturing biased researchers.

The author will argue that what the different approaches gain in generality, they lose in detail content; and visa versa. The DESIGN work is too general to offer strategic help. The specialised application of traditional MANUFACTURING work is unsuitable to the working environment.

As the foundation of his proposed design/manufacture control strategy, he will foster an approach that considers the holistic system of design and manufacturing working mutually together towards a common goal. This removal of functional boundaries is perceived more suitable to this research environment.

This theme is receiving considerable attention with the development of Computer Integrated Manufacturing (CIM). One approach promotes the idea of organising a company around its business goals, not its functional departments. For example, the Product Definition Process would encompass all the people needed to fully define a new product; this would include design, marketing, manufacturing, purchasing. It is viewed as a more efficient means of organising personnel to meet the demands of a modern business and to ensure a more effective use of information technology solutions [66].

Chapter three investigates this system, establishing it as the most appropriate approach in the selected environment... Based on this, Chapter four will examine a control strategy.

3.1 DEFINITION

The three approaches, DESIGN, MANUFACTURE and INTEGRATED are all subsets of Design Science. Figure 9 shows the commonality of each approach against the principle goals of Design Science; promote creativity, technical consistency, effective selection of alternatives and control of the general environment.

Common to all three approaches is ensuring a consistent technical design is achieved and the environment is maintained under control.

	DESIGN	MANUFACTURING	INTEGRATED
CREATIVITY	✓	X	X
CONSISTENT TECHNICAL DESCRIPTION	✓	✓	✓
SELECTION OF ALTERNATIVES	✓	X	X
CONTROL OF ENVIRONMENT	✓	X	✓

Figure 9 System boundary

3.2 TECHNICAL CONSISTENT DESIGNS

Three of the most common limitations to achieving technical consistency have been selected; the selection of material, embodiment of cost and the limitation of selected manufacture processes, Figure 10.

	DESIGN	MANUFACTURE	INTEGRATED
MATERIAL	✓	✓	X
COST	✓	✓	X
MANUFACTURING PROCESS CONSTRAINT	✓	✓	✓

Figure 10 System boundary; technical design

The established Technical Systems in both research

environments adequately support the requirements of material and costing. For example, the formulation of common printing inks restricts the designer's choice to high quality grades of stainless steel and exotic plastics. These limitations are well and widely understood; again due to the size and operation of the Company. Costing profiles are strongly influenced by such limitations. A premium must be paid when buying and processing such exotic material. Because of the mid volumes, cost reduction exercises do not achieve a scale of volume on "penny" savings. Energies are directed at larger savings accrued from removing over engineered features and poor material/process selection; huge savings have recently been made by replacing metal components with lower cost plastic mouldings.

This has left the research programme to concentrate on supporting the restriction of the manufacturing processes used.

Figure 11 expands the manufacturing constraints to match the exact requirements of the collaborators. The three selected to argue the author's approach are the rationalisation and minimisation of parts and process layout.

	DESIGN	MANUFACTURE	INTEGRATED
MINIMISING PARTS	✓	✓	✓
RATIONALISING PARTS	✓	✓	✓
PROCESS LAYOUT	X	✓	✓

Figure 11 System boundary; manufacturing constraints

A) MINIMISING PARTS

DESIGN

Many design texts recognise the good practice of only designing the minimum number of parts

required[67][68][69]. It is clearly a waste of design, drawing, checking and administration resources to create superfluous components. The work is not a philosophy, but a recognition that excessive components represent waste. Each application must decide its own philosophy for implementing such a programme. For example, a directive to just reduce the number of components may well increase costs as fewer, more complex designs are produced.

MANUFACTURE

The investment required to establish robotic assembly facilities has focused attention on the differences between what a designer generates and that which a robot can efficiently handle. Studies have linked successes to reducing the number, and complexity, of components presented to the assembly cell [70][71][72].

A classical example to achieve this[73] has found great success in securing successful implementations and reducing overall piece part costs. Using this method, typical savings of 30% can be expected in the number of piece parts and assembly time[74]. Numerous other methods and examples all quote equally impressive savings [75][76][77][78].

The common method of application of these approaches requires the designer to compare and mark the design

against set criteria. A matrix of numerical information can then be manipulated to yield design improvements.

The Design For Assembly Handbook [73] was originally based on research concerned with the coding and classification of small parts for automatic feeding and orientation[79], and has found particular favour in the high volume sector. The general method of operation requires the designer to collect as much information about the design as possible. The book classes useful items as engineering drawings, three dimensional views, models, prototypes or existing versions of the product. The next step requires the assembly to be taken apart ("or image how this might be done"), identifying each part as it is removed and assigning it a identification number. This data is then entered into a worksheet.

The designer then reassembles the product. As each part is placed in the assembly, notionally or physically, the designer must assign numerical attributes to each part relating to such criteria as ease of handling, handling time, ease of insertion, insertion time, operating time and cost. These are all derived from lengthy and complex tables linking geometric features to the each requirement. The final column asks the designer to assess the theoretical minimum number of parts required at that stage of the operation. The Handbook acknowledges that this is a particularly important stage in the analysis. It gives the designer three criteria for parts remaining separate;

- * Relative motion necessary between it and other parts in the assembly.
- * Parts must be made of a different material.
- * Reasons of assembly or service.

Analysis, and the following redesign, must then attempt to improve the design and reduce the estimated time and costing figures calculated earlier. This is best achieved by taking the opportunity of reducing the part count, so reducing the number of parts handled, and redesigning remaining parts so they are easier and quicker to handle and insert.

Applied as a post design audit, examining and marking a finished design, the considerations of assembly are being treated as external to the main demands of the design project. They do not form an integral part of the design brief.

It has been noted [80] that the approach described in the Handbook has several weakness when trying to apply it's principles in such an integrated manner. The sheer complexity of the analysis method, assigning component codes, is claimed to be difficult to learn and use. The coding method only indicates a potential deficiency in the design, offering the designer no direct assistance on how to improve the design. The knowledge used to generate the coding tables is specific to a particular operating environment, and could not easily be modified to suit a new problem.

INTEGRATED

The first collaborator's decision to invest in automated assembly hardware was supported with the need to develop new Design For Assembly techniques that matched their commercial and technical demands. Time scales required that the analysis should work with the designer, from the earliest conceptual stage, offering positive advice as the design progresses. The methods must be able to handle all the mechanical components designed; these range from large castings to delicate gaskets.

This demanded a solution not just to pull manufacturing expertise into the design domain on demand, but one to INTEGRATE the two functions into a seamless whole. The goal was continuous support of the designer, from conceptual, through layout and into detail design.

The resulting minimising parts philosophy[81] uses similar criteria to the Design For Assembly Handbook to assess if parts can be minimised. The knowledge to do this however is coded into the general scheme of the Computer Aided Design system to help the designer recognise design deficiencies as they are designed. The computer tool is responsible for finding the potential to minimise parts, the decision to do so is left to the designer. Working this way, the requirement to minimise parts forms an integral part of the design specification, not an external assemblability issue.

B) RATIONALISING PARTS

Minimising parts reduces the total number of parts to be handled. Reducing the range, rationalising, to be handled is just as important. Each approach, Design, Manufacture and Integrated, share a general approach, differing only in application. The first stage is to generate a detailed list

of all preferred components and sizes.

DESIGN

Promote the list as a guide to good practice.

MANUFACTURE

The general approach described for minimising parts forces the designer to record every item used in an assembly. Deviation from the preferred list will be immediately apparent.

INTEGRATED

This method offers the designer an on-line list of all preferred components throughout the design process. The request to use a non standard item is prompted with a list of all the preferred sizes nearest the initial specified.

C) PROCESS LAYOUT

Robotic assembly demands that the design of the product matches the layout of the proposed cell. Selecting the most appropriate set of grippers for the product range is vital to keep cost down and promote minimum assembly times. This specialised work has only been addressed by the MANUFACTURE and INTEGRATED approaches.

MANUFACTURE

Efforts to rationalise and minimise the number of components required makes a major contribution to reducing the problems of selecting the range of grippers required to assembly a product. Typically one gripper can handle three components [70]. If this is unacceptable, multi purpose

grippers capable of handling more parts must be developed [82]. This approach is expensive and inflexible to design changes.

Gripper selection tends to be left until the end, once design is finished.

INTEGRATED

Again, the operating environment forces us to consider the implications of tooling during the earliest design stage, as regards both initial cost and tolerance to product change. A prototype system [83] has been developed to help select the lowest cost or the minimum number of grippers required. The analysis is driven using data extracted from the CAD system. This allows the designer to test the suitability of different grippers across an entire product range. The designer can then make timely design modifications to accept existing tooling.

In line with the efforts to rationalise and minimise parts, this INTEGRATED approach demands an INTEGRATED control strategy.

3.3 CONTROL

To date, the INTEGRATED approach has been applied without any control. The analysis modules have been used by the professional designer without recourse to an application philosophy. The next stage of the research must develop that application philosophy. In common with DESIGN based work, the approach adopted will concentrate on the importance of an structured approach to design. Process control theory will be explored to provide a control strategy, Figure 12.

Dealing with such a complex environment, one where conflict appears to emerge, a Systems Approach was felt appropriate. The problems should not be studied from just a Design or Manufacturing perspective, but from where the problems emerge; the interface between design and manufacture. This is when the designer must offer his work for manufacturing approval.

The adopted systems approach has two important features; a hierarchy with emergent properties and communication and control. A hierarchy was introduced when proposing a definition of design. It showed how different characteristics emerged at different levels.

The Communication and Control of these activities must now be the focus of attention. The challenge facing communications is to move beyond the technical problems of getting the message through to ensuring that the correct meaning is received and interpreted. To do this the author will develop a model of how different decisions arise and are taken at the Design/Manufacturing interface. First however, a general control strategy will be developed using established closed loop control theory.

	DESIGN	MANUFACTURE	INTEGRATED
STRUCTURED APPROACH	✓	X	✓
CONTROL THEORY	✓	X	✓

Figure 12 System boundary; control

CHAPTER FOUR SYSTEM MODEL

The case has been argued for a novel design support framework. This Integrated approach regards Design and Manufacture as a whole. This ensures that manufacturing process constraints are integrated into the design, not just accommodated.

An application philosophy must now be developed.

A theory of Systems promotes the ideas of Communications and Control as key requirements for successful operation in the complex real world. These will be the focus of the application philosophy. Two models will be used.

The characteristics of the Design Process will be established using process control theory. The results will enforce the need for an iterative mode of operation. This approach provides a mechanism to continually monitor forward progress and compensation for disturbances in the process and surrounding environments. It will also be shown that the process cannot exist in isolation.

A second model will investigate the actual Design/Manufacture interface at an information level. Using the hierarchy of design, it will explore the range of inputs required to take different design decisions. A spectrum of decision making will emerge, mapping to the hierarchy. It will be shown that problems of Functional Description can be answered as they arise. At the other extreme, more complex decisions relating to the Functional Problem demand a wider audience and so take more time to make.

4.1 PROCESS MODEL

The elements and operation of a common control strategy will be discussed. Applied as an ideal model, its impact on the design process will be considered. Account will then be made of the differences between the ideal case and the real world. The operation of key elements will be tested. From this the characteristics of the control strategy will be established.

This work is not directed at finding the transfer functions of a design process, more the assimilation of knowledge gained from one environment into a similar environment.

4.1.1 CLOSED LOOP

A process is established to do work. The inputs could be material or information, the outputs more material or information. For example, a chemical process may convert a range of raw materials into a single, new, material. Similarly, a statistical process may take raw numerical data and produce new data.

Methods must be established to ensure that the operation of the process is controlled; it achieves its goals quickly and efficiently. Closed loop control is a strategy that seeks to achieve this by using a feedback path to monitor the present position and a controller to amend the processes actions. Figure 13 illustrates the key elements of a closed loop control circuit[84][85][86][45].

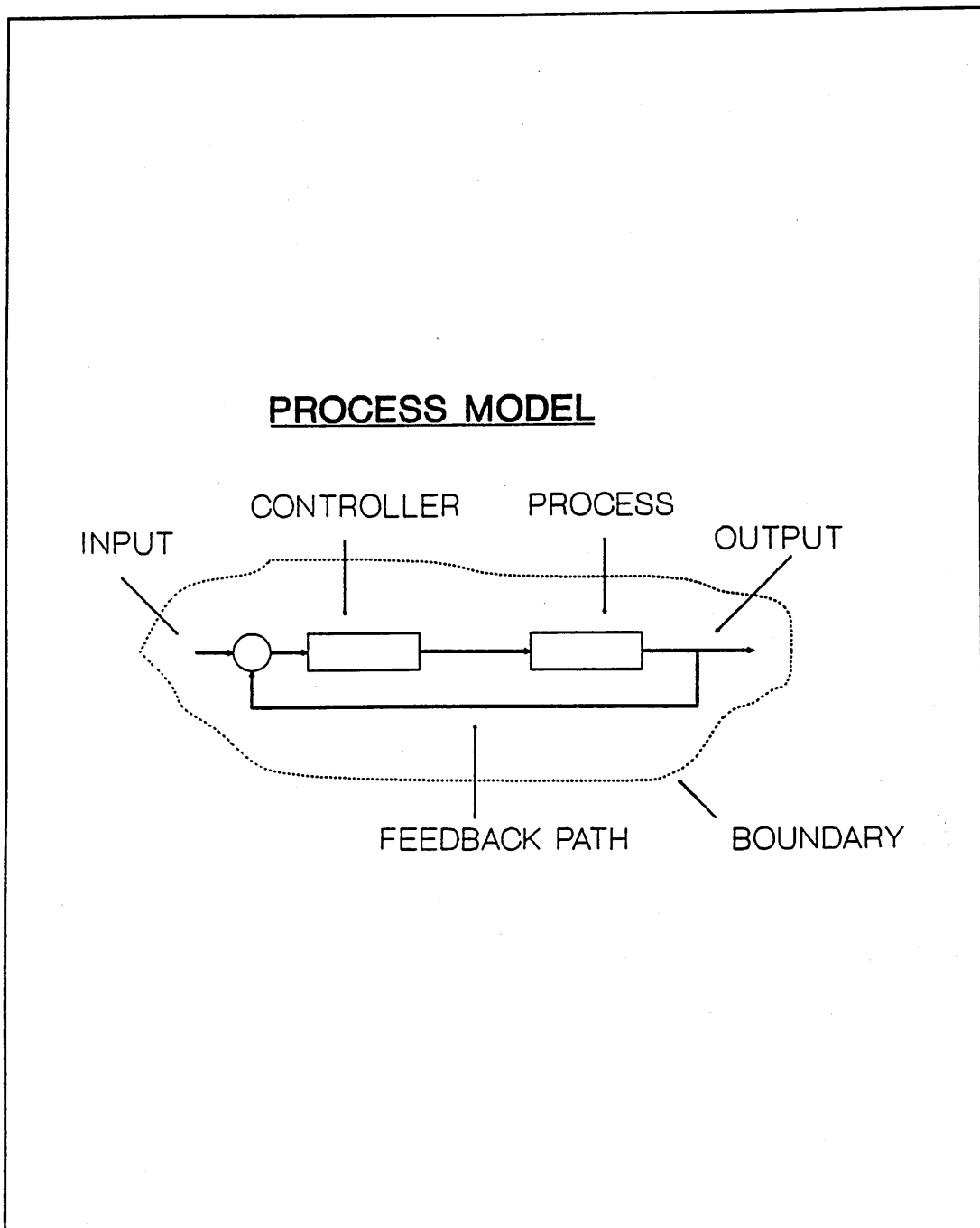


Figure 13 Closed loop process control

FEEDBACK

Closed loop control is established to directly monitor the actions of the process, so that it's next move can be calculated. To do this, the output is sampled and compared

to the original input. The difference is the extra work that must be done.

The continual monitoring ensures that any errors made are trapped and compensated for. The closed loop strategy is therefore less demanding on process resources. If the forward path does not have the exact characteristics, the combination of controller strategy and feedback can be made to compensate. Feedback can also help to compensate for external, unwanted disturbance signals.

CONTROLLER

The controller is the interface between the input signal and the process. Its characteristics dictate how the system responds. Three main controller strategies exist, each with different characteristics. A common strategy combines them into one controller.

A **PROPORTIONAL** controller supplies a signal that is a proportion of the input. It has no reference to the present position, only the magnitude of error. Using this method, a rapid response can be achieved, but the output will never reach the input - an offset always exists. An **INTEGRAL** controller can be used to eliminate this offset. It calculates the input by adding a proportion of the error to the last known position - iterative. It is inherently slow. A combination of the two produces a control that is quicker than just an integral element, but always reaches it's goal, unlike a proportional controller. If the gain, the value that multiplies the error, is too large the system will become unstable. To compensate for this a **DERIVATIVE** term can be added. The output represents the rate of change of the error. Initially large, output tails off as the output reaches it's goal.

4.1.2 CONCEPTUAL MODEL

A) OPERATION

A conceptual model of the design process is built up using the essential elements found in a closed loop process control system. Figure 14 illustrates this conceptual design model.

This conceptual model is only concerned with what happens inside the design process. Interactions or interference with other tasks are of no consequence. To enforce this the boundary of the model is drawn exclusively around the design domain. The inputs to the process are therefore restricted to only information directly concerned with the primary needs of the design. The output is a document that describes the solution, typically drawings. These form part of the inputs for proceeding activities such as manufacture. A feedback path is used to compare the output of the design process with the initial requirement.

The process is started with the input of a need. This is fed to the design process via the design manager. The design process generates a first attempt at a solution. This solution is immediately fed back and compared to the initial input. The difference between the two is now the input to the design process.

The design manager dictates the strategy used to reduce this difference. Using principles of proportional control, the design manager would only brief the design process with the problems to be solved. For example, asked to design a vehicle to move quickly across water, the initial solution may specify a single hull sail boat. The design analysis may decide that the whilst the boat approach is satisfactory, wind power would not be fast enough.

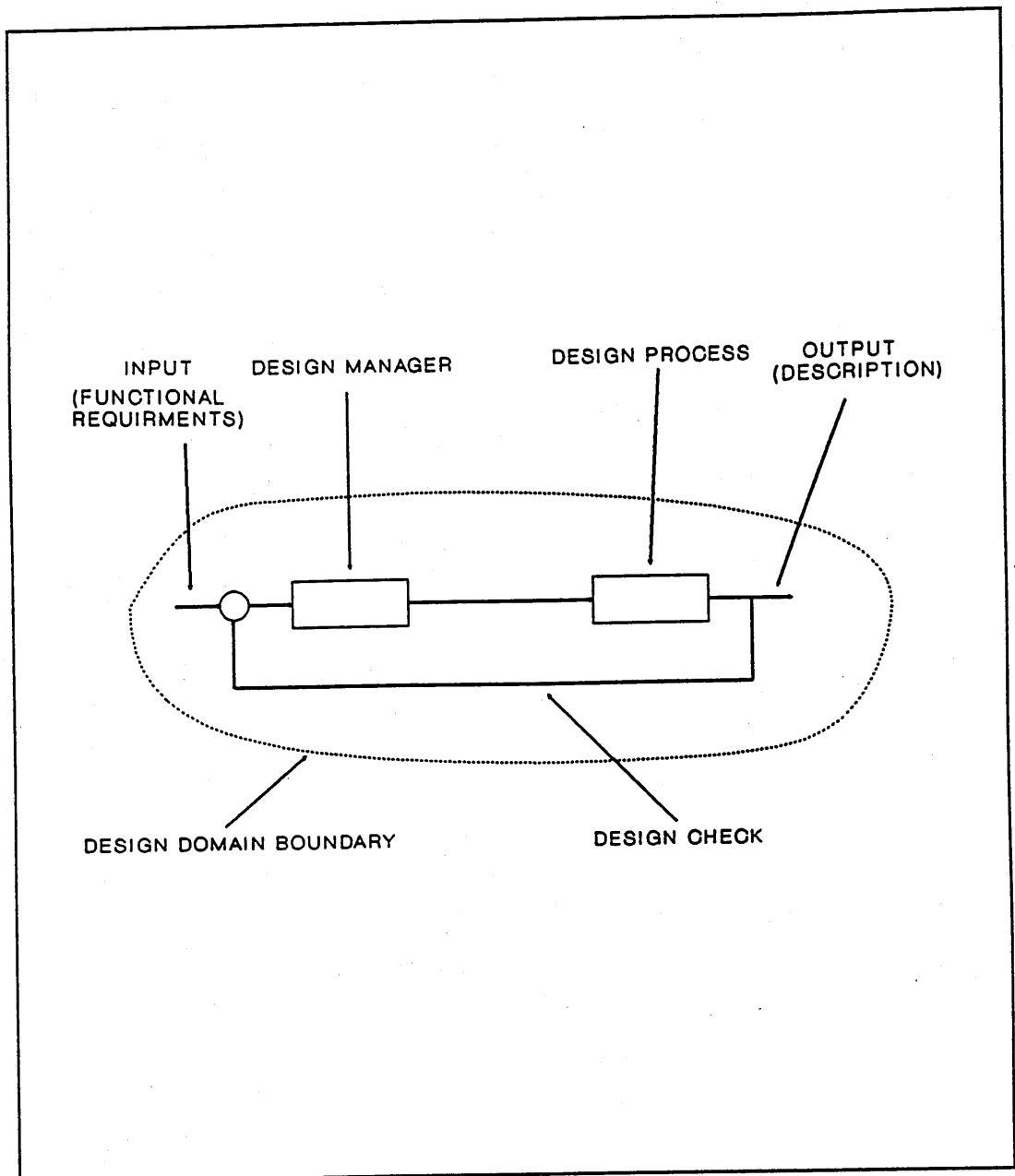


Figure 14 Conceptual design process model

The new brief would then only ask for a propulsion system that is faster than sails. No reference is made to the existing design, only the design deficiency to be solved.

The more sophisticated integral control strategy over comes

this problem by determining the new position as a small addition to the last position. This continual reference to the last position ensures that the next level of design problems are solved within the context of the design that generated them. Working this way, the problem of the lack of speed would be related not just to the use of sails, but the overall design. The next attempt at the design may replace hull/sail concept with say a Hovercraft concept.

The proportional/integral/derivative control strategy is adopted. Theoretically, with this strategy, the design process should always be able to achieve the goal; a set of technical descriptions should fully satisfy the input.

The real world experience shows that this is not always true. Design projects often fail or are compromised even if the results meet all the functional demands. A recurring theme is the failure to account for manufacturing process constraints; just because it can be drawn, it does not mean it can be made. To understand why, the components of the model must be reassessed.

B) EVALUATION

The need to apply control is a recognition of the lack of management. If unrealistic targets are set, insufficient or inadequate resources assigned or the process is terminated prematurely, no amount of formal control will ensure success. These factors and their supervision remain the property of the process manager. Time management can offer a competitive edge.

An integral term controller was selected because of it's zero offset characteristic - the output will always follow the input. This is achieved by ensuring that any actions are made with reference to the present position.

The combination of the input/output and operating boundary present the greatest opportunity to account for the model's failure. The conceptual model was isolated in the design domain; it could only receive functionally related inputs and its outputs were limited to drawings to satisfy those functions. Whilst success may have been achieved with drawings, failure was found once they were transferred to the next function - "it cannot be made".

In transferring the drawings to a new domain, say manufacturing, for approval, they lose the context in which they were generated; the designer's brief asked for it to work, not for something that could be made. This illustrates the mismatch of goals between the isolated design requirement for a product that works and mounting commercial pressure for a product that works and can be efficiently manufactured.

Implied expectations in the output begins to emerge once they are removed from the original domain and then subject to such analysis. This criticism is out of context with the original brief. These expectations must therefore be regarded as a prime reason for failure; if the designer did not know of assembly constraints, how could they be incorporated.

The designer must be made aware of these requirements as early as possible. Again, from control theory, two methods exist for feeding the requirements into the design process; as a disturbance or part of the original brief.

Maintaining the boundary tight around the design domain, these additional constraints could be fed in as a disturbance - noise. Noise is an unwanted signal that cannot be removed, but must be compensated for. For example, we cannot prevent the roads from getting wet when

it rains, so we learn to compensate for the effect it has when driving. A closed loop systems can compensate for disturbances, but it is considered to be an unwanted, undesirable effect. This is not considered to be a productive means of handling the requirements of a manufacturing function in the context of this research.

The second approach proposes that the additional constraints are made part of the original design brief. The boundary is redefined including all the affected parties, with their expectations being stated at the very start. This recognises that in a modern business no one function or requirement is more important than another. Each makes a vital contribution to the overall success. This integration reflects the needs of a Product Definition Process linking together all the resources required to fully define the product. It is in line with the overall approach adopted by the author.

4.1.3 CONCLUSION

This approach demonstrates that design cannot exist in isolation. To generate complete designs, the inputs and operating boundary must reflect the broad range expectations demanded of its outputs. To strive towards total satisfaction of these requirements, principles of integral control should be applied. Problems should be solved with respect to the system that generated them; solutions should be approached in a series of iterations. This closed loop operation must promote small, quick, iterations to trap and solve problems quickly.

4.2 COMMUNICATION MODEL

Process control theory has provided the top level control. A model is now proposed to study the information level of the proposed Integrated interface. It will concentrate on the decision making tasks at the design/manufacture interface. Using the hierarchy of design it will demonstrate that a range of decisions exist that require a varying response from the hierarchy. This is judged to effect the time required to take those different decisions.

4.2.1 CONFIGURATION

The first stage of modelling considered a simple flow of information at the Design/Manufacturing interface. Figure 15. The first task must be to receive the information required. Checks must ensure that the right information has been sent, and sufficient data is available on which to base decisions. It can then be tested against the new requirements, for example the rationalising of parts. A process of validation must check that no compromises have occurred before updating the source and progressing with the next item. The sheer complexity of checking the source and authorizing any changes presented a problem; who should be responsible.

The second model, Figure 16, pursues this further. The information is still received as before, with an initial check ensuring that everything asked for was received. Having successfully passed, two operations must now run concurrently.

The first, as before, tests the design against the new requirements, for example minimising or rationalising parts. A second operation must take the same information and map it against the Design Hierarchy developed earlier.

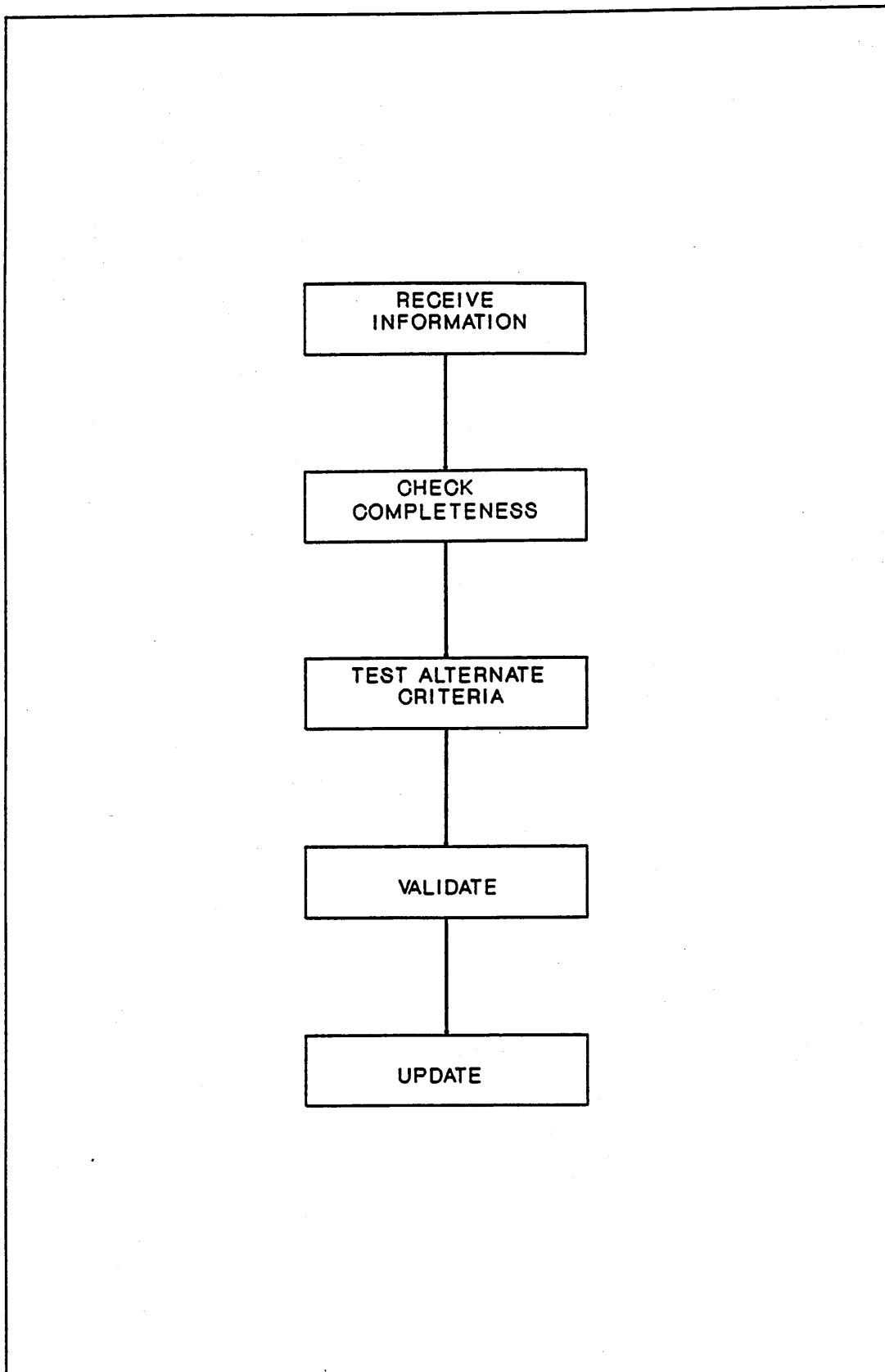


Figure 15 Design/manufacturing interface model (1)

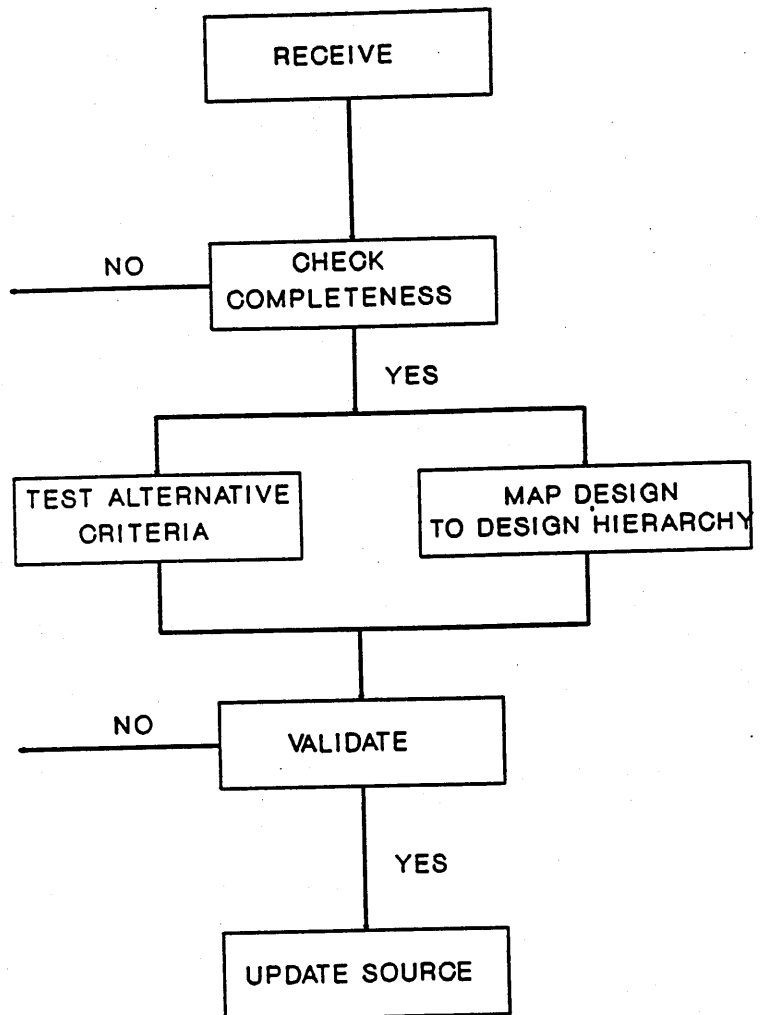


Figure 16 Design/manufacture interface model (2)

This will associate different aspects of the design with centres of responsibility, the Design Authorities.

The validation process can now cross reference the parts of the design that have been changed during the testing process to the appropriate Design Authority responsible for that part of the design. The decisions to accept the modifications can be targeted to the right resource.

This validation task is a key operation in the integrated interface. The timing of decisions is critical to ensure efficient use of resources.

Figure 17 details the information flow at the point of validation. By matching the type of decision to be taken with the phasing of the resources required, it becomes apparent that a range of decisions exist.

At one extreme are decisions that only effect the way the product is described, and so require an input from the third level. For example, when using the parts rationalisation module described earlier, the designer's own action of selecting a non standard component prompts a response. The test recommends an alternative and the designer can respond immediately.

At the other extreme however are the more complex decisions that can affect the actual function problem being solved and the subsequent functional requirements. Such decisions must be delayed until a consensus can be achieved across all levels of the design hierarchy. For example, if a proposed change will degrade the design's operating characteristics, the full range of expertise is required to evaluate if the change is necessary; the effect can perhaps be minimised, or the reduction in performance tolerated.

Such complex decisions, typically, take longer to be made.

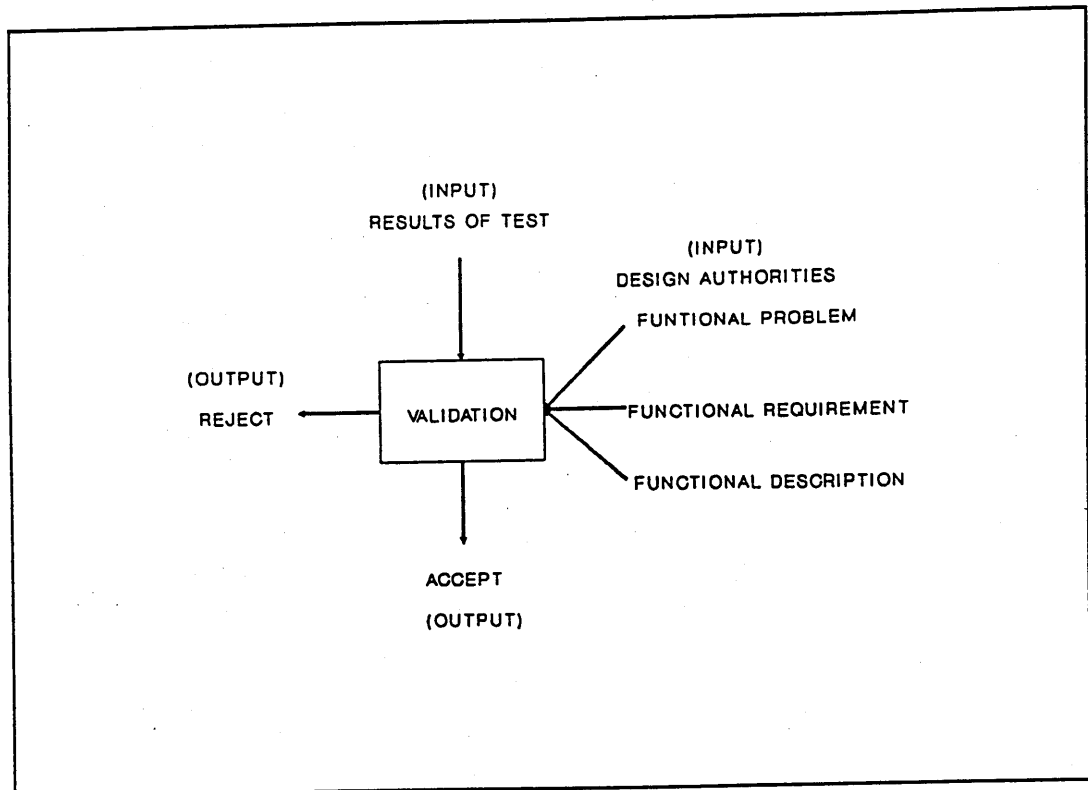


Figure 17 Decision validation

4.2.2 CONCLUSION

The model has investigated the communication mechanism present at the design/manufacturing interface. It has concentrated on the decision process required to verify design changes. By breaking the design down into a hierarchy of responsibility, it is suggested that decisions requiring only the input from the lowest level can be taken as they arise. More complex decisions requiring an input from the middle or top level will tend to take longer as more people are involved.

4.3 SYSTEM CONCLUSION

The two models have investigated the demands of a control and communication strategy for the adopted Integrated approach.

The control model enforces the need for a closed loop controller, promoting small, quick iteration with a measure of integral control. The inputs and operating boundary must go beyond just design to include all surrounding functions with an interest in the finished product.

The study of the communications found a range of decisions to be taken, each requiring the input from different levels in the design hierarchy. Typically, low level decisions occurring at the lowest level can be taken as they occur; more complex ones requiring an input from the middle and top levels take longer to make.

The next stage is to examine these concepts in light of real experiences and compare them to existing work.

CHAPTER FIVE TEST AND VERIFICATION

Chapter Four suggested conceptual ideas for communication and control in the proposed Integrated environment. Chapter Five will examine these issues in the selected working environment.

The range of decisions found in the communication model will be classified. The terms Procedural and Declarative will be used. The intended meaning is derived from their use in defining different computer programming languages[87]; A Procedural language moves in a strict order, one instruction at a time. A Declarative language needs only to declare data and intentions once, for it to be known and accessible throughout the entire program.

The simple decisions are Declarative in nature. Examples found result from a declared intention; always ensure minimum parts are designed. The opportunity to solve these decisions as they occur is often found to be a necessity. The more complex decisions are proposed to be Procedural in nature. They demand a wider range of inputs and tend to take longer to solve. They can often stop the whole process until a decision is made.

The different controller strategies are examined. It is suggested that proportional control is the way many decisions are taken. The ideal characteristic of zero offset from integral control is investigated. A structured policy of cause and effect analysis is recommended as a good approximation. Derivative is discussed as a means of monitoring resources activity.

This approach is then applied to three working examples. The first considers how the aspects of control and communication apply to the Integrated minimising parts

method. It is suggested that the post design audit approach can cause a simple decision to be excessively complicated, leading to time and cost penalties.

The second looks at the application of the strategy in controlling a concurrent engineering application. Whilst saving time may be a focus of many applications, the author forces the view that product quality and cost must share an equal platform. To achieve this, the desired parallel methods of working, Declarative, must at times be supplemented with the more traditional series, Procedural, approach.

The third application tests the theory's ability to organise an Engineering Change policy to coordinate, control and disseminate information relating to product design changes. A classification of change is mapped against the design hierarchy, highlighting the need to pull changes through using members of the original design team. This will target problems to the appropriate resources, promote ownership of the problem and ensure long term reliability data is fed straight back to those responsible for the initial design. The decision to change will then be taken within the context of the original design.

5.1 COMMUNICATION

The model of the design/manufacturing interface suggested that a range of decisions exist requiring a different approach to obtaining a solution. At one end are simple decisions that occur and can be solved by the lowest level in the design hierarchy.

They have been seen to occur when the designer is asked to constantly ensure that the design meets manufacturing process constraints as well as functions demanded. The

rationalising of parts is typical. The goal of such a constraint is to ensure that the designer only incorporates an agreed range of components into the design.

For example, during any stage of design, the designer may select a certain size bolt, say a 316 Stainless Steel M10x50mm cap head. Supported by the Integrated parts rationalisation module, an immediate response is received if this not a preferred size. An alternative can then be selected from the preferred list. The prompt would list the nearest by material grade, thread size, length or drive type. For example a Mild Steel M10x50mm cap head may be available. The professional designer must now rank the alternatives against the design requirement. In this case the material had to be 316 Stainless Steel. A M8x50mm Stainless Steel cap head was selected, design calculations checked and the design progressed.

The need for the decision arose because of the designer's actions. Supported by the rationalising routine, an acceptable alternative was quickly selected and the design progressed unhindered. A Declarative decision was encountered and made.

Important, however, are the implications of not taking such decisions as they arise. For example, had the bolt been part of a flange coupling joint, Figure 18, six M10x50mm bolts would have been needed to carry the load, as shown. The change to an M8 would result in a change of the flange design to accommodate an extra 3 bolts. If this was not found until the production procurement, either the new bolt would have to be bought, consider any problems with assembly tooling, logistics and costing profiles, or the design would have to be changed, incurring extra drawing time and possible retesting. A final alternative would be to lower the power from 250 to 166KW. The original

selection is no longer just a bolt, but an integral part of the design.

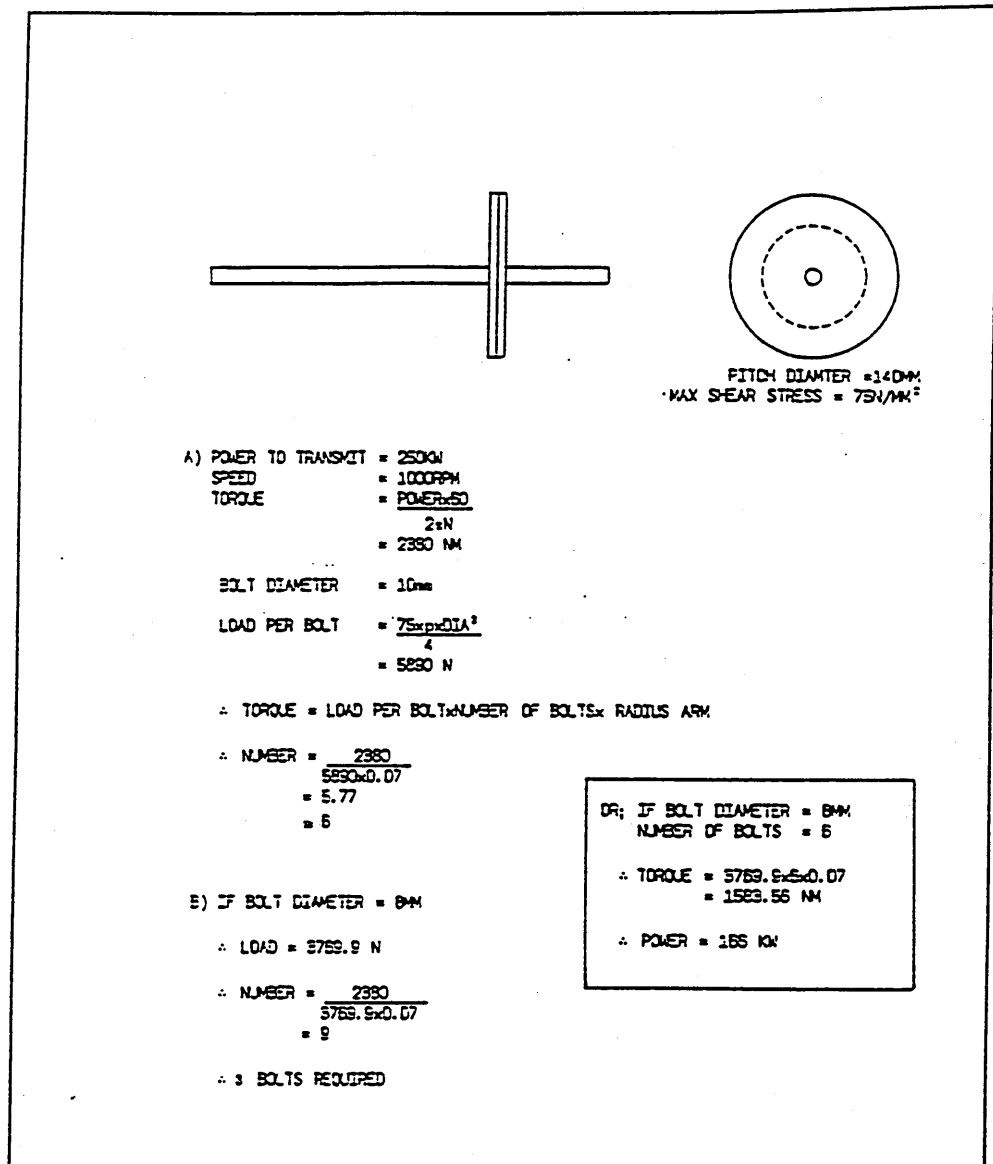


Figure 18 Design rationalising

What was an apparently a "quick" decision owned by the designer, has been transformed into one requiring input from production, purchasing, marketing and sales. It is costly and time consuming.

The options of down rating the performance is an example of

a Procedural decision. It requires an input from a wide range of interests. What else has been designed around the original specification?, Is a new motor required and available?, Availability of spare?, Will the product work?, Is it still what the market wants?. The emergence of these fundamental questions must cause the design to stop and wait for the consensus from all the effected parties; it is a decision caused by the designer's actions, but well beyond his own authority to take.

Figure 19 maps the characteristics of simple and complex design decisions against the Integrated Design Support Framework's terms Declarative and Procedural.

DESIGN DECISION	CHARACTERISTIC	INTEGRATED DESIGN SUPPORT FRAMEWORK
SIMPLE	<ul style="list-style-type: none"> * EFFECTS ONLY THE PRODUCT'S DESCRIPTION * DECISIONS ARISES AND CAN BE TAKEN AT THE SAME LEVEL * DECISIONS MUST BE TAKEN AS THE NEED ARISES 	DECLARATIVE
COMPLEX	<ul style="list-style-type: none"> * EFFECTS FUNDAMENTAL PRINCIPLES OF THE DESIGN * WIDE RANGE OF RESOURCES NEEDED TO TAKE DECISION * CANNOT BE TAKEN IN PARALLEL WITH OTHER DECISIONS 	PROCEDURAL

Figure 19 Communication Framework

5.2 CONTROL

The top level control model suggests using a closed loop, iterative design process with integral control as a productive strategy. All the expectations of the design should be known from the very start; this has been pursued with the explanation of Declarative advice.

The closed loop operation is paramount to ensure that the results of the design process are continually checked against the initial requirements. Closed loop theory also suggests that this strategy helps compensate for deficiencies in the resources used in the process. This is logical; even the best designer can make mistakes. A goal of the closed loop controller must be to have small, quick iterations to trap and sort problems before they can become locked into the design.

Three controller strategies were discussed, Proportional, Integral and Derivative. The proportional controller cares only for the magnitude of the error. For example, if a designed feature continually fails, a proportional approach would just keep replacing the component or redesign the failure point. Experience shows that many of us work, and are judged this way. For example, preventing a failure with good design is rarely noticed or praised. However, solving a problem caused by bad design attracts attention. This is particularly so if the problem aspires to stopping production.

The integral control strategy presents an interesting dilemma. If it could be achieved the design process under control would always achieve it's goal; There would be no mismatch between the original requirement and the achieved solution. This may be an ideal, but the author feels that methods are available to promote it's operation. Presented

with such a failure, the integral approach would treat the failure as an effect. A series of experiments would then attempt to find the cause. The cause could then be designed out.

A good example of this is fatigue induced failures. Known to result from the application of oscillating loads, failure occurs with stresses well below the normal yield point. Some aircraft disasters were eventually attributed to vibrational stresses being transmitted to unexpected parts of the wings and fuselage [88]. The design problem was then to stop the vibrations, not to strengthen the failure points in the wings and fuselage.

A derivative control strategy is applied to balance the accuracy, but lack of speed of an Integral controller, with the speed, but inaccuracy and potential instability, of Proportional control. It monitors the rate of change of error. This could be adapted to help monitor resource utilisation as the design progresses. At the start of a design, many problems are faced. The first attempts during conceptual design will generate and test many ideas. A large number of problems will be encountered and potential solutions found. More time is spent generating ideas than finding detail solutions. Embodiment rigorously tests the more favourable ideas against the product specification and compatibility with each other. Attributes to link concepts emerge. As a design converges into detail design, the problems left should be fewer, but the time to solve each one will increase.

This would suggest that if the design is subject to many, rapid changes as it approaches it's proposed end a problem must exist. An explanation could be that as the problems missed in the conceptual/embodiment phases emerge, attempts are being made to remove their effects; the causes are

locked into the design. For example, an attempt to rationalise parts used once the design is finished would result in the design being compromised.

An effective control strategy must therefore promote a closed loop operating method, striving for small, quick iterations to trap and sort problems quickly. The boundary of operation around this process must encompass all the requirements expected in the final design. An effective control strategy must strive for the principles of integral control. This is best achieved by ensuring that the design progresses in a clear, structured manner, generating ideas and solving problems with respect to the systems that generated them. Figure 20 maps the essential characteristics from the control theory domain to the Integrated Design Support Framework.

CONTROL MODEL	CHARACTERISTIC	INTEGRATED DESIGN SUPPORT FRAMEWORK
METHOD OF OPERATION	* ENSURE OUTPUT IS CONTINUALLY CHECK AGAINST INITIAL REQUIREMENTS	CLOSED LOOP
BOUNDARY	* DECIDE RANGE OF INTERACTIONS AT THE START OF THE PROJECT * MAP OUT INDIVIDUAL INVOLVEMENT FROM THE START	ENSURE ALL REQUIREMENTS ARE KNOWN FROM THE START OF THE PROJECT AND ARE CONTINUALLY ENFORCED
CONTROLLER	* DECIDE METHOD OF CONTROLLING THE PROCESS	INTEGRAL CONTROL, PROMOTING ITERATIVE PROBLEM SOLVING TECHNIQUES

Figure 20 Control Framework

5.3 MINIMISING PARTS

The Integrated minimising parts routine has been developed to work with the designer, presenting the opportunity to influence the design at the earliest stage. It is driven by the designer's actions and so only requires their input in solving many of the problems posed. Similar to the question of rationalising components, many features can be easily modified before they become locked into other design features. Minimising parts is a Declarative task requiring a continuous thread of support throughout the design process. Attempts to make late decisions may reduce opportunities for saving, incur time delays or compromise the design.

The approach[89] generates a short list of possible combinations by discounting a list of all occurrences of touching against a rule base of reasons for not joining.

The initial list is automatically extracted from the CAD database. This is best achieved by designing the product using a Solid Modelling CAD system. The knowledge rich data structures employed supports such questioning. The rule base then automatically discounts any occurrences if there are reasons of assembly, maintenance, material or relative motion necessary for them to remain separate. Reasons of assembly are checked using an operator supplied assembly sequence. When a material difference is found, a prompt inquires if a common alternative is available. A list of final alternatives is offered to the designer. Their professional judgement is entrusted with the final decision.

Whilst alternative methods [73][77][78] were developed for a different type of product, their application methods are

just as unsuitable. It has been suggested that they are essentially an analysis tool with which to assess the suitability of a design for assembly[90]. Their applications are certainly time consuming requiring some training to understand the vast array of charts and tables used. The post design method will encounter situations where trivial features are locked into a wider design concept so that their removal is no longer cost effective.

Attempts are being made to move the principles to the front end of design in a bid to compensate for this. One such piece of work[91] involves the designer in a lengthy question and answers session with a computer program describing designed features using the Boothroyd indices. A manipulation routine then assess the design against set criteria. Such an approach would have prohibitive time scales.

A more advanced research programme [92] is using Artificial Intelligence techniques to help establish the consequences of design decisions on assembly costing. Linked directly to the Computer Aided Design system, the opportunity exists to offer redesign advice as the design progresses.

5.4 CONCURRENT ENGINEERING

Delays in getting a product to market on time can be costly. A reported loss in profits of 33% was experienced when a project was delayed by six months [19]. The Xerox Company[93] instigated sweeping changes to keep pace with competitors producing new products at half the time and cost. Companies are now paying close attention to the way they design and introduce new products.

Reducing time scales can be achieved by running concurrent

tasks. Concurrent Engineering is an attempt to displace a traditionally series design/develop/manufacture approach to product design with a more parallel approach. It seeks to design the product and the process together. Time should be saved and the products quality should increase; long term issues such as manufacturability, testability, reliability etc will be addressed during the design phase and not left until the design is finished [94]. Figure 21 illustrates the general concept of running tasks in parallel. The immediate result is to reduce the time from conception to installation from T2 to T1.

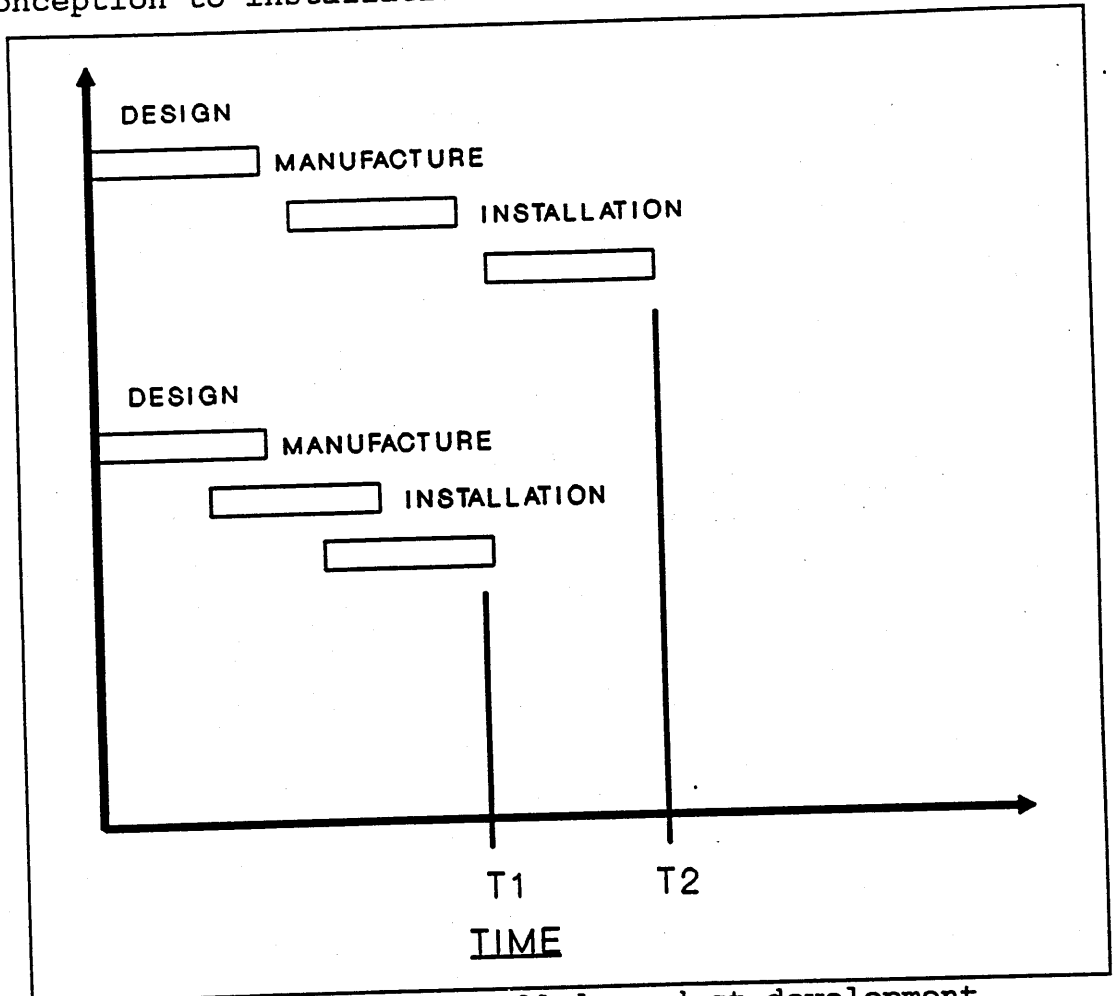


Figure 21 Series and parallel product development

The prime enabler for this approach is team work; the integration of people, tasks and setting to achieve a common goal[95][96][97]. This must be supported with methods and technology [98].

The second collaborator has adopted Concurrent Engineering as a way of reducing their new product introduction time scales. Applying principles of his control and communication strategies, the author suggests that Concurrent Engineering is more than just team work. Engineers from different departments cannot be just placed in one room and told to work together; their environment must be structured to support the different demands of Declarative and Procedural decisions.

Two projects were experienced, Figure 22. In both the author was fully involved. In the first project he took control of manufacturing issues mid way through the design phase, then organised and supervised the preproduction build. The second project was covered from the first team meeting to the preproduction build; a wide range of situations was encountered.

The Company manufacture using semi skilled manual labour, organised in functional cells. The product's complexity and volume prohibits automated assembly. Great reductions in lead times and inventory levels have been achieved by planning and controlling production with a mix of Just In Time and Material Requirement Planning.

To maximise these gains all new products must be designed to match the environment. The design of bought out components has to reflect the selected supplier base; the JIT policy is actively reducing it. To reduce supplier lead times, no design must require the input of more than one sub contractor. To simplify material flow, the design of in

AUTHORS EXPERIENCE

1) NEW PRODUCT INTRODUCTION

- MULTI MILLION POUND INVESTMENT
- RAPID INTRODUCTION
- SIGNIFICANT UPLIFT IN TECHNOLOGY
- MID DESIGN TO START OF MANUFACTURE

10 MONTHS

- PREPRODUCTION BUILD

2 MONTHS

2) MAIN PRODUCT UPGRADE

- REACTING TO MARKET PLACE
- MULTIDISCIPLINARY TEAM
- TOP DOWN COMMITMENT
- CONCEPTION TO PRODUCTION

6 WEEKS

- FULL PRODUCTION

3 MONTHS

TIME SAVED > 2 MONTHS

Figure 22 Concurrent engineering experience

house subassemblies must match the configured manufacturing cells.

The product structure was selected as the most important criteria; most of the designers know the local supplier base, very few understood the new manufacturing methods.

Enforcing the requirements for the products structure is a Declarative task. To ensure the design meets it's

introduction targets, no time was available to restructure the drawing package and bill of material between the development work finishing and the start of production procurement. The Manufacturing Engineers responsible had to ensure that this work was done as the design progressed. Efforts to modify the structure once in production incurred the costs of change and diverted resources from the next project.

Just as important however are any occurrences of Procedural decisions.

An ink jet printer is a complicated machine. Based on empirical laws of physics, it is a complex package of microprocessor controlled high voltage electric circuits embodied in precision engineering components. A systems approach to design and development is used. Extensive test programmes rigorously explore the operating envelop of each module; a range of temperature and mechanical tests are used. Confidence is built up over time.

To ensure confidence is not misplaced, a manufacturing acceptance test is drawn up. Working from the initial product specification, a final test programme is devised. The product must perform 100% before production procurement can begin. This final test is Procedural. It cannot be run in parallel with development work because it is to test the final efforts of the design work. The risk of starting procurement before it has passed is considered too great.

Similarly, the final check of a drawing package. Using a Computer Aided Design system will contribute to improved designs, but it is not until every drawing in an assembly is finished and combined into an assembly drawing can all the necessary tolerance checks be made; preferably supported with manufactured units. Whilst a designer may

check drawings as he goes along, a final check must be made.

This procedure will require an input from more than just the designer. Checks must be made to ensure all problems posed have been solved. Once higher levels in the hierarchy are involved, time scales are affected.

The requirement for testing and checking, illustrates that within a general concurrent environment, there is still the need for some series activities if the time to produce the product is not going to compromise the quality of the product. Talk of running design and manufacture totally in parallel need to be tempered; the integrated approach recognises the difference between tasks that can be run together, Declarative, and ones that must remain in series, Procedural.

5.5 ENGINEERING CHANGE

Throughout every stage of a product's life there will often be a need to change some parts of the prescribed design. This process is called an Engineering Change. Engineering Changes are not specific to any industry, product type, technology used or volume of manufacture.

Four factors are considered to stimulate Engineering Changes; increase quality, lower costs, optimise the manufacturing process and the introduction of new products. The request for change can effect the manufacturing processes being used as well as the product.

If a product is of poor quality, a change is required to improve it. This can account for the processes used in manufacture, problems found in commissioning/service and

end user operation. Financial pressure to increase selling margins may be applied to reduce the manufacturing cost of the product. This can be achieved by replacing existing components with new, more cost effective alternatives. Similarly, competitors may drive a company to reduce the time required to satisfy customer orders; this will impact upon diverse factors such as the manufacturing processes used and the inclusion of components on a long supplier lead time.

Driven by the customer, all these factors may combine to stimulate the development of a new product. In this instance time is paramount to ensure that the new product is first into the market place.

These criteria can be used to help structure the change environment. For example, the cost associated with testing new components may lead a company to restrict changes to only those that directly effect product safety.

A clear and concise mechanism must be built to coordinate and control changes in an effective manner. This is particularly true when details of change must be transmitted and implemented across different manufacturing sites. This section details how the author's core theory of the design hierarchy, control and communication have been applied in formulating an Engineering Change procedure at Domino. It is anticipated that it will be equally applicable in many industries in this sector.

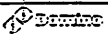
The key to the approach is recognising where the need for change arose, and then targeting the right resources in the right time frame to sort the problem and implement a global solution. It is anticipated that the core element of this approach will be formalised in a planned integrated engineering database at Domino. Such an Engineering Change

policy is not an excuse for poor design. It must form part of a business' strategic plan to improve product design, trapping problems and preventing them from re-occurring. It must be a positive way of recording and informing long term design reliability data.

5.5.1 PRESENT SYSTEM

The present system is driven by two paper documents, an Engineering Change Note and a Concession Note. The Engineering Change Note procedure is used to document and implement planned change. Such occurrences could range from trivial errors on a drawing to the introduction of a new product into manufacture. The document, Figure 23, records a summary of the change, reasons for the change, category, authorising signatures, applicable comments for individual departments and a list of changes to relevant drawings and Bill Of Materials. The document serves several purposes. It firstly indicates that a deficiency exists with a product or process. It then serves as the documentations to record the change and a means of communicating its implementation.

The Total Quality ethic and planned registration for BS5750 demands that all changes are documented and fully traceable. Change notes are continually raised, but are assessed once a week at two Engineering Change Committee meetings. The first meeting assesses each change and then ranks importance into high or low priority. Depending on priority, each change must then pass through a single department for any engineering input, drawing changes and updates to the relevant Bill Of Materials. Once this work is completed an authorised change is then passed to the second Manufacturing Engineering Change Committee where the logistics of implementing the change are settled.

ENGINEERING CHANGE																								
Originator:	Desig:	Eng:	Date:																					
Products affected and part nos:		Product name:																						
Description:																								
Reason:																								
Engineering:																								
Sgt:		Date:																						
<table border="1"><thead><tr><th>Category of change</th><th>(X) Type of change</th><th>(X)</th></tr></thead><tbody><tr><td>A-Redescribe</td><td>1-Safety</td><td></td></tr><tr><td>B-Parts & items not stocked</td><td>2-Constructive/Reliability/Improvement</td><td></td></tr><tr><td>C-Parts not assembled</td><td>3-Design error</td><td></td></tr><tr><td>D-Outstanding orders</td><td>4-Marketing requirement</td><td></td></tr><tr><td>E-Future orders</td><td>5-Production requirement</td><td></td></tr><tr><td>F-Documentation only</td><td>6-Cosmetic components</td><td></td></tr></tbody></table>				Category of change	(X) Type of change	(X)	A-Redescribe	1-Safety		B-Parts & items not stocked	2-Constructive/Reliability/Improvement		C-Parts not assembled	3-Design error		D-Outstanding orders	4-Marketing requirement		E-Future orders	5-Production requirement		F-Documentation only	6-Cosmetic components	
Category of change	(X) Type of change	(X)																						
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Technical notes: Y/N Number:																								
APPROVALS FOR RELEASE																								
EC Committee:		(Signature) Date:																						
Development manager:		ECR No.																						
Manufacturing engineering:		EC No.																						
Cust. No.		Date: 27/02/2016 19:00																						
		Sheet 1 of 1																						

ENGINEERING CHANGE			
Documentation check list with alpha suffix			
MECHANICAL	(A-E) PCB artwork	SOFTWARE	
(M) Assembly drawings		ECRm	
Detail drawing	FLUICATIONS	Source code	
(P) Pict diagram	Manual		
(R) Assembly instruction	Pocket book	LOGISTICS	
(M) Modification instruction	Operator instructions	BOM of material	
		Options	
ELECTRICAL	PICTORIAL	Locate items	
(M) Block diagram	Sales brochure	Spares list	
(M) Wiring diagram		Configuration sheet	
(G) Circuit diagram	SPECIFICATIONS		
(M) Service diagram	(T) Test	PART DATA	
(M) Survey of changes	(M) Technical	INDEX	
Custom drawing		M/A	
(M) PCB drawing		ENG	

EFFECTS OF CHANGE OUTSIDE R&D:		ENGINEERING
Quality / Safety:		
Marketing: (Sales Brochure)		
Publications:		
Test engineering:		
Service:		
Purchasing:		MANUFACTURING
Stores:		
Manufacturing: Rotate stock: Y/N		
Current stock: Allocated: Orders:		
Certification: BS IEC VDE UN etc.		
Comments:		
Manufacturing change board chairman:		
Effective date:		
		DOCUMENT NUMBER: 20-0011-01-01-00-0
		EC No.
		Sheet 2 of 1

Figure 23 Engineering Change Note

This committee is chiefly the concern of the manufacturing/purchasing function. The author played a key role in both of these teams.

To compliment this planned change procedure, a Concession Note is used to authorize unplanned change. Such changes

typically occur when goods are received or a manufacturing process delivers components that do not conform to specification but are fit for purpose. The Concession Note, Figure 24, records the parts concerned, batch details and a description of the deviation found. A range of authorising signatures releases the concession. A link is kept between relevant Engineering Change notes and Concession Notes.

A characteristic of this system is the lengthy bureaucracy needed to administer changes and a time lag from submitting a change to it being implemented. This contributes to a reduction in the operating efficiency of the business and impairs the operation of Concurrent Engineering.

A reason for this is the way the change procedure treats all changes the same, regardless of their severity, size or importance. The initial grading into high or low priority is more a comparison against other changes and not a measure of their own merit. For example, the final stage of transferring a new product from Development into Production is the first batch of machines to be built using production personnel. This build is carried out remote from the shop floor in the Preproduction Build room. The goal of this approach is to sort out any remaining problems prior to entering full production. Such occurrences are minimised by effective manufacturing input during the early design stage, but in reality problems are still found. A typical problem found is a mismatch between components that have been produced as small batch prototypes mainly on manual machines tools, and identical items produced in production volumes on automatic machines.

On a recent preproduction build the author was involved with a problem on a sheet metal component. Prototypes had proved it possible to fabricate a box using sheet stainless

TEMPORARY CONCESSION			
Product / Assembly:		Part No:	
Assembly / Piece / Process:		Part No:	
Batch / Quantity / Period:		Description of Deviation and Justification (Please quote all known part nos. & dsg. refs.)	
Method of Identification/Segregation (As far as possible)			
Previous related concessions			
None/Rd. No: TCN:			
Will any of the following be affected, if so Commercial Manager must sign below. Delete items not affected:			
Reliability	Servicesability		
Safety	Interchangeability		
Performance	Product Life		
Originator	Print:	Sign:	Date:
Supervisor/Manager	Print:	Sign:	Date:
Design Authority	Print:	Sign:	Date:
Quality Manager	Print:	Sign:	Date:
Commercial Manager	Print:	Sign:	Date:
Manufacturing Manager	Print:	Sign:	Date:
Other Comments / Information			
Circulation: Above signatories plus following: J.Butler, G.Hutton, R.Oldfield			
Recommendation for alternative to be a permanent second source/for design change. (Yes/No) (If yes an EC number must be entered before issuing.)			
Sign:		Date:	EC No:
This drawing is unauthorised and must not be used to develop or produce the wrong version of Domino Airtex Ltd. Containers, England.			
		DOCUMENT NUMBER DP-JO-01-14-01-01-01-01	
		TCN No:	
		Sheet: 1 of	
NOTE: NO AUTHORITY IS GRANTED PRIOR TO FORMAL ACCEPTANCE BY ALL APPROPRIATE SIGNATORIES			

Figure 24 Concession Note

steel. Once in production a problem in holding the calculated tolerances resulted in the base of the box distorting. The only fix available was to reinforce the face concerned. Because the build activity was separate from the main production area, only the pre-production build programme was disrupted as units were dismantled, reworked and rebuilt. The close working group and resulting ownership of the problem ensured it was sorted quickly and

implemented. Other problems encountered include minor changes to the length of wiring looms and the quantity of different Free Issue items detailed on the Bill Of Material's. As trivial as they may seem, such problems must be trapped and corrected before commencing full production. Using the present system, each change must follow the same path before being officially released to the shop floor. This approach pushes changes through in a top down manner without due regard for those responsible for the original design.

5.5.2 INTEGRATED APPROACH

To stream line the Engineering Change procedure and ensure changes are efficiently implemented, the author has applied his theories of communication and control developed at the design/manufacturing interface. An Engineering Change procedure is promoted that pulls changes through from the bottom, targeting the resources responsible for the original design with the task of sorting out the problems.

Three aspects of process control theory were found to be applicable to the design environment. The overall process must be iterative, operating with full knowledge of what is finally required, using the best principles of integral control. The iterative approach ensures that the process is continually monitoring it's performance against initial requirements. Striving for small, quick iterations ensures that deviations are trapped and sorted at the earliest possible opportunity. Ensuring that the full expectations of the design are known at the start of the design process, typically enforcing both functional and non function demands such as manufacturing process constraints, promotes solutions that are right first time. It has been shown that periods of redesign to account for such deficiencies will not only incur time penalties but also compromise the

quality of the final solution. An integral controller is an attempt to promote further the ethic of right first time. A best attempt at achieving this ideal is to structure the design process so that problems are solved with respect to the system that generated them and not in isolation.

By targeting Engineering Changes to those responsible for the original design these principles will be applied. The iterative mode of working is continually checking the final design against the original brief. By involving those responsible for the original design it ensures that they are constantly updated with the long term performance of their original design decisions. The integral control ethic is also maintained because the new problems are assessed and solved within the context of the original design.

The concept of Declarative and Procedural decisions was found when analysing decision making at the design/manufacturing interface. Simple, declarative decisions were found to effect only the functional description of the product, typically arising and being solved by the actions of the design draughtsman. It was shown that such decisions must be taken as they arise. More complex Procedural decisions effect the more fundamental principles of the design and so require a greater range of inputs. If the same principles are used to analyse and authorise Engineering Changes a similar range exists. At one extreme are relatively simple decisions that only effect the description of the product. Such changes would include the length of wires or quantities of components on the Bill of Material. These changes should be handled solely by those responsible for creating the original description. At the other extreme are changes that effect fundamental design parameters - for example the modification of a feature that is causing quality problems. Such a change must be considered from both a technical and

commercial view and would require the input from members of the full Engineering Change Committee.

This targeting of responsibility will promote ownership of the problem, ensuring changes are implemented rapidly and effectively. To implement the Integrated approach Design Authorities must be assigned to each product. The Design Authority is not a single person, but key members of the product development team, each from a relevant business function. These teams will own changes related to their product and they will be jointly responsible for ensuring it is quickly and effectively implemented.

As changes are raised, each must be given a unique serial number and logged on a database. The first stage of implementation requires the Engineering Change Committee to assign the change to the appropriate Design Authority and a Change Classification code. Three categories are available, 1, 2 and 3, reflecting the range of changes available, Figure 26. Class 1 changes are the most complex changes found, typically effecting the fundamental design principles whilst class 2 effect engineering principles. Class 3 changes are the most simple changes found, typically modifying the functional description of the design.

For example, Figure 25 illustrates a very simple component. It is designed to have a sealing plug pushed through the hole before pushing the plug into an open hydraulic fitting. The tab acts as a gasket, indicates the presence of the plug and aids its removal.

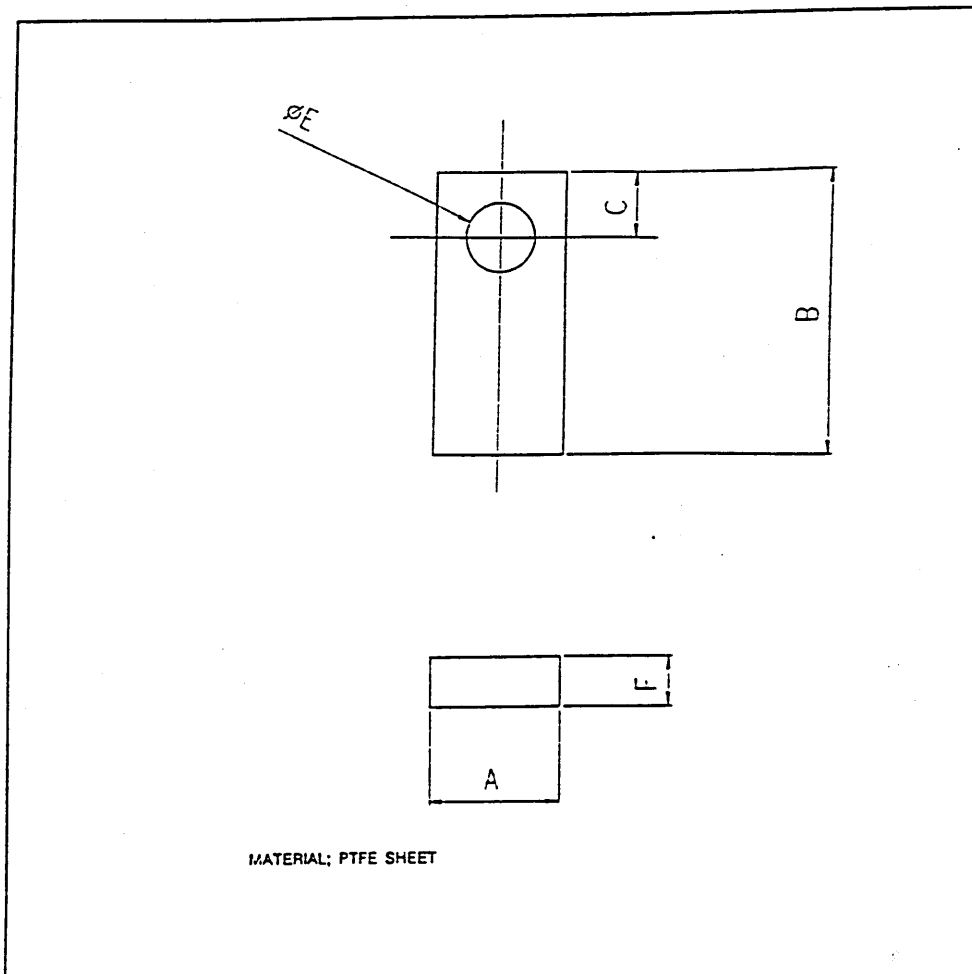


Figure 25 Locating tab

If an Engineering Change is requested, the category of change must be assigned - class 1,2 or 3. To do this, it is necessary to understand how and why each feature of the product was designed; this is achieved by mapping each feature against the Design Hierarchy, Figure 5, considering in detail the initial problem to be solved by the design, the functional requirements of the design and the way the designer has described the solution.

For example, consider three features of the design shown in Figure 25; the material selected, the size of the "E" hole and the overall length "B".

The decision to select PTFE was driven by the original problem -act as a gasket, indicate the presence of a tab and aid its removal. A request for change must be considered against these initial criteria - for example, a lower cost solution may be to manufacture the tab from paper. This approach would not meet the criteria to act as a gasket nor aid the removal of the plug. Such a change would effect the fundamental operation of the design and so constitutes a Class 1 change.

The size of the "E" hole is largely dictated by the size of the sealing plug to be used; this is in turn derived from the size of hole to be plugged. These parameters emerge as the functional requirements of the design are developed. A request to change the hole size to accommodate existing manufacturing tooling, and so help lower costs, must take account of these decisions; a Class 2 change.

The length of the tab "B" is the primary method of indicating the presence of a plug. The only restriction placed upon the designer is the balance between product cost/wasted material in having an excessively long tab. In this case, the designer chose an arbitrary length sufficient for the tab to be easily gripped by hand. A change to this feature would be Class 3.

Class 3 changes can be immediately transferred to the appropriate Design Authority for action. The team must action the change, producing all the documentation necessary to implement the change. This information is then returned to the Engineering Change Committee for final ratification. The team must then implement the change across all manufacturing sites.

Class 1 and 2 changes are more complex. The Engineering Change Committee must review the severity and importance of

the change, from which resources can be allocated to investigate the problem further. Once it is clear what actions are required, the change can be down rated to a class 3 change. It can then be passed to the appropriate Design Authority for action. By structuring the Change procedure this way, Figure 27, the responsibility for the change is targeted at the resources responsible for the original design. This will facilitate the pulling of changes through the change system as the demand arises, requiring only the input from the appropriate Design Authority. This will make the process of Change more effective in taking the right decisions and reducing the time scales required.

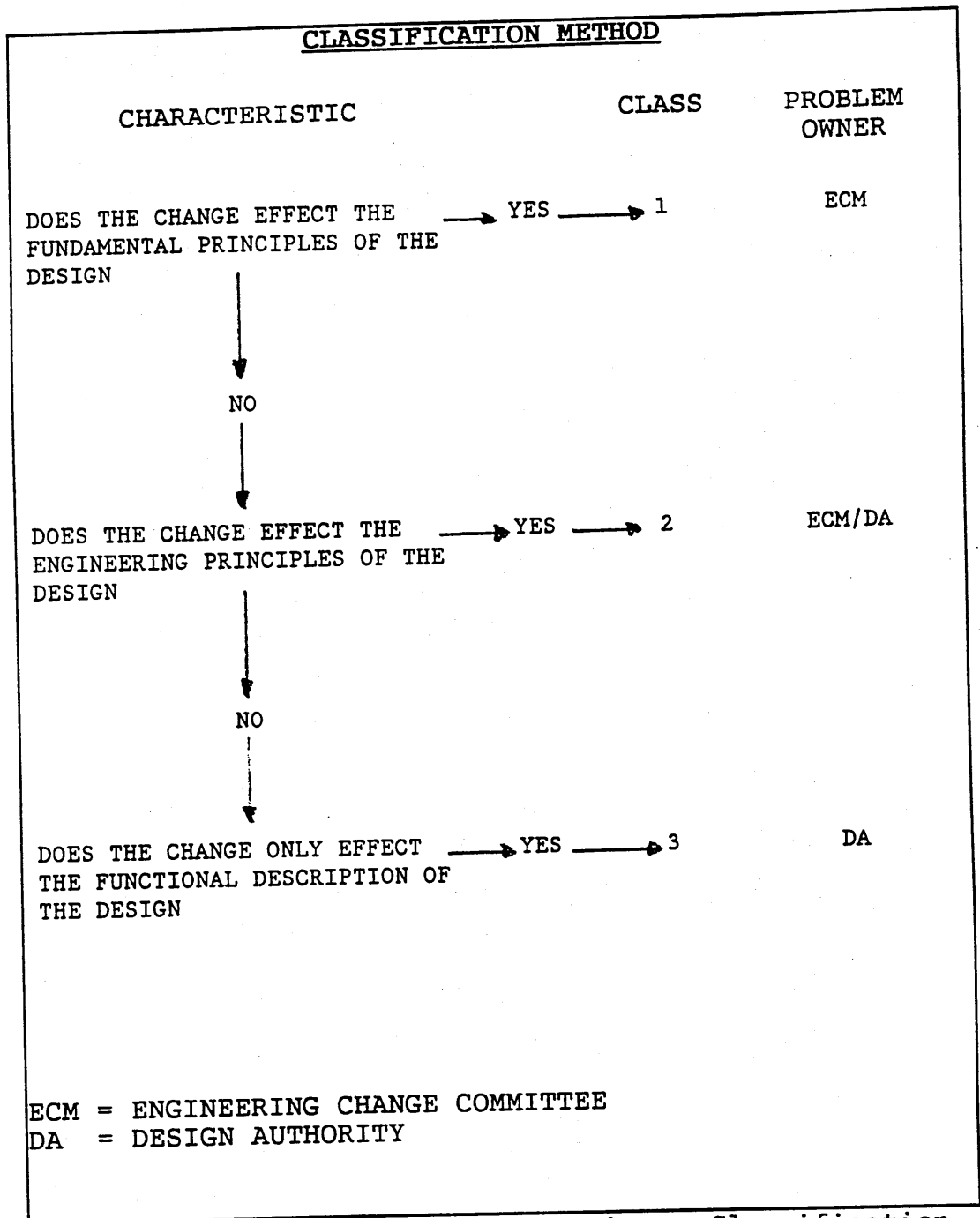


Figure 26 Integrated Engineering Change Classification

PRESENT METHOD

- * TOP DOWN
- * PUSH CHANGES THROUGH
- * RESPONSIBILITY REMOVED FROM DESIGN ORIGINATOR

INTEGRATED ENGINEERING CHANGE METHOD

- * BOTTOM UP
- * PULL CHANGES THROUGH
- * TARGET RESPONSIBILITY TO THOSE RESPONSIBLE FOR THE ORIGINAL DESIGN
 - CLOSE THE LOOP ON THE DESIGN'S LONG TERM PERFORMANCE
 - ENSURE THE CHANGE IS WITHIN THE CONTEXT OF THE ORIGINAL DESIGN

Figure 27 Integrated Engineering Change Procedure

CHAPTER SIX CONCLUSION AND DISCUSSION

Engineering Design is a response to the needs of industry to generate new ideas and products in a structured manner. The formal process is used to structure available resources to ensure that the best solution to the problems posed is accurately described.

The first stage of design is to decide exactly what needs to be designed. Understanding the problem must investigate and document all the expected characteristic of the final design. This would combine the functional requirements of the product with other demands such as cost targets and assembly process limitations. Typically, such exercises often only cover a proportion of the problem to be solved, leaving many more issues open to general interpretation and judgement. As the design progresses, the designer must not only strive to meet the documented requirements, but also decide how to handle the more open parts of the specification. This additional burden not only slows the design programme, but it can also threaten the success of the final design.

The maturing of automated assembly techniques highlighted the fact that not just any design would suit automated assembly techniques, but only ones which were deliberately designed to suit. Design For Assembly has attracted both academic and industrial interest. The rewards for ensuring a product works and can be efficiently assembled are high. Failure could result in a perfectly functional product not being cost effective to produce.

The traditional approach to do this would attempt to modify the final design in light of such additional criteria. Such periods of process planning or production engineering are common in many companies. This is considered to produce sub

optimal designs because established features of the design must be disrupted in order to accommodate the new demands. A more progressive policy attempts to force these issues from the very start of the design process - treat them as part of the design requirements, not an retrospective demand. This is also in response to commercial demands to reduce product development timescales - get it right first time.

This additional loading on the designer would be counter productive if it led to a reduction in the designer's efficiency. Techniques have been developed that remove the burden of finding such design deficiencies, whilst offering positive advice on how to improve the design. The designer is then left to exercise professional judgement on what to change. Such an approach, developed at The CIM Institute, satisfies the demands of the selected environment, but lacked an application philosophy. To develop this philosophy the author has focused upon the design/manufacturing interface. The approach does not preselect or impose design or manufacture as dominant, rather as complimentary.

Systems theory was selected. It studies such complex bodies as wholes. One where contributions cannot be separated or importance adjudicated. A system is characterised by it's hierarchy of operation and the methods of control and communication used within it. The hierarchy is found to have properties that emerge only as a direct result of interaction of the different levels. These properties are characteristics of the system.

The design problem has different interpretations at three different levels. The top level must condense the wide and varied demands of the new product into a concise product definition. This level is the product champion; it must

represent the global view of the customer, the manufacturer, the salesman, the service engineer and the financier.

The middle layer must then produce alternative concepts to meet those demands. The operator will need to know what caused the demands, the technical and social implications of trying to satisfy them.

The best alternatives can then be passed to the next level. Here they are interpreted into the detail technical descriptions. The operators are constrained by a tight technical description of what is required. From these descriptions, the final product can be made. The hierarchy is used when modelling the design/manufacturing interface.

Design is a decision making process. Process control theory has been used to establish control. A communication model can show the way decisions are taken at the interface.

Process control theory establishes the need for a closed loop operation. This iterative operation continually monitors the output of the process against the initial requirements. The goal must be for small, rapid iterations to trap and solve problems quickly. A boundary must be established to reflect the full requirements of the results. All requirements must be known at the start and form part of the product specification. The design will be compromised if changes are needed once it is finished; the design process cannot operate in isolation. The overall control strategy must promote the analysis of cause and effect when faced with problems. This approach is considered to be a good attempt at establishing integral control; the achievement of no offset between the initial requirements and the final results.

In communication and decision making at the design/manufacturing interface the action to verify and approve changes to the design is important. A range of decisions exists. At one end were simple decisions that arose because of changes generated by the actions of the lowest level. These decisions must be taken as they occur. If left until later in the design process, they become locked into other design features. The request for change now effects a wider range of features, and so must be authorised by the middle and top layers of the design hierarchy. These are more complex decisions, taking more resources and time.

A Declarative decision is one that must be taken as it arises. A Declarative task is one that must form a continuous thread throughout the design to ensure quality results. Rationalising and minimising of parts are Declarative tasks. An example illustrates that if these decisions are not taken as they occur, the affected components become locked into the design; removal can then compromise the design and be costly.

A Procedural task must remain separate. The example of final testing of a design is used to illustrate this. Development work cannot proceed on features that are subject to a final test.

The results of the control and communication models satisfy the demands of the first environment; the importance of Declarative advice is now understood both as a means of reducing time scales and ensuring optimum design. The established techniques promote an iterative approach to design; they force the designer to review his actions against specific criteria. The control theory explains what is happening.

Work at the second collaborator has drawn upon the general lesson of the control model; the importance of the operating boundary, iterative operation. Commercial demands have demanded a reduction in time scales to develop and introduce new products. The concurrent running of design and manufacturing tasks was a prime objective. The communication model highlighted the need for a structured operation to ensure quality was not sacrificed for time. Declarative and Procedural decisions and tasks were tackled as appropriate. The Declarative enforcement of product structure ensured it matched the present manufacturing method. The Procedural manufacturing acceptance test ensured the product matched fully the initial specification.

Using the work to structure and control an Engineering Change policy has illustrated a general application of the philosophy. The range of Engineering Changes found map to the design hierarchy. Declarative and Procedural decision making is used to distinguish between the different types of changes found, from which an effective strategy is proposed with which to handle the change. Control theory promotes good practise for closing the loop on long term design issues.

RECOMMENDATIONS FOR FURTHER WORK

The thesis is based on academic research in a practical environment. It has been shown to have practical value in that selected environment. The next academic stage would be to test results with different designers, for example electronic hardware and software and in different industrial settings. From this, more general rules and working principles will emerge.

The collaborators can now progress with their respective implementations with more confidence. The author is involved with the development of an engineering database system which plans to support the laying out of designs to meet the manufacturing process constraints.

The category of Declarative decisions offers the greatest scope for continuing the research initiative. We must better understand them and their influence on the design. Methods must be found to support and influence their effects as they occur. This is particularly significant as the application of Concurrent Engineering expands. The demands of working across remote sites and different companies will require the development of the process within a more complex organisational environment.

The proposed framework has contributed the necessary structure to expand The CIM Institute's research programme into the Product Definition Process, Figure 1. The application segment addressed is "Design Methodology", "Design for Manufacture and Assembly" and "Concurrent Engineering". The core research area is decision making.

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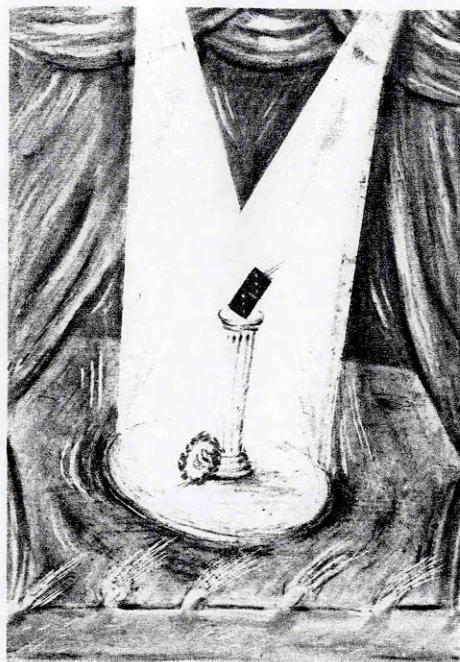
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APPENDIX A DOMINO AMJET LIMITED



I N T R O D U C I N G



The story began in 1971 when Graeme Minto was researching multijet ink printing, in Cambridge Consultants. Work stopped on the multijet project and changed to simpler applications. In 1978 Graeme Minto left Cambridge Consultants to form Domino, with a licence to manufacture and market ink jet printers. He was the first chairman of the company. Domino's first printer, Unijet, was sold the next year. It was used in the printing industry to number books of lottery tickets and other documents.

1 0 3 0 9 5 3 0 9 5 2 4

BEST BEFORE

An important breakthrough for Domino came with the EEC directive to label perishable goods with a 'best before' date, and in 1981 Solo was introduced. The market for Domino printers expanded rapidly and Solo 2 and Solo 3, technically much improved, were successively launched. As well as direct sales in the United Kingdom, Domino appointed distributors in Europe.

... a
sustained
programme
of
research
and
development



All ink jet printing is based on three main features. It is noncontact, and therefore is particularly suitable for industrial situations where, although the surface to be printed may be uneven, a consistent quality of print is required. It is microprocessor controlled and so what is to be printed can easily be stored, retrieved or changed. It can match the speeds of fast production lines in modern factories and plants.



The Solo family was based on continuous ink jet technology, and Domino's own design of the highly versatile drop deflection technique. This technique involves electrically charged droplets which are deflected as a matrix to form characters on a surface to be printed. Ink is pumped through a small nozzle, about the diameter of a human hair and vibrated to form a jet of equal sized droplets. Domino printers form 64 000 drops every second which can all be given an individually selected charge by induction. The droplets then pass through a constant electrostatic field and charged drops are deflected sideways, the higher their charge the further they are deflected. It is this deflection in line across a moving surface that creates the dot matrix from which characters are formed. Unused drops are collected and carried back to the central ink reservoir for re-use.

... creating
technology
to
meet
the
needs
of
our
customers

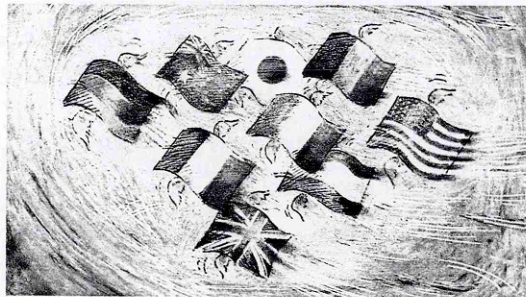
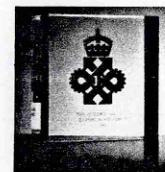
In 1982 Domino was awarded the first prize of £50 000 in an award scheme sponsored by Hill Samuel Merchant Bank for small newly established manufacturing businesses.

The company's expanding business made a move to larger premises essential, and towards the end of 1982 it relocated from Milton to Bar Hill near Cambridge.

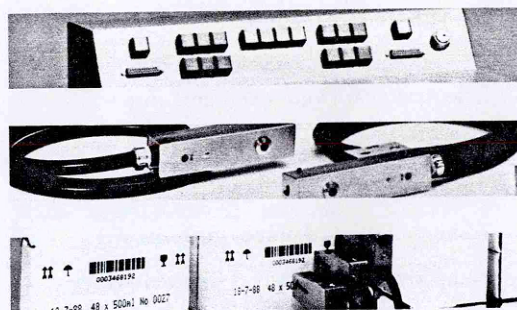
The next year Domino entered into a trading agreement with American Technologies Inc. The two companies combined their resources into a new company, Domino Amjet Limited, which was owned 51% by Domino and 49% by American Technologies. Sales spread to the Americas, Australia and New Zealand. In Holland a European subsidiary was established, Domino Amjet BV. In 1984, the Solo family was increased by the addition of a new generation printer Solo 4, and Codebox was introduced. The Bar Hill premises were extended. A subsidiary, Domino Printing Systems Vertriebs GmbH was established in Germany.

1985 was the beginning of a new era for Domino. The company was floated on the Stock Exchange and shares were 43 times over subscribed. Domino Amjet Limited became a wholly owned subsidiary, the Cambridge Company buying out the minority shareholding held by American Technologies. Codebox gained for the company the Queen's Award for Technological Achievement. The Ink Division was formed in Liverpool and the ink manufacturing business of the principal supplier was acquired.

... our
principle
the
twin
goals
of
quality
and
reliability



Domino's inks are specially developed for its printers. It manufactures general purpose, very fast drying, reduced odour and speciality inks. The ink management system is the heart of continuous ink jet printing. It warns the operator when the ink cartridge and filter should be changed, it also automatically maintains ink viscosity at the correct level, special ink sensors tell the operator when levels are low and guard against interruptions in printing.



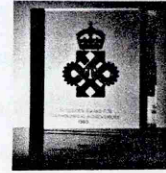
The product range was extended by the addition of Solo 4/4 with two heads, and a multi-headed system Elan, for the printing industry.

In the next year, Domino launched Macrojet, its first valve-jet or large character printer. Valve-jet printing uses a much simpler concept. Characters are formed from a row of nozzles, one for each drop in a column of the dot matrix. Behind each nozzle is a valve which is computer controlled and opens to allow a drop to be ejected under pressure. This allows fast drying ink to be used by Macrojet and opens up additional application areas for the large character coding of non-absorbent surfaces.

... with
a
clear
commitment
to
customer
support



By 1986 threequarters of all machines made in Cambridge were sold outside the United Kingdom and for this, in 1987, the company received the Queen's Award for Export Achievement.



In 1987 Domino acquired the ink jet division of American Technologies Inc.

The new company, Domino Amjet Inc serves the markets in the USA, Canada and South America.



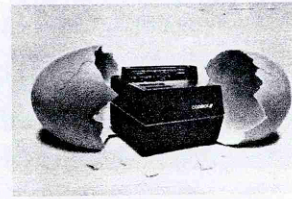
In 1988 Domino celebrated its tenth anniversary. In its first decade it had become a world-wide company and a leader in ink jet technology. Domino Amjet Inc. moved to a 72 000 sq.ft. site in Gurnee, Illinois. In the United States it won Packaging Magazine's Gold Award for innovation.

In May 1989 the new Dutch headquarters were opened and in June the United Kingdom company moved into its new 100 000 sq.ft. headquarters in Bar Hill, Cambridge. Here the operation is all under one roof and Domino continues to grow from strength to strength.

... a
reputation
for
honesty
and
integrity



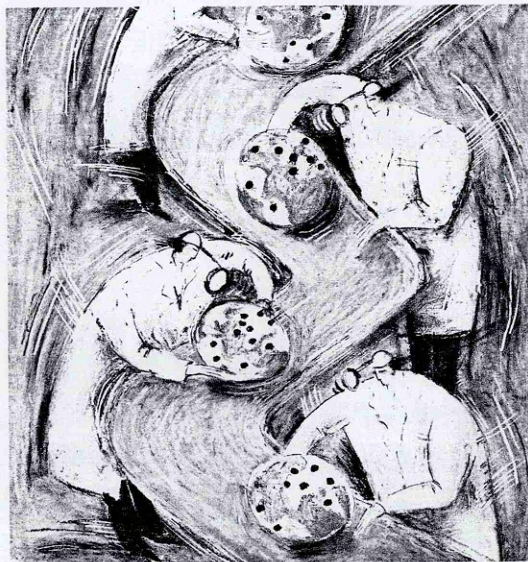
Domino's business aim is to become the world leader for industrial electronic overprinting equipment, meeting the needs of every industry where variable information is required on a wide variety of surfaces. This objective is well on the way to being achieved.



Domino has a wide range of well established products, printers and inks, and an extensive research programme designed to extend this range.

Quality and reliability are Domino bywords. Domino's primary concern is for its customers. Its aftersales service is second to none. It offers training to its customers' staff so that printers work to maximum efficiency.

... and
encouragement
for
innovation,
communication
and
respect
for
the
individual



Domino in the Commercial Printing Industry

The very first Domino product, Unijet, was used to print numbers on lottery tickets.

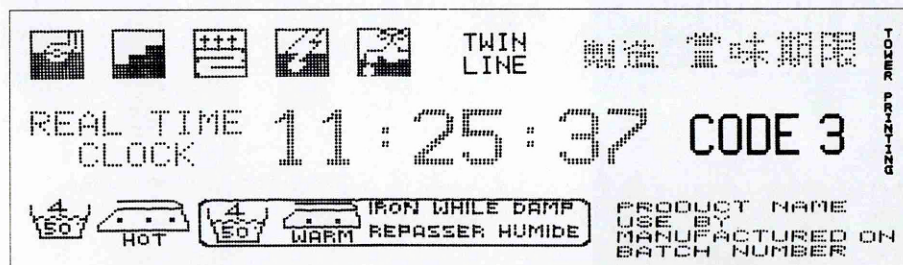
But, from 1981, the company's expansion came from coding and marking, which now makes up 85% of its business.



However, the Graphics division of Domino makes up a significant contribution to the company's prosperity: Domino International Graphics in Holland, DAInc Commercial Printing in the USA, and UK Graphics in England.

These divisions specialise in equipment for numbering, addressing and personalising mail. Variable data can be mixed with fixed text messages, logos or barcodes. The products can be used with web or sheet fed presses, folding machines, saddle stitchers, bindery lines and mailing bases.

... an
established
international
group
aiming
for
no
less
than
world
leadership
in
electronic
overprinting



Domino in the United Kingdom

Bar Hill, Cambridge, is the centre of Domino's activities. Administration, research, manufacture, marketing, service, and training, are all there. Every department is supplied with the most up-to-date equipment.



In addition there is a Scottish office and support centre in Stirling University's Innovation Park; and customer and service training and the ink manufacturing plant near Liverpool.

Service engineers are regionally based to cover the whole of England, Scotland and Wales. As Domino equipment is known for its reliability, service engineers spend much of their time installing new equipment. Additionally, full maintenance can be carried out regularly and individually designed service contracts are available, including a 24 hour call-out service.



...these
are
the
foundations
upon
which
Domino
has
been
built
and
has
grown

Company Aims And Objectives

Our aims as a group of companies

We, the Domino team, intend to become world leaders in electronic overprinting by:

- Developing technology that meets the needs of our customers
- Delivering quality products on time
- Giving support our customers can rely on
- Efficiently managing our business through planning and control without bureaucracy
- Promoting employee pride and satisfaction through participation and reward
- Generating an attractive rate of return for our investors

Our place within industry and the community

We intend to remain a socially responsible company within the community and a good employer by:

- Being an attractive and exciting organisation to work with
- Providing good prospects and remuneration
- Promoting good working conditions, social activities and a friendly atmosphere
- Increasing local prosperity
- Encouraging links between education and industry
- Respecting the environment
- Supporting local charities and community activities
- Maintaining an honest and professional image



Domino related success factors

To achieve our aim requires a successful team that:

- Has common goals with clear objectives
- Thinks internationally
- Encourages innovation
- Communicates clearly
- Plans its resources and meets commitments
- Operates simple responsibility
- Respects the individual

Customer related success factors

Our success depends upon Domino achieving greater customer satisfaction than our competitors in all these related areas:

SUPPORT

- Fast response
- Listen to feedback
- Knowledgeable staff
- Customer training

PRODUCTS

- Fit for purpose
- Good quality
- Value for money

IMAGE

- Good reputation
- Honesty & integrity
- Personal contact

We all have a part to play in supporting the hub of our business — CUSTOMER SATISFACTION