A Specification For A Next Generation Cad Toolkit For Electronics Product Design

by

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To Barbara for her support and encouragement.
Abstract

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Electronic engineering product design is a complex process which has enjoyed an increasing provision of computer based tools since the early 1980's. Over this period computer aided design tool development has progressed at such a pace that new features and functions have tended to be market driven. As such CAD tools have not been developed through the recommended practise of defining a functional specification prior to any software code generation.

This thesis defines a new functional specification for next generation CAD tools to support the electronics product design process. It is synthesized from a review of the use of computers in the electronics product design process, from a case study of Best Practices prevalent in a wide range of electronics companies and from a new model of the design process. The model and the best practices have given rise to a new concept for company engineering documentation, the Product Book which provides a logical framework for constraining CAD tools and their users (designers) as means of controlling costs in the design process.

This specification differs from current perceptions of computer functionality in the CAD tool industry by addressing human needs together with company needs of computer supported design, rather than just providing more technological support for the designer in isolation.
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<td>AQAP</td>
<td>Allied Quality Audit Procedure</td>
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<td>BCA</td>
<td>Board Construction Advisor</td>
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<td>Mean Time Between failure</td>
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I would like to thank Pat Pearce, Peter Jagodzinski and David Hughes for their support and supervision during the project. Thanks also must go Jan Bennett for his enthusiasm and great debate that helped to keep the fun in the project.

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Author's Declaration

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award.

Relevant scientific seminars and conferences were regularly attended at which work was often presented; external institutions were visited for consultation purposes and several papers were prepared for publication in academic journals and as conference papers:

Presentations & Conference papers


• P.F. Culverhouse (1993) Design is not just technology, IEE presentation, Plymouth, 4 October.

Academic papers


Signed: 

Date: 14 June 1994
CHAPTER 1. INTRODUCTION

1.1. BACKGROUND

1.1.1. The Electronics Designers' Toolbox Project

This thesis was undertaken as part of SERC/ACME grant number GR/B 83924 on the subject of electronics engineering product design.

The Electronics Designers' Toolbox (EDT) Project focussed on developments in computer aided support tools for electronic engineering product development, on a 5 to 10 year horizon. The stated aim of the project was to develop a functional specification for next generation Computer Aided Design (CAD) tools for Small and Medium sized Enterprises (SMEs). The project supported two research assistants, the author of this thesis and Mr. Jan Bennett working under the guidance of Professor David Hughes at the University of Plymouth.

The aim of the project was to understand the current limitations of computer aided design (CAD) tools in industry, to identify the linkages from design into production, to develop a model of the design process used in the electronics industry and to formulate a functional specification intended to serve as the basis of the next generation computer support toolset for design.

1.1.2. The scope of this thesis

The electronics industry is broadly split into two categories: (a) primary component manufacturers, for example integrated circuit design fabricators, resistor and capacitor manufacturers; and (b) secondary manufacturers or original equipment manufacturers (OEMs) who use these components to produce sub-assemblies and finished goods. In general it can be said that primary component manufacturers manipulate the raw physical parameters involved in each product domain, so for example capacitor manufacturers design such devices with a knowledge of the permitivity of certain chemicals and compounds and with an understanding of their limitations under varying conditions of
applied voltage, current and humidity. Integrated circuit manufacturers design their circuits using detailed knowledge of semiconducting compounds, their electrical characteristics and their topological properties. Secondary manufacturers use these components to construct high functionality products for markets such as aerospace, military, consumer electronics, control systems and information systems (to name but a few).

Secondary producers do not, in general, have to understand the basic physical parameters involved in the correct function of the electronics devices employed in their designs. The circuits they design utilise secondary characteristics of their components, for example a transistor designer understands charge carrier mobility and edge effects that alter signal transfer characteristics of the device, yet an engineer using such a transistor will only concern himself or herself with parameter transfer curves derived from the device physics but not representing these characteristics explicitly, for example the transistor gain or Beta. It is this separation of concerns that divides the electronics sector and it is the latter section of this market, the secondary manufacturers that constitute potentially the largest market for CAD tool vendors. It is this market that the EDT project, and thus this thesis, concentrated on.

The EDT project focussed on providing electronics product designers working in a team-based environment with comprehensive support for all aspects of the electronics product development cycle. Such an approach would comprise elements of human computer interface, applications software, engineering data management, databases and communications. It would also incorporate design and manufacturing data, information and knowledge together with the often considerable engineering "wisdom" derived from years of product design and development experience.

In addition a review of the literature of the design process, from both a human and company view, was undertaken. This served to place the company visits in context with current research into human cognition and company economic and functional processes.

As part of this overall program of work, this thesis presents a new model of the electronic engineering product design process as derived from the above researches. The model is
used to develop aspects of a functional specification for next generation CAD tools and examples of usage are given.

It is quite clear, however, that the process of electronics design takes place in a far wider context than simply that of an individual design engineer seated at a workstation. The project, therefore, looked beyond the individual designer and embraced also the department, company and external business environment in which the design activity takes place. The latter forms the basis of Jan Bennett’s thesis and is outside the scope of this author’s thesis.

1.2. OVERVIEW OF THESIS

1.2.1. Objectives

The objective of this thesis is to develop a functional specification for users and vendors of electronics design tools. In order to do this it will be necessary to identify current CAD tool limitations in the context of electronics product design and to review current industry product design practice. A specification for a model of the electronics design process will be developed that is based on world wide best practice.

1.2.2. Contribution of this thesis

1.2.2.1. Functional specification

The contribution of this thesis is highlighted by the development of a functional specification which will enable both users and vendors to specify a resilient design capability which supports industry best practice. Detailed investigation of the research literature and discussions with the leading CAD tool vendors and users of tools indicated that surprisingly no such specification exists.

Functional specifications for CAD design tool kits were sought from CAD tool companies, but none were forthcoming. A number of executives at these companies stated that the underlying CAD tool technology [1,2] and customer demands were changing too quickly to allow CAD developers the “luxury” of following a traditional software development
plan involving requirements analysis and functional specification definition prior to implementation. Rather the industry was driven by immediate customer needs and CAD tool kits were being developed by direct customer feedback mediated by industry supported CAD tool user groups.

Unfortunately it is now becoming increasingly evident that the lack of a functional specification is causing considerable difficulties as vendors become unable to respond to new requirements.

1.2.2.2. Functional requirements

The functional requirements of CAD systems for electronics engineering product design have been identified from the field work and literature survey undertaken by the author. For the first time the CAD tools have been assessed for their shortcomings and problems of usage that affect electronics design in industry. This together with an evaluation of the real needs of engineers operating in an industrial setting has allowed the author to develop a functional requirements for a next generation CAD tools that have to operate within the socio-technical environment that exists in industry. This is in contrast to existing CAD tools and frameworks where only technological considerations are accounted for.

1.2.2.3. Design process model

The value of the author's design process model is highlighted by the dearth of design process models that account for both industrial and human factors in design in the electronics sector. In addition existing design process models have been derived from either mechanical engineering or architectural research.

The model extends existing design process descriptions by specifying technical and commercial activities that must be carried out during product development. In doing so, the model acknowledges that specific information and its corresponding documentation are necessary to the design process. A consequence of this is that mechanisms have to be provided to deal with the information and documentation generated during the design
phase of a product. These mechanisms are dealt with in chapter 8 of this thesis, entitled "A functional specification of an electronics design support toolset" and summarised above.

A significant aspect of this process model is the definition of design paths that are specific to the activities normally undertaken by electronics engineers engaged in design. These design paths allow both CAD tools and engineering management to constrain the tasks and the creativity of designers in a natural way that fits the demands of the company product development process. Ensuring that engineers are prevented from being overly creative when designing products where innovation is not warranted and controlling the amount of design a product "endures". So, designers are more constrained when performing repeat order designs or variant designs than when developing innovative or strategic designs.

Complexity metrics are developed that allow design management to monitor the process of design in a formal way. Enabling managers and designers to review design capability from project to project in a formal and more rigourous manner. And in doing so avoiding the ad hoc methods still commonly employed in design project estimation in the electronics industry.

1.3. THE STRUCTURE OF THIS THESIS

Chapter 2 defines the methodology used to collect data from the case study companies. A discussion on the reliability of the techniques and on the quality of the data is presented.

Chapter 3 reviews existing design process in industry, introducing three design practices, design by prototype, design by simulation and design by concurrent engineering. In addition CAD tool usage and their limitations are described, together with a brief discussion of the link between design and other parts of an electronics business.

Chapter 4 introduces the results of the case study survey, including elements of good and bad practice found in electronics product design. The case study data are discussed in relation to a number of best practice yard sticks from in the literature.
Chapter 5 is a literature survey of design process models, both from the company and from the human viewpoint. A discussion of their usefulness in an industrial setting is also presented.

Chapter 6 derives a model of the design process based upon a consideration of existing design process models together with the case study results. A case for improvement to existing models of design is presented, together with two metrics that allow design management to assess design complexity and yield.

Chapter 7 describes the value and use of the author's model in relation to company best practice and to CAD tool utilisation in electronics product design. The value to designers, their management, the CAD tool users and to a company as a whole is discussed.

Chapter 8 defines the functional specification details of CAD tools that are required to implement the requirements.

Chapter 9 concludes the thesis with a discussion of the limitations of the existing work and potential further work.

1.4. SUMMARY

The background to the EDT project and the work to be undertaken in this particular thesis has been presented.

The contribution of this thesis is highlighted by the development of a functional specification which will enable both users and vendors to specify a resilient design capability which supports best practice. Detailed investigation of the research literature and discussions with the leading CAD tool vendors and users of tools indicated that surprisingly no such specification exists.

Unfortunately it is now becoming increasingly evident that the lack of a functional specification is causing considerable difficulties as vendors become unable to respond to new requirements.
A detailed generic model of the electronics design process is also developed that builds upon a literature review of existing models of the design process. It also reflects aspects of design best practice gained from visits to over 20 companies engaged in electronics product development world-wide.

Current theoretical models of the design process define and develop activities concerned with the technology of design practice. It may be seen that these are all limited in their industrial application by their failure to explicitly link design with the commercial demands of manufacturing and product development. Unfortunately this is a significant short-coming and one that in this thesis seeks to explicitly attack and resolve.

Company design control, integrated design documentation and design scope limitation are all important in the overall process of design, yet current CAD tools fail to adequately support these desirable features. Until CAD tools can address these practical issues electronics design will continue to be dogged by management and communication problems.

1.5. REFERENCES FOR CHAPTER 1.

[1] Personal communication Paul Francis, senior CAD tool consultant, Racal Redac, 1990
CHAPTER 2. METHODOLOGY

2.1. INTRODUCTION

Data was collected through a combination of literature survey, industrial visits and discussions with design staff of system vendors. The literature survey covered design theory, CAD tool support and their usage.

The industrial visits were carried out through a series of structured interviews with engineering designers, their management and production management. The literature survey placed the industrial visits in context with current design research.

The aim of the company visits was to provide data on the spread of design activity, the design tools used, their problems and limitations, and also to derive a set of industry best practices for electronics product design.

The methodology employed in this data collection phase was derived to provide the data upon which the author's design process model and functional specification were based. Structured interview techniques were employed as the main data collection tool. Each interview normally lasted 3 to 6 hours with at least four senior design and production personnel in each electronics company.

2.2. LITERATURE SURVEY

The literature survey was carried out to underpin the industrial visits. This covered a number of research areas and concerned the acquisition of both theoretical and practical knowledge. The survey covered industry best practice, current design practice, CAD tool usage and limitations, design theory and process models and finally theoretical and practical considerations of CAD tool functional specifications.

Literature concerning international best practice was sought, obtained and used as a yardstick against practices and procedures uncovered during the industrial visits.

Design practice knowledge was sought from a variety of sources including British Standards, text books and from consultants in the field. CAD tool usage and limitations was
similarly sourced, with additional material being obtained from senior design and management personnel in the top two CAD tool suppliers in the world, Mentor Graphics and Racal Redac. In addition direct contact was made with the CAD tool Framework Initiative in the U.S, a group sponsored by the CAD tool industry, who are developing integrative framework specifications for a common base platform for CAD tools.

Design process theory was sought from a wide variety of sources. It was noted that a large proportion of the publications concerned the process of mechanical engineering design and architectural design, with little information being found on the process of electronics product design. A review of the relevant publications is presented in chapter 5.

Finally a review of existing CAD tool functional specifications was undertaken. This task was thwarted, however, for upon consultation with a number of leading CAD tool vendors, it became apparent that comprehensive functional specifications had not been employed in CAD tool development programmes. However, specifications were obtained from other related areas in for example Information Systems.

2.3. INDUSTRIAL VISITS

In order to establish a base-line for the work, the author identified current technical approaches to electronics product design, as well as to the management of the design-to-manufacture cycle, through a series of in-depth structured interviews with senior design and production staff at eighteen UK and mainland European electronics manufacturing firms. Similar case study visits were undertaken by the project team to eight leading U.S., Japanese and Korean electronics companies and research institutes. This trip, which was jointly funded by SERC's ACME Directorate and Mentor Graphics (UK) Ltd., investigated the state-of-the-art in product design in a sample of leading electronics manufacturers in the United States, Japan and Korea. Companies and organizations visited are described in outline in appendix 1 .

Although the case study survey and the world trip results are the results of visits to a small number of companies engaged in electronics product design, care was taken to make the sample as representative as possible. For example, the industry was broken in to broad
Methodology

sectors (automotive, aerospace, process equipment, consumer products) and the major CAD tool vendors were requested to provide names of companies that had purchased CAD tools recently and who were regarded as "good sites" (by CAD tool vendors within the U.K). Both the Department for Trade and Industry and the major CAD tool vendors were also asked to recommend companies with world beating techniques in electronics design. They could not supply one UK based company name, stating that no one company had "got it right", but there were several companies that seemed to have aspects of their company design strategy under control and were showing signs of "excellence in design". The number of companies contained in the lists drawn up numbered fourteen, a capacitor manufacturer and an integrated circuit manufacturer were also added, to allow comparisons of primary and secondary component manufacturers. Divisions of two large multi-national European companies were also visited, making the total eighteen. Adding the USA, Korean and Japanese company visits a total of 26 companies is obtained.

The author maintained a close contact with leading vendors, their customers and companies engaged in electronics product design. This was time consuming, but it ensured that the issues and problems suffered by electronic product designers in industry have been explicitly addressed.

In addition to the above study visits data on the short listed companies competing for the UK Engineering Design Award was obtained and the senior designer of the winning company (Technophone) of the 1990 award was interviewed to ascertain the process of design within this award winning company.

Questions were chosen to gain an in-depth understanding of how each of the case study companies currently develops its products. To that end, a research question set was developed, tested and refined as the case study visits progressed. Interviewees were questioned regarding, among others, organisation strategy, the position of design within that strategy and the organisation's overall approach to product development. Particular emphasis was placed on establishing the methods used to control the product development process and on design methods.
Interviewees were also asked, where relevant, to reveal details of their manufacturing methods, quality programmes, information storage and distribution methods as well as their approaches to production and marketing.

As far as possible attention was focussed on identifying problem areas, though examples of engineering design “Best Practice” were also sought.

In summary information was sought in the following areas:

- Nature of design tools used and problems with their use
- Integration of design function with other computer-aided parts of the organisation
- Design environment/company culture
- Design methods
- Risk assessment at conceptual design stage
- Simulation techniques/software used
- Engineering change control policies
- Design/production interfaces
- Component policies
- Standards –ie. ISO9000 and environmental impact of different manufacturing approaches
- (JIT,OPT,MRPII) on the design function

This information was obtained using a template of questions to force a structure on each interview, but within the structure some open-ended questions were asked. Please refer to appendix 1. for specific details of the questions template.

### 2.3.1. UK and European Visits

Data was collected through lengthy semi-structured interviews, usually lasting between 3 and 6 hours, carried out at each of the organisations listed in Appendix 2., table 1.

The companies visited varied in size from very large firms down to medium- and small-size concerns. The interviews were ordinarily conducted by two members of the EDT research team who, together, questioned up to four design and production managers at a time. In only two cases were Managing Directors available for questioning.
2.3.2. Overseas Visits

Data was collected through similar semi-structured interviews, on many occasions lasting for up to two days, at each of the design sites visited. The interviews were ordinarily conducted by two members of the research team who, together, questioned groups of design and production managers and staff. As Appendix 2 demonstrates, a considerable number of very senior design, R&D and executive staff managers, particularly in Japan and Korea were identified and interviewed. In addition to these interviews, the overseas visits included demonstrations of design tools, which sparked discussion regarding their effectiveness and future development directions, as well as guided tours around production facilities.

2.4. DESIGN PROCESS MODEL

A detailed design process model was developed to aid the comprehension of the electronics product design process [3].

The model was iteratively refined and tested during the course of the research in discussion with industry design managers and engineers during the case study visits. Additional validation was sought from CAD tool consultants and from peer review in the literature.

Aspects of this model are presented in chapter 6, a fuller description is contained in appendix 3.

2.5. TECHNIQUES AND RELIABILITY OF DATA

Initially, the state of the art in engineering design was sought from CAD tool vendors and from the literature. Information on the limitations of CAD support for the design process was obtained from these sources and reported in [4] and [5]. Confirmation of these results was sought from electronics design engineers, production engineers and their management during the series of structured interviews.

Additional confirmation was sought in subsequent overseas visits to the US, Japan and Korea. Interviews conducted during these visits were primarily to compare and contrast the
design process in the UK and Europe to that in identifiable centres of excellence in design and manufacturing.

The data obtained from these visits allowed the author to comprehend the major problems facing product designers in the industry and to derive a set of Best Practices for the design process.

Questions were free-format in that only the categories of knowledge sought were defined and the actual construction of the question was left to the interviewer. This simplified the interviews since the mix of interviewees varied considerably from company to company. Questions were guided by a set of templates covering all aspects of engineering design. The template categories are presented in appendix 1.

2.5.1. Validation

Each interview generally lasted six hours and covered a number of topics. It was usual to introduce the project first, followed by a question/answer session covering the topics set out in the questionnaire. Attempts were made to ensure that all the questions set in the questionnaire were covered and adequate answers were obtained. Data collected from the case studies was validated during each interview by repeating the key responses back to the interviewees. This allowed correction of inaccuracies as the interviews proceeded.

Since at least two researchers attended each case study meeting, it was possible to additionally validate the findings by cross checking the two (or more) versions of the transcribed notes taken during each meeting.

A final validation was undertaken, by seeking feedback of the functional specification from professional designers and their managers, by peer review and also by design management criticism of the design process model.

2.5.2. Limitations

The case study data was obtained using structured interviews. This is a qualitative technique that is well established in the literature (for example: [6] and [7]) and although a
relatively small number of interviews were carried out the consensus between different companies allows the author to suggest that the data was obtained from a sufficient number of companies to make the conclusions drawn from them valid.

By holding interviews with groups of people the danger of obtaining too narrow a view of problems within design in a company was avoided. Group discussions during an interview can also reduce the occurrence of an individual’s bias and post-hoc rationalisations through group conversations and interactions.

2.6. SUMMARY

A data collection methodology has been presented. The techniques employed have been described and a discussion of their limitations undertaken.

The methodology adopted by the author sought to identify industry best practice in design as well as providing data and information used in the development of a model of the design process. The process model together with industry best practice have been used to develop a functional specification of an electronics product development CAD tool kit. The process model, industry best practice and the functional specification are described in subsequent chapters.

2.7. REFERENCES FOR CHAPTER 2.


CHAPTER 3. COMPUTERS AND THE DESIGN PROCESS

3.1. INTRODUCTION

This chapter presents a view of design practice prevalent in the electronics product industry. The data has been obtained from company visits and literature survey as discussed in the preceding chapter on methodology.

This chapter is intended to set the scene for the case study results and acts as a background chapter to a discussion of design process models.

3.2. ENGINEERING DESIGN

An overview of the electronics engineering design process will now be introduced to place into context current design practices, which are discussed in section 3.3.

3.2.1. The Design Process

The product design process, outlined in figure 1 below, as defined by BS7000 [8] is the commonly accepted standard for describing the process of engineering design. This model has been derived from extensive work on mechanical engineering design by Pahl and Beitz [9] over the past ten years (please note that only a few activities at each level in the sequence have been listed; refer to [9] for a more complete description). As can be seen from this figure, engineering design is a sequential progression of iterated steps, requiring (1) that the product specification is complete and understood by the design team (2) that the specification is examined for possible conceptual solutions (3) that all feasible concepts are explored in order to select the most appropriate solution to manufacture (4) that the concepts are developed in detail to circuit descriptions and finally (5) that the necessary documents, circuit layout and assembly diagrams and worksheets are written in preparation for manufacture of the product.
Figure 1: Overview of the Product Design Sequence

Each major phase consists of creative stages followed by subsequent stages of analysis and criticism. These stages are repeated to the satisfaction of the design team until all known problems have been identified, understood and avoidance action recommended. Approval to progress onto the next part of the design process is gained by peer group assessment and company, market and financial considerations. If Pahl & Beitz's model of mechanical design is placed into the context of electronic design a number of different activities may be seen to occur in succession. Six basic processes map across from mechanical engineering to electronic engineering, as illustrated in table 1. This mapping was presented by the author in [10].
Table 1: Outline Model of Electronic Design Process

<table>
<thead>
<tr>
<th>Design Stage</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 Understanding requirements</td>
<td>- form model of users requirements</td>
</tr>
</tbody>
</table>
| #2 Form concepts to possible solutions | - analog  
- digital  
- microprocessor  
- dedicated  
- form major blocks |
| #3 Check concepts (theory) are compatible with requirements, estimate: | - costs  
- speed  
- size  
- noise  
- note standards where appropriate  
- other engineering costs (manufacturing issues) (form fine detail where important at this stage) |
| #4 Form detailed block diagrams, define fine details, calculate: | - amplifier gains, noise  
- bit widths  
- circuit blocks - if digital do datapaths then control paths  
- ensure noise performance |
| #5 Check detail links up, calculate: | - costs  
- real size  
- real speed  
- ensure conformance to standards |
| #6 Design circuits, build and test | - ensure performance  
- ensure function  
- ensure manufacturability |

It is important to understand that the electronic circuit design of an electronics product is but one part of its development programme. Mechanical engineers, environmental engineers, production engineers, test engineers and many other company specialists ensure that the product operates correctly and can be manufactured in volume efficiently and with a high yield. A design technique known as concurrent engineering [11,12] is being employed in companies to encourage and support team based design. Concurrent engineering specifically requires manufacturing issues to be dealt with as they arise during the design process in consultation with production engineers and others; rather than being passed “over the wall” to production engineering from design at the end of the design phase. This technique has been used successfully to develop innovative products and associated production processes in parallel and is now becoming embodied in CAD tool systems as a set of procedures to share data between mechanical and electronics engineering design tools.
3.3. ELECTRONICS DESIGN PRACTICE

Electronics product design covers a wide range of disciplines, from mathematics to the physical layout of electronic circuit boards and from microwave physics to instrumentation amplifier design. It demands the skills of production technologists, mechanical engineers, electronics engineers, industrial designers, and many others, at various points in the design process. In addition, electronics products span the spectrum of design complexity, some taking the effort of a single engineer, others requiring teams of engineers to complete. So on a project by project basis design strategies can be expected to vary according to the size and scope and nature of each design task, making categorisation of design a seemingly difficult task. However, a number of common features of the design process may be discussed by abstraction of the activities normally undertaken. These may be grouped into several categories, from customer specification elucidation, through conceptual design to circuit schematic development and circuit layout plan, to build instructions for assembly, design validation and quality control. Research in this area has a long history with many of these salient points being raised and discussed by Asimow [13] amongst others in the 1960's.

The latter stages of design, from circuit design through circuit layout to assembly and production may be described and implemented in a number of different ways. The three methods predominant in the industry for achieving these tasks will now be discussed.

3.3.1. Design by prototype

Here designs have an initial customer specification, the customer may be internal or external to a company. These specifications of requirement are developed by marketing and development engineers to fit the needs of the company (often by reviewing prospective costs and profits). The resulting product specification is then translated into a schematic circuit description and built. The prototype is called a development or design prototype and is modified as necessary to correct design and fabrication faults that are discovered upon testing.

This build-test-modify loop is repeated to the satisfaction of the engineering team and at least until the product or circuit functions correctly. The circuits are then production
existing engineered to ensure the product will be easy to manufacture and test. A final check prior to trial production, called qualification, is used to check that the product meets manufacturing specifications and also its original specification, this may involve the production of a small batch of samples. This process is called design by prototyping (see figure 2) and in the survey was the most common method of designing an electronics product.

Although design management in all 18 UK companies visited during the case study recognised the need to change to mixed team design (concurrent engineering for example), only 2 companies had successfully changed their design methods, the remainder suffering from lengthy development phases common in the design by prototype method.

![Figure 2: Electronics Design By Prototyping](image)

### 3.3.2. Design by simulation

The use of computer aided design tools has, in the past ten years, allowed engineers to explore a design's functionality by simulation in computers. Such systems provide libraries of software models of electronics devices, symbolic representations of which may be planted into circuit schematic diagrams. The diagrams are then compiled to link together the models into a network and a simulator provides numerical and graphical feedback to the development engineer of the circuit behaviour (see figure 3). Simulation techniques allow
designs to be proved without the construction of any physical circuits. Although this can save money in the development process, design proving is only as thorough as the development engineer wishes it to be, and the circuit behaviours are only as good as the models of the circuit components.

![Diagram of Electronics Design By Simulation](image)

**Figure 3: Electronics Design By Simulation**

Design by simulation has recently found an expanded role in electronics design with the advent of field programmable logic arrays. Such devices are becoming commonplace in digital electronic circuits as a means of replacing discrete logic elements in compact arrays. However, they cannot be bread-boarded (by constructing functionally equivalent discrete electronic circuits) as access to their function is only via complex programming schedules based on Boolean logic descriptions of function. Simulation of these Boolean expressions is now possible and engineering design staff are purchasing these CAD tools for the specific purpose of programming these logic arrays.

### 3.3.3. Design by concurrent engineering

Design by concurrent engineering recognises that tuning a product for optimal manufacturing is important, and so places substantial production engineering effort up-front of its traditional place in the design process (depicted by the flow chart in figure 4).
The aim is to simultaneously engineer the product’s function whilst explicitly considering its manufacturability and allowing production engineers to develop the manufacturing process along side the development of the product itself. Prototypes are often built in the factory, rather than in a prototyping shop. In concurrent engineering practice this can raise the development cost of a prototype. However, significant reductions in the overall product development cost have been brought about by cutting the number of design modifications needed during the pre-production phase of a project. This is made possible by building the evolving prototype to production standard, (ie. accounting for production tolerances, test and assembly issues) rather than to the tighter specifications often found in design prototypes.

![Diagram of Electronics Design By Concurrent Engineering](image)

Figure 4: Electronics Design By Concurrent Engineering

Only 2 of the 18 UK companies visited during the case study visits had attempted concurrent engineering or (mixed) team based design. The remainder understood the need to change and were trying to develop methods of altering their current work practices.

Concurrent engineering places an additional burden on the channels of communication within a company, as more activities are able to progress in parallel than previously. This

**(Note):** A commonly used definition of concurrent engineering is held to mean that the production processes themselves are also engineered during the design phase of a project. The flow chart shown in figure 4 above does not show any process development as it is not always necessary to the product development process.

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makes communication in all its forms (speaking, documentation, memos, etc) central to concurrent engineering.

### 3.4. SUMMARY OF DESIGN PRACTICE

Traditionally, electronics design has been a remit of specialist design groups. Typically specifications of a prospective product are developed by marketing personnel and passed to design following company approval of the programme of work.

Designers working singly or in teams would then develop circuit schematic diagrams of the evolving design, these would be converted into real prototype electronic circuits by wiremen and women constructing the necessary circuit boards as defined in the schematic diagrams. Each prototype would be tested to explore the correctness of the design. Subsequent modifications, to ensure the required functions are realised, would also be performed by the wiring personnel. The design would be released to production engineering after a number of these design-build-test-modify loops had shown the design to be functioning correctly (the design by prototype cycle).

In the early 1980’s schematic diagrams were drawn by hand by the engineers themselves. Circuit board layout diagrams and track routing were also manually designed and drawn. The large amounts of information handled by people in this process inevitably led to mistakes being made, mainly resulting in wiring faults and component placement problems in the prototype. Each fault usually requiring one iteration of the design-build-test-modify cycle to correct.

Computer Aided Design tools (CAD) were developed to capture the circuit schematic diagrams and also to aid in the process of electrical conductor routing and the placement of components during the design of a printed circuit board. Developments in maze routing algorithms have enhanced the routing abilities of CAD tools for layout of circuit boards, but the testing of the circuit board is still through design by prototype. The design process was, and still is, in many industrial companies a series of mainly manual activities, with computer support tools helping to capture the schematic diagrams and to place components and route circuit wires during the layout phase of development.
In contrast to this a new technique has slowly been gaining acceptance in industry in recent years, where a prototype construction has been largely replaced by simulation of a prototype using computer based model of the circuits, so called design by simulation. The technology for the simulation of complex electronic devices grew out of the computer support tools required to aid the development of new semiconductor integrated circuits, where the cost of building a prototype was found to be very high, bordering on the prohibitive. The investment in CAD tools for integrated circuits design has a number of significant advantages over the existing design by prototype technique; for the cost of CAD tools for integrated circuit (IC) manufacturers has only had to be lower than the cost of building each modification to the design to be cost-effective. The time taken to develop circuits by simulation has also rivalled the time taken to design by prototype and has encouraged significant growth in the usage of CAD tools for circuit simulation in the IC industry.

Design by simulation is practised by a few case study companies, the other companies claiming that the designs were too complex for the simulation tools to handle, and some stating that it was quicker to build and de-bug it (design by prototype). Design by simulation is mandatory in companies that design integrated circuits, where the very high non-recurrent engineering costs make repeated prototype fabrication expensive and thus make the purchase of computer aided simulation tools cost effective [14].

Digital circuit simulators have failed to satisfy the needs of the majority of electronic engineering companies due to the complexity of many real-world designs and the need to mix digital circuits with mechanisms and analogue circuits. Both areas that are currently poorly supported by digital simulators. So, design-by-prototype is still commonplace in industry.

Of the 18 UK companies, 1 had no CAD at all and the remainder used schematic capture for circuit design and board layout. Only 1 company of the 18 was working toward 100% design by simulation, the others stating they were more concerned with design to manufacture problems than attempting to simulate their designs.
A review of publications in two relevant conference series shows that academic research in this area is pre-occupied with the development of CAD tools for the design of integrated circuits. Table 2 shows that in 1984 the emphasis was on VLSI design support and digital design tools as against high level design support tools or analog design tools. The situation has not altered recently.

**Legend:**
1. Analog cct
2. Digital cct.
3. VLSI dev.
4. VLSI fab
5. Digital place & route
6. Analog place & route
7. High level analog
8. High level digital
9. Design management - VLSI
10. Design management - general
11. PCB place & route
12. PCB reliability
13. Misc

**Table 2: Distribution of design tool papers across 13 categories: a comparison**

The extended wedges in table 2 depict the largest category of papers, for example in 1984 31% of presented papers concerned VLSI development tools and 23% dealt with low level digital circuit design tools. In 1990 at the International Conference on Computer Aided Design 25% of papers were concerned with low level digital circuit design, 22% with VLSI development tools and 20% with digital circuit place and route algorithms. In the same conference proceedings only 9% dealt with high board level design issues and only 9%
again were presenting work on analog design tools. In 1984, no papers were presented on analog design tools and only 4% concerned board level issues.

It is clear from this survey that the underpinning research necessary to support commercial computer aided design tools has focussed on digital logic technology and its underlying integrated circuit process technology. This is not surprising since, compared to analog circuit design, digital circuit technology is considerably simplified with its inherent high noise immunity and the comprehensive Boolean logic that describes its circuit functions.

Whatever design process is practised it is likely that computer support tools will be employed where appropriate to enhance the productivity of engineering staff. The next section shows how such tools are currently used and how they affect the product design process.

3.5. DESIGN TOOLS

3.5.1. Introduction

Over the past decade, company design engineers have been confronted by a significant number of work practice changes, many of which have been directly attributable to developments in computer support tools. For example, Computer Aided Design (CAD) has done much to automate the drafting office and speed the product design process. But unfortunately it has not had such an impact on company design technique, partly because of circuit board simulation complexity in the analog domain and partly because designs can often be constructed and tested more quickly than they can be simulated by computer, as discussed above. Growth in the simulation market has generally been limited to the design of integrated circuits, where high non-recurrent engineering costs have ensured that CAD is a cost-effective technique.

CAD tools for the electronics industry are widely available and quite varied in their level of support for the design activity. Most tools offer “point solutions”, providing very specific support to the design engineer. So, for example, CAD tools may be purchased to provide
Existing schematic capture, design simulation, circuit synthesis, circuit layout, circuit fault analysis, circuit testability analysis, circuit parts assembly sequencing, and test pattern generation.

Providing the glue to hold these "solutions" together has now become a priority for all the major CAD vendors, but it is anticipated that it will take some time for useful systems to evolve [15]. In addition, the CAD tool marketplace is highly competitive with software offerings being developed to run on essentially two kinds of entry level hardware: personal computers (PCs) using the MS/PC DOS operating system and workstations running on UNIX or a similar operating system. The personal computer market has a low cost of entry and at the moment only offers circuit schematic capture and limited simulation and layout facilities, although this is changing rapidly. The workstation market offers tool integration at company level, and can handle the larger data sets required for more complex design tasks.

3.5.2. Limitations of existing tools

As a general rule, CAD tools do not provide any management information in support of the design process, nor do they attempt to embody design knowledge other than in the form of circuit schematic diagrams and test vectors. Some manufacturing process knowledge, printed circuit board layout rules for example (source: Hewlett Packard), may be embedded in the tools in order to ensure that the board layout adheres to such internationally recognised standards as DIN, BSI and ANSI. However few CAD tool vendors offer this facility at present. Such knowledge may also comprise in-house "best practice". Theoretical and practical knowledge employed in the process is not held in machines and has to be captured, where appropriate, by technical authors for product production manuals and field service guides. Additionally, design "best practice", company standards and design practices are still usually held in the form of paper notes.

Nevertheless, efforts to provide a common design description language amongst vendors of CAD tools have produced EDIF 2.0, a standard which allows designs captured on one vendor's equipment to be simulated/placed/routed on another vendor's system. These developments have led to low cost design entry stations being offered to the market which
Existing

provide good design migration facilities to large-vendor kit from third party PC based tools (cf: CF3000M from Phase Three Logic for under £2,000 per node for schematic circuit capture).

3.5.3. CAD tool usage

PC-based software tools are much more widely available now and the development of Intel 486 and Pentium based machines is now perceived to put PCs on a par with workstation computers. A price/performance difference exists, however, as workstations usually embody leading-edge technology, although this distinction is now disappearing. The PC-compatible machines are normally lower priced as a result of their slower operating speed and larger market. Software written for the IBM PC or PC compatible market is normally priced on a volume distribution basis rather than being treated as bespoke packages.

It is interesting to note that PC software performance has so far followed a similar historical path to that of workstation CAD tools. Schematic capture and circuit layout programs were the first to be offered to the market. These were followed by circuit simulation tools which had performance levels commensurate with processor memory space and CPU speed. Manual routing/placement was followed by auto-routing with a bias toward moderate packing densities on the final circuit boards. It is only recently that Bills Of Materials (BOM) and Computer Numerically Controlled (CNC) interfaces have appeared in PC based products.

The sophistication of the routing software is improving as tool developers tackle analogue circuit layout. However, until the memory limits imposed on programmes under the DOS operating system are removed, very high component packing densities will only be obtained using workstation-supported software suites. It is also feasible with workstation CAD layout tools to automatically configure documentation from layout drawings and schematics, something yet to be seen in the PC tool market. PC-based tools are also limited in their ability to constrain the draughtsman's final layout with respect to the manufacturing
Existing

process, for example by limiting conductor widths or preventing buried “via holes”
(electrical connections made through the fabric of a circuit board) from being used.

Workstation machines normally have a more complex operating systems than PCs, making
them more difficult for first time users to master, although the author believes that the file
naming conventions on workstation machines balance this in part by easing document
control when compared to DOS based machines, where file names are limited to 8 ascii
characters.

All workstation CAD vendors offer thermal simulation and a text editor or document
publishing system. These, and other tools are normally added to existing software suites by
either writing interfaces to third party tools or by buying the developing company and
coupling the tool closely to one’s own CAD suite. The closer the linkage, the more
automatic the data transfer, the less human error is likely to occur.

In addition, the major CAD/CAE tool vendors all currently encapsulate their toolsets in an
integrated “framework”. The framework approach implies that a unified database is
created for each new project and that design information from the tools employed during
the project add or modify the design database in an error free way. If properly implemented
it means that a design may be archived simply by storing the database. Retrieving the design
in later years, when the component libraries employed are bound to have changed, would be
considerably simplified since the entire component data would also have been saved.
Provided the designer adheres to some ground rules, the old design should be fabricatable
upon re-issue of the design and production information.

Described in this way, implementation of the framework approach may appear trivial.
Problems are bound to occur, however, due to the rapid evolution of computing hardware
technology, which may mean that today’s machine storage formats may no longer be
sensible in the future. Ironically, the technological stability of paper may continue to make
it the simplest and best archival method, surpassing even microfiche in the length of its
shelf life.
3.5.4. Word processing editors

Word processing systems have evolved rapidly over the past 10 years. They now offer good graphical user interfaces as well as spell checking and high quality formatting procedures. Recent innovations include grammar checking and desktop publishing facilities. Although it is not appreciated by many people that grammatical checking is a very complex task, the systems that are in the marketplace are simplistic and they will almost certainly benefit from subsequent revisions and enhancements.

Word processing tools have traditionally been kept separate from CAD tools and many are developed and sold by companies not involved in engineering design software development. The separation leads to complications of use in an engineering environment, since the sophistications of schematic diagram and layout diagram checking are not available to word processing systems. This forces engineers to draw their diagrams using specialised CAD tools, yet document them using separate word processing facilities. Inevitably this leads to version control problems and transcription errors as well as penalising the engineer, who may well forget critical pieces of information that arose during the creative process of circuit design, yet were lost in the separate documentation process.

This is even true amongst the leading software packages in the field, where for example Mentor Graphics provide a desktop publishing tool that can only embed circuit schematic and layout diagrams in a document. Requiring that circuit schematic diagrams be created by engineers using independent diagram editors. This assumes implicitly that designs are always (and only) represented as schematic diagrams by engineers which is an anachronism today, now that complex diagrams may be easily created using word processing tools.

This is a significant failing of current CAD design systems.

3.5.5. Schematic Capture tools

The schematic editor is the source of a considerable amount of production information, both for layout and for documentation. In particular Bills of materials (BOMs), circuit
Existing layout netlists and circuit board dimensions provide a significant amount of the information necessary to the production of an electronic circuit. However more information than this is necessary to bring a circuit design into production. This has been ignored by suppliers of schematic capture tools, resulting in a lack of facilities relevant to designing products in industry.

3.5.5.1. Supported features

Delving deeper into this important engineering design issue, there is no doubt that circuit schematic editors currently provide designers with a wide range of command functionality, each of which falls into a number of categories. Such categories include:

(a) Human interface commands for scaling views of diagrams; for navigating around hierarchical designs.

(b) Drawing commands for specifying the shape, size, colour of component symbols and text; for copying, deleting, sizing, rotating components or text; for wiring between pins of components with single or busses of diagrammatic electrical connections.

(c) Naming commands for specifying the labels of components, electrical connections, test points, sub-circuits; for the provision of textual or graphical comments.

(d) Checking commands for checking all components have names; for reporting wires with floating ends, wiring nets or components with coincident instance names; for checking that components or sub-circuits are of the latest revision.

(e) Circuit listing commands allowing the printout or plotting of a circuit; for hardcopy or for bills of materials.

(f) Circuit preservation commands to allow circuits to be saved to computer disc, often updating a version number for each design so saved.

3.5.5.2. Unsupported features

Whilst schematic capture tools provide a dazzling array of facilities, they often lack features that are required for design management, product design and production
Existing

engineering. These features, where lacking, have to be provided by manual methods. Some are described below:–

(a) Checking of illegal electronic circuits, for example components with no wiring to their input pins or circuits with outputs joined together in an illegally wired OR configuration (called electrical rule checking).

(b) Purchase price estimates for circuit components to allow budgetary calculations for the evolving product.

(c) Estimates of manufacturing complexity and yield.

(d) Controls for the proper archiving of designs.

(e) Controls for the proper access authorisations to designs that have been released for manufacture, in order to ensure that such designs cannot be modified after they have been signed off for production.

(f) Controls to follow recognised engineering change note practices for production control of designs, i.e. numeric and alpha numeric version control.

(g) Other circuit component attributes that affect mechanical, test, environmental or production engineering. For example, a list of component height information would be of great value to the enclosure designer, as would an estimate of thermal output of a circuit in the early stages of design.

(h) Ancillary information relevant to the circuit design and the decisions taken by the design engineers that would be of value to technical authors or test engineers, for example.

Additionally, storing information and data in computing systems in a manner that ensure that both humans and computers may both access it with ease.

3.5.6. Circuit Simulation Tools

Electronic circuit simulation has fragmented into a considerable number of niche markets. These include digital simulation, analogue simulation, mixed digital/analogue simulation...
Existing (mixed mode), digital signal processing (DSP), electro-magnetics and microwave simulation. Discrete time simulation (for digital modelling) of Boolean logic is static in development terms in commercial products at present, with most recent enhancements conferring portability or the adoption of standard interfaces upon the simulation tools, for example as part of the CFI development programme. Continuous time simulation is almost universally performed by Berkeley Spice (the industry standard), a device level simulator.

All personal computer continuous-time simulation tools interface to Spice running as a batch process. Commercial products based on Spice, for example Hspice or Pspice together with other enhancements of the Spice standard, offer improved simulation speed and better convergence than Spice itself and are gradually replacing Spice in the discrete device simulation market.

3.5.7. CAD libraries

A major short-coming of CAD tool usage is that the libraries of components employed by designers must, for many designers, be up to date and hold a comprehensive set of the latest technology devices. To allow complete 'design by simulation' such libraries need to hold device simulation models too.

However, due to the time consuming nature of developing the complex software models for today's complex integrated circuit devices the library models can never be immediately available for the newest devices, nor can they be completely error free.

In practice companies that attempt to lead the design revolution by employing design by simulation tools pay a penalty not only in the financial cost of these latest models, but also in extended design times due to faults in the software models of the devices they are attempting to simulate.

This state of affairs cannot only be solved by CAD vendors offering 'hardware models' of components, where the functionality of a new device is derived directly from a sample of that device, but the timing parameters are obtained from the manufacturers data sheet. This works well for digital devices (apart from the high cost of such hardware development systems), but no equivalent is yet available for complex analog devices.
3.5.8. Logic Synthesis

A significant growth area in digital design techniques has evolved from logic compilation, a technique allowing a library of sub-circuits to be flexibly combined by a circuit definition written in a hardware description language. Logic synthesis is a similar technique in which the circuit optimisation is much improved, allowing certain engineering costs to be traded off in the automatic design process. Hence, for example, circuit power consumption may be traded off with circuit silicon area and allowing designs to be synthesized in weeks of computer time rather than months of designer time.

A high degree of sophistication can only be fully realised in full custom integrated circuit design, however, since ultimate control over the circuit parameters can only be made at this level of design detail. All the major vendors have some form of logic synthesis tool, some are specifically full-custom, some are specifically semi-custom. GEC-Plessey Semiconductors, for example, offer Gatemap as a logic synthesis tool for gate-array designs. Logic synthesis tools are currently limited in their ability to insert test logic structures, thereby allowing good fault detection coverage of the synthesized circuits.

Recent developments in digital signal processing can allow such circuits to be described and simulated in a graphical environment. The logic description so derived can then be fed into a logic synthesizer, thereby generating a full custom integrated circuit, for example from an ELLA (a hardware description language) description to LOCAM (a logic synthesis tool from Philips).

3.5.9. Layout and Routing

Circuit layout and routing tools have been among the most successful CAD tools from the point of view of electronics product manufacturing companies. They have revolutionised drafting offices throughout the world and enhancements continue to improve the functionality of products offered to this market. Personal computer systems can cope with large designs, but do not offer such wide ranging facilities as workstation tools. For many applications this is not important, however, since many companies just use the CAD tool to
Existing manual tape methods of component placement and track routing of a printed circuit board.

Nevertheless, many routers are poor at layout due to their lack of specific knowledge of analogue or high speed digital circuit design constraints. They are thus only able to perform well on low and moderate frequency digital designs. Furthermore, some layout and routing software suffers from an inability to constrain the routing and placement process. This kind of weakness can easily lead to the definition of circuit configurations which are difficult to fabricate and which result in low product yields. This is an important consideration, particularly where software tools are expected to replace expert draftsmen.

Other limiting factors include the number of wires/components or via holes possible and the lack of availability of certain types of output format. Gerber output is the de facto standard, for example, as it is the most common type of photoplotter. The ability to produce drill tapes should also be a standard offering since manual intervention in this area can lead to very costly iterations in circuit board versions.

An additional source of concern with regard to layout and routing tools is the quality of the library information which is being offered as standard. Surprising difficulties can be encountered when attempting to add a new component profile into the CAD tool. An example of this kind of problem concerns uncertainty over whether screw holes be labelled as such, thereby preventing the routing software from regarding the screw hole as an electrical connection. In some layout tools this is impossible to specify.

A recent report by McLeod [15] puts revenue for CAD tool vendors for integrated circuit layout tools at $2,216 million for the year 1991, compared to $637 million for circuit board layout tools. Dataquest are quoted (in [15]) as predicting a continuing 23% growth in the integrated circuit layout tool market as against a 17% growth in circuit board layout tools. McLeod suggests that the reason for the shortfall revenue for circuit layout tools (in what is a larger potential market than for integrated circuit layout) is the lack of integration between tools in CAD vendor design suites. Francis [16] in a personal communication suggests that circuit board development tools fail to meet customer needs in the productionisation of an
existing electronic circuit board. Currently Racal Redac lead this field with a number of software products to help circuit board assembly and layout tasks.

3.5.10. Computer Aided Software Engineering Tools

The underlying philosophy behind Computer Aided Software Engineering Tools (CASE) tools is the creation of an environment in which the design task is made explicit at an early stage in the development cycle. This means that the software engineer’s task is not just “coding” but also involves “problem solving”. In addition, a historical record of all CASE supported projects should make it possible, in time, for software designers to improve their estimates of the cost of particular software projects [17]. As usual this gathering and reuse of such information must be undertaken in the light of experience. The difference now is that records of project progress, problems and failures may be captured in a more formal way than has been possible in the past.

It has belatedly been recognised in the electronics industry that, just as planning, documentation control and the generation of drawing revision histories are central to product design and manufacture, the adoption of a structured approach is of crucial importance to the development of the software embedded within today’s electronics products.

CASE tools may improve code re-use [18], but this is obviously dependent on the nature of the software project. Where real-time operation is required, for example, code optimisation would be necessary in each project to ensure maximum processing speed and an adequate response to real-world interactions.

3.5.11. Conceptual Design Support

Models of the electronics design process, for example BS7000 [9], describe hierarchical refinement of design, from conceptual, through behavioural, functional and finally circuit level descriptions. In practice, the early conceptual designs will have elements of lower level descriptions, where these are appropriate. However, although circuit level CAD tools exist and functional and behavioural languages provide modelling and description facilities at the intermediate layers, there is little support for concept formation.
Existing

What is clear, however, is that both mathematical tools and abstract black box simulations are needed. The former are provided by commercial products such as Macsyma and Mathcad, the latter by Saber, Ella and Helix and VHDL. Although VHDL supports only digital functional and architectural designs.

Only one case study company had attempted to use high level functional modelling at the conceptual stages of design. Design engineers commented that a lack of formal methods to convert such high level descriptions of product function into lower level circuit descriptions prevented the technique from being useful.

3.5.12. Links to Other Parts of the Business

Achieving success in the modern competitive business environment requires investment in a range of advanced manufacturing techniques. On the hardware side, these might include CAD/CAE systems, automatic insertion machines, automatic test equipment, robotic assembly and conveyor systems and flow or re-flow soldering equipment. Effective production control, on the other hand, could involve adoption of either a MRP/MRPII or a Just-in-time approach (or, more likely, a mixture of the two). It might even be appropriate to use the Optimised Production Technology approach in situations where there are critical bottle-necks of resources.

The point is that different tasks will need to be run on different — usually interconnected — computers which, typically, will have been purchased from different vendors. This disparity in machine types significantly increases the difficulties involved in connecting them together so that data can be rapidly, accurately and intelligibly moved between applications. Considerable work has been undertaken to alleviate these problems. In particular, the International Standards Organisation has produced a reference model, known as the Open Systems Interconnection, for organising the tasks involved in communications and networking. The MAP protocol extends this to factory communications [19], although it is understood that the purchase of a full implementation may be prohibitively high for small and medium size enterprises.
With regard to printed circuit board design and assembly, on the other hand, the free flow of data both within the design area, as well as between design and manufacture, is currently hampered by the absence of any commonly accepted industry standard for defining printed circuit board (PCB) designs [20]. The Gerber plotter format, for example, while ostensibly the defacto standard for describing such board level features as tracks, pads, vias and groundplanes, comes burdened with a series of variants (inch/metric, variant decimal point positions, variable separating characters). In addition, the “standard” is unable to specify such crucial things as aperture lists and hole positions.

Under such circumstances, communication becomes possible only in the most fortunate circumstances and the solution appears to lie in the use of “neutral” files to translate from one incompatible format to another. This “solution” often results in the loss or corruption of vital data, a problem the US-based IPC is attempting to eliminate with its D-350 “Printed Circuit Board Description in Digital Form” data format standard[21].

There is an important distinction to be made between “linking” and “integration.” This is especially true in light of competitive pressures currently driving many companies towards Computer Integrated Manufacturing.

Linking usually involves the transmission of data, in a neutral format, between a series of modules, either CAD system to Computer Numerical Control machines, for example, or between two CAD systems. For this to occur, software is required at both ends first to convert the data into its neutral format and then to re-convert it in the receiving module. Between CAD and Computer Aided Manufacturing (CAM) such links are becoming increasingly formalised through the adoption of such standards as the Initial Graphics Exchange Specification [22].

Integration should be seen in a much broader context than linkage, in that it allows genuine two-way communication between modules. Therefore, in addition to the CAM user accessing the CAD geometry, for example, integration allows designers to access CAM module tool files, thereby improving design-for-manufacture as the CAD user designs for the tools currently available. The importance of this issue is highlighted by recent research
findings [23] which indicate that one of the principal factors contributing to Computer-aided Production Management system failure is unanticipated change in integration requirements. The research cites a number of the case study companies which were forced, by hardware and software incompatibility factors, to replace expensive Computer-aided Production Management systems when it became apparent they would not integrate with existing Sales Order Processing systems, for example, or with new CAD systems.

Developments currently taking place in Electronics Design Automation frameworks are clearly moving the electronics industry closer to the “Holy Grail” of integration though it will be some time before anyone is able to offer a completely integrated Electronics Design Automation system, particularly one which is affordable to SMEs.

3.5.13. Electronic CAD tool Frameworks

While the array of sophisticated electronics design automation (EDA) toolsets currently on the market have all been designed to ease the engineering task of developing complex electronics products, they all suffer from being essentially “point solutions” to specific design problems. Until recently, EDA vendors have made little effort to provide the “glue” necessary to seamlessly integrate the various software tools.

That situation has changed dramatically over the last few years. The electronics industry is now beginning to witness the emergence of electronic CAD “frameworks”, system software packages which permit the use of multi-vendor design tools in one tightly linked environment [24]. Such frameworks have also been defined more widely in [25] to include “all of the underlying facilities provided to the CAD tool developer, the CAD system integrator and to the end-user (integrated circuit or system designer) necessary to facilitate their tasks”. Figure 5 below illustrates the components of a modern engineering CAD framework.

Many of the major EDA tool vendors are currently extending their own framework technology, and the possibility exists that, in the not-too-distant future, a de facto framework standard may emerge. In 1991 Mentor Graphics, for example, released its
Existing

Version 8.0 concurrent design environment, incorporating the company’s Falcon framework. Cadence, on the other hand, had been first to market in 1986 with its Design Framework product. Others such as Valid Logic, Viewlogic Systems and even IBM, HP and Digital Equipment Corporation (DEC) have recently jumped on the framework bandwagon. In fact, DEC and Cadence have teamed up to jointly develop future design framework technology [26] as part of DEC’s “Synergy” program to support its PowerFrame design framework product.

Figure 5: Components of a modern engineering CAD framework

Cadence, in particular, was the first vendor to emphasise the task of integrating “foreign” tools into a single CAD system and managing the history of the design data. Mentor’s Version 8.0, on the other hand, is said [27] to provide a single environment, with tool collections for the major segments of product development software, logic and system development, circuit board layout and manufacture and mechanical design and manufacture. The system, which is built upon an object-oriented database management
Existing system, allows different design teams to concurrently work on a project and to interchange data. It also permits team members to monitor each others’ progress and even to use tools from the other areas.

In parallel with the ongoing framework research and commercial development activities, work is also progressing on the standardisation of interfaces to a CAD framework. The most active effort in this area is being undertaken by the CAD Framework Initiative (CFI) — an international group of industrial, government and university participants whose aim is to “develop industry acceptable guidelines for design automation frameworks which will enable the coexistence and cooperation of a variety of tools” [28]. Other work in this area is being carried out by a variety of European and international research groups, for example JESSI [29] and STEP [30].

Despite the massive investment currently being made in framework development, however, it seems unlikely that a truly easy-to-use, complete and fully functional framework will ever be brought to the market. Underlying technologies, as well as our understanding of the nature of the electronics design problems, are all evolving far too rapidly for any system to meet all user and CAD tool needs for very long.

3.5.14. Bill of Materials Linkages

The centralisation of product information in the bills of materials (BOM) represents a potential link in the business integration chain, particularly since, in most companies, such information represents a common thread running through the business activities. The problem with viewing the BOMs in this light is that they have traditionally been used to *define products*, either for engineering department use or as a means of gaining customer approval. They have also served to inform manufacturing how to put the product together and to allow accounting to cost the product [31].

Recently, though, BOMs have increasingly been used in product planning and in factory scheduling, uses made necessary by the increasingly competitive environment in which companies must attempt to predict what the customer wants and then provide products which reliably meet those needs. Increasingly, though, leading edge companies are actively
Existing

seeking to understand and meet the "latent needs" of their customers — those products which customers might truly value but have never experienced or would never think to ask for [32].

The quality of those predictions will directly affect customer service and company inventory levels, particularly in the case of consumer products which are usually completely assembled and distributed before a single sale is made. If the predictions are accurate, the customers will get what they want and inventory levels will be low. Where the predictions are bad, on the other hand, customers will fail to buy and stocks will remain high, with potentially devastating consequences for company profitability, cash flow and return on assets.

Hence it is quite clear that, to be truly integrative, BOMs (and the product structure data they contain describing the relationships between products) must reflect a variety of organisational viewpoints. For example, the structure of a product from an engineering point of view is often related to the way engineering drawings are decomposed [33]. From the viewpoint of manufacturing/assembly, on the other hand, the BOM structure should reflect the way in which the product is being manufactured or assembled, while in the case of goods flow control, it important that the BOM structure indicates the flow of goods within the company. The sales department, meanwhile, is primarily concerned with the final products which are available for selling and accounts may use the BOM as a tool for calculating product costs [33].

Unfortunately, the fact that current computer-based BOM processing systems are mostly unable to support such diverse functional product structure data requirements [33] makes use of BOMs as an integrating tool difficult.

3.5.15. Links to Machine Tools

A number of machine tool linkages exist, either in actual or potential form, although many are currently implemented as manual interfaces. The only defacto standard layout tool to photo-artwork is GERBER format, developed by the leading photoplottler company of the
same name. Circuit board panelisation is offered by most CAD tool vendors but only affects photoplotter artwork and drill tape list construction.

On the other hand, ASCII coordinate lists and drill sizes may be extracted from a design database in the appropriate format for a PCB hole drilling machine. Although no standard data format appears to exist, the human readable format is acceptable since the amount of data involved is relatively small. Additionally, optimal sorting of this data can save drill machine time and set-up costs.

Racal-Redac offers post-processing tools for through hole and SMD component placement, and are the market leaders in this area. The company provides direct linkages to specific machine tools from circuit board layout packages such as Visula CAM Expert. These post-processing tools facilitate component sequencing, prioritised according to component size, as well as the production of numerically controlled drill drive files. Visula also uses a database of machine description files to support a variety of pen, photo and raster interfaces. New interfaces can be quickly added by defining an appropriate machine description files in the database. The company claims to support a range of over 110 such manufacturing interfaces.

A review of current machine tool products has revealed a lack of standard data formats, defacto or otherwise. However, machine tools have become much more sophisticated and many now offer micro-computer control interfaces. As a result, a number of machine tool vendors provide assembly operation sequencing as added value software for their products, allowing machine operators to configure the machine steps from manual programming of the tool. As there are currently no defacto machine interface standards, the manual methods which have become popular have led directly to a duplication of effort in defining aspects of the machine tool operation by PCB designers, production engineers and machine operators. Manual intervention and duplication in the process has led to programming errors that could be avoided by direct electronic linkage between CAD system and machine tool.

In this respect, users of Computer Aided Engineering (CAE) equipment have been more fortunate since automation of aspects of the shop floor has forced information into CAE
Existing tools, enabling them to be used for both management purposes and shop floor control. Links from design through to shopfloor, allowing drill tapes and artwork to be transferred in machine-readable format, are haphazard in the electronics sector and the control of test equipment, component insertion and onsertion machines often requires manual intervention to translate the design data into machine control coordinates. This is due to the relative newness of computer interfaces and the lack of a common standard in data formats.

3.5.16. Engineering Change Control and Release Control

Few CAD/CAM tool vendors can supply engineering change control (ECC) software, one notable system from Consilium called Workstream handles all factory floor control including ECC. Electronics product companies that do possess computer controlled ECC have had to develop it themselves, ICL [34] and ITT [35] are but two examples.

Care must be exercised when evaluating computer supported change control and configuration management systems for a number of CAD tool vendors do provide such systems, but they only provide superficial support for true factory ECC since they are, in fact, document preparation systems that provide change control of documents, but not of drawings.

CAD tool support for change control of drawings is often limited to version control of drawings in a numerical form, requiring strict manual intervention to operate alpha-numeric control. Tracking of ECC is non-existent.

The issue has been complicated by the fact that machine tool manufacturers add value to their machine tools by providing “intelligent” interfaces to ease manual programming of the tool. Often these interfaces obstruct machine transfer of data from design to manufacturing by being tailored to the human/machine interactions involved in the creation and subsequent editing of machine control files.

3.5.17. Standards

The extensive standards work being undertaken world wide, both with regard to data transmission between applications and data translation, is vital for the future development
of the electronics design automation (EDA) industry. Unfortunately, progress has tended to lag behind "real world" commercial needs, and many EDA vendors only support standards such as EDIF and IGES, for example, in order to reassure customers that they are not going to be locked into single vendor solutions. As a consequence, EDA vendors have typically adopted a two-tier approach which involves offering EDIF for translating netlist and connectivity data and IGES for mechanical data while, at the same time, providing proprietary capabilities for handling the more "intelligent" aspects of design such as library information.

While it would be unrealistic to expect the early emergence of a series of globally accepted "super standards" which have all the answers to the industry's data translation requirements, both the U.S. DoD's Computer Aided Logistics (CALS) initiative [36] and the commercial development of a variety of framework architectures offer considerable promise. The CALS initiative, with its emphasis on the use of concurrent design in future defence systems, will have a considerable future impact increasingly affect on the non-defence sectors. In the past, EDA vendors have supplied individual design tools which have been "point solutions" to design problems and, as a result, tool integration has focused on interfaces and data exchanges between these "point solutions." However, the kinds of concurrent design techniques discussed in CALS require a more global view of the design environment. This broader perspective is essential to coordinate the activities of large design teams and different design disciplines throughout the entire process.

3.6. PROBLEMS WITH CURRENT ELECTRONICS DESIGN TOOLSETS

John [37] highlights a number of current CAD deficiencies in the mechanical engineering arena which can equally be applied to electronics design support tools. He notes, for example, that CAD system designers are insufficiently familiar with design and that too many CAD systems require engineers to be computer scientists. In addition, he points to interfaces which are too clumsy, too slow and which facilitate too limited graphical interaction. Above all, however, Hongo et al [38] and Marshall [39] criticise current CAD
systems for their poor support of planning, synthesis, evaluation, conceptual thinking, decision-making and aesthetic judgement.

Marshall [40] has established that computer-based support tools have been developed principally to provide "point solutions" to specific bottlenecks in the design process with communications between such point solution products carried out through a sequence of netlist translators. Having discovered that, while computer-support tools are becoming increasingly powerful, their implementation at customer sites is often poor.

Work designed to alleviate design tool support shortcomings has been proposed by the ESPRIT Microelectronics Work Programme [41]. However, this effort has been focusing on the efficient use of existing technologies and has not addressed the needs of future generation electronics designers, particularly in regards what needs to be done to translate design into efficient manufacture. More relevant work has been carried out by SERC's Rutherford Appleton Laboratory ECAD Project [42], although this, too, has focused on the evaluation of existing electronics design tools and does not address future requirements.

There are currently a number of toolsets which support both IC and printed circuit board (PCB) design. Mentor Graphics is market leader in IC design with such tools as Quicksim, Quickgrade and Quickfault while Racal Redac currently leads on PCB design with Visula. There is, however, no single commercially available toolset which integrates these design areas despite the fact that the Open Systems Foundation (OSF) is attempting to remedy this state of affairs.

In addition, the recent emergence of new moulding technologies means that products such as telephone handsets can now be fabricated without requiring a printed circuit board to mechanically support and electrically interconnect components on a 3-dimensional surface. Circuit patterns are formed directly onto the moulded structures, thereby offering considerable advantages in weight reduction and overall assembly costs [43].
3.6.1. Long term Issues

Current toolsets fail to address the design and manufacture issues posed by such emerging technologies, however, though there can be no doubt that future electronic products will present designers with a complex mix of digital, analogue and mechanical design problems to overcome. Especially since the ingress of digital electronics into the high speed applications domain is growing, fuelled by predictions of computing power over the remainder of the decade, shown in figure 6 above.

In the long-term, however, key issues which will need to be addressed are ease of use and ease of learning, ease of library creation and maintenance, speed versus accuracy and circuit complexity, and the provision of high quality support for the design management process together with accompanying “best practice” design methodologies.
Existing

Ease of Use:
As computer support tools become more complex and offer facilities to more and more of the engineering staff of manufacturing companies, the degree of training required to allow access to a wide variety of people, each with different skill levels, is growing. CAD tools currently pay only limited attention to human-computer interface (HCI) considerations. Commands tend not to be intuitive, miss-typing is not forgiven and error reports tend to be complex, difficult to read and interpret.

Ease of library creation/maintenance:
The heart of any CAD system, whether for circuit simulation or for circuit board layout, is the library of basic components. The usefulness of such libraries depends directly upon the nature of the component information held, how easy they are to use, update and modify and upon the representation accuracy for a given library component parameter. Circuit simulation and layout component models held in such libraries require accurate timing and behavioural information for simulation as well as detailed descriptions of physical attributes such as size and topology for layout.

Market demand for systems level (digital circuits) or arbitrary analog circuit simulation will require considerable computing power. However, this problem may be overcome in the next few years as machines are developed with the levels of computing power predicted in Fig. 6 above. Specific solutions exist at present, although these are not cost effective for all companies.

Faults (bugs) in software models of real circuit devices also hamper the acceptance of new models. Until the quality control of such software is deemed adequate by the users of simulation tools a reluctance by the industry to employ simulation as a development tool for competitive advantage will pervade.

High quality support for the design management process:
Current toolsets provide engineering managers with very little computer support during complex design review activities. Good quality computer-based support, particularly for project management, would be helpful particularly in instances where projects are being
undertaken across several company sites. Design is a small part of a large process hence a key issue which needs to be addressed is the provision of management tools and techniques which can be used to control the overall design process. How do you manage a project in a distributed fashion? How do you get information flowing between people who need it? Inability to successfully manage these aspects of electronic product development is one reason why so many projects fail [44].

In addition, toolset vendors need to be more aware of the fact that intensifying time-to-market pressures in the electronics industry mean that engineering managers and designers are daily confronted by high levels of uncertainty. Whether they are having to make strategic, operational or merely tactical decisions, under conditions of uncertainty engineers can easily ignore factual information even when it is available. Instead, they may make predictions based on “heuristics” [40], which could have unfortunate business implications for the company.

Finally, design tool support for manufacture (DFM) is of paramount importance. Currently this is only partially supported by the major CAD tool vendors, with Racal Redac offering the most comprehensive support for computer aided engineering and computer aided manufacturing interfaces. Yet the best companies in the world at DFM have had to write their own support tools (which is discussed in chapter 4. as part of “Best Practice”).

Support for Best practice design methodologies:

Support tool vendors recognise that the mere purchase by manufacturing companies of sophisticated CAD/CAE systems provides no guarantee that design engineers will produce good designs. However, vendors are currently unable to advise their customers regarding how best to design, test, manufacture and support their products.

Methodological support for the product development process would reduce the amount of risk involved by providing a pattern for success. Such support would enable companies to adopt a more structured approach by drawing extensively on the lessons of international design-to-manufacture “best practice.”
3.7. SUMMARY

This chapter has developed descriptions of design practice in the electronics industry and detailed a number of short-comings of CAD tools that effect industrial design practice.

3.7.1. Design practice:

Product design in the electronics industry is generally follows one of three routes, design by building a prototype, design by constructing a computer simulation and design by concurrent engineering. Each has its market niche and is summarised below:

- **Design by prototype**
  This traditional method for design provides a serial pathway for the development of an electronic product. The iterative development loop extends to pre-production and can thus be costly (in time and man-power) when design faults are detected during the pre-production phase, requiring the design to be passed back to design engineering for re-working.

- **Design by simulation**
  Circuit simulators have failed to satisfy the needs of the majority of electronics engineering companies due to the complexity of real-world designs and the need to mix analogue and digital circuits with mechanisms and other mechanical systems. For these categories of designs it is still regarded as quicker and better to design by prototype.

- **Design by concurrent engineering**
  Concurrent engineering practices offer shorter design cycle times. However a penalty is exacted on companies practising this parallel engineering technique. An efficient and effective communication is required between all information sources and sinks within such an organisation.

  An additional burden is placed on the channels of communication within a company, as more activities are able to progress in parallel than previously. This places communication, in all its forms, central to successful concurrent engineering.


3.7.2. CAD tool limitations:

- **Word processing**
Word processing tools have traditionally been kept separate from CAD tools and many are developed and sold by companies not involved in engineering design software development. The separation leads to complications of use in an engineering environment, resulting in an implicit assumption that designs are always (and only) represented as schematic diagrams by engineers. This is an anachronism today, now that complex diagrams can be easily created using word processing tools and is a significant failing of current CAD design systems that inhibits document creation and editing by engineering staff.

- **Schematic capture**
Significantly design schematic capture has developed as a means of describing a circuit function in sufficient detail for subsequent circuit placement and routing for circuit board development, or to provide a netlist for a circuit simulation tool. This appears to have been at the expense of providing a simple and integrated design documentation system which is essential for a resilient company design capability.

- **Bills of materials**
Bills of materials derived from CAD often form the definitive build state of an electronics product. They are used by many groups within a company as data for a diverse set of activities. However, they are not afforded the same priority in CAD tools. There is no standard representation for such bills, CAD tool developers creating their own formats as necessary. CAD tools also pay no attention to company needs and fail to endow bills of material with the necessary information to them to be used as a single, well controlled, company wide database.

- **Engineering change control**
Critical to the operation of a CAD tool in an industrial setting is the ability to track design versions, to adhere to engineering change approvals and to correctly control the archiving
Existing

of designs. Systems lacking such features force design staff to either follow these controls and checks manually (with possible attendant errors) or to not adhere to any checks or controls at all!

- **Management information**

  Current toolsets provide engineering managers with very little integrated computer support during complex design review activities. What CAD tool developers fail to recognise is that design is but one small part of the product development process. Design also needs to be controlled in formal ways, as other parts of a company.

- **Best practice**

  CAD systems must be developed to embody appropriate elements of industry best practice. This not only ensures that the tools support industries best design methodologies, but that they also incorporate the appropriate human interfaces and checks as well as drawing from the correct information sources and sinks. Designers and designs must be constrained to adhere to be company best practices.

### 3.8. REFERENCES FOR CHAPTER 3.


[14] Mr. Kenn Lamb, Plessey Semiconductors, design manager (Roborough), 1991 (personal communication)


[28] CAD Framework Initiative, 4030 West Braker Lane, Suite 550, Austin, Texas 78759.

[29] Joint European sub-micron silicon initiative (JESSI), UK. contact: Professor R.A. Laws, Rutherford Appleton Laboratory, Didcot, Oxon, UK.


[42] RAL, SERC's Rutherford Appleton Laboratory, ECAD Project.


CHAPTER 4. BEST PRACTICES

4.1. INTRODUCTION

This chapter is split into three sections, the first describes product development problems in case study companies. Later these are contrasted to international best practices, as obtained from detailed interviews with companies having world class reputations in product design and development, from the U.S to Japan and Korea. And concluding the chapter a set of recommendations for UK companies is presented.

4.2. INDUSTRY PRACTICE AND PROBLEMS

The evaluation of the design-to-manufacture performance of the case study companies has been carried out using certain United States military [45] and commercial [46, 47] best practices as yardsticks. The performance categories discussed in detail are:

- Design policy
- Parts and materials selection
- Concurrent Engineering
- Configuration management
- Defect control

While it might be considered unfair to measure those case study companies operating in non-military sectors of the electronics industry against military best practices, the author feels that the lessons which can be learned are sufficiently instructive to justify this approach.

Whilst accepting that these categories are important, three other issues for discussion arise from the case study data, these are:

- Management of design
- Support for design within overall business
- Support for conceptual design

In general, the case study visits revealed that all participating companies were successful in getting their respective products to the marketplace in the face of stiff competition.
However, those successes were overshadowed by the clear evidence that they were, in most cases, obtained at considerable unnecessary cost in product development iterations caused by such factors as lack of rigour in product specification, over-the-wall approach to design and inadequate testing.

In addition, most companies in the study appear to be focusing largely on producing products which perform a function at an acceptable standard of cost. They seldom appear to be thinking in terms of design for low inventories, for example, for minimum number of parts/processes or for high yield. Rarely, also, were companies found that took a strategic view of product design. This impression was reinforced by the fact that, in some cases, designers were said to be indifferent to component costs while, in others, they were kept ignorant of the wider possible impact of their work on corporate business fortunes.

4.2.1. Design policy

A Design Policy is a statement supported by controlled engineering manuals, procedures or guidelines which attempts to reduce the risk in the design process by implementing fundamental design principles and practices. These design policies . . . should be visible and followed, with checkpoints to validate compliance and tailored to a specific project or product area [45].

A number of companies visited fared poorly when measured against this yardstick. In one instance, the company had no written account of how its products were being designed, such information having simply become a function of group memory and experience. This represented an extreme case, however, since the majority of companies were able to produce design policy documents to the research team and, in some instances, the team were permitted to take these documents away following the interview.

It very quickly became clear, however, that the mere existence of such policy guidelines could not guarantee that they would be applied in a disciplined manner by design engineers, particularly in situations where they were working to unrealistic deadlines. Examples of violated design policies include simulation not done for lack of time, customers being allowed to talk changes into specifications, product specifications not being checked for
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consistency and standards being considered last because of pressure to get the product to the marketplace.

The fact that many of the design and production engineers interviewed appeared to spend a significant amount of time involved in high-stress “firefighting” indicates that companies need to understand the causes of such dysfunctional activities and to develop appropriate policies and procedures for minimising their occurrence.

Companies registered as holding BS5750:part 1 (ISO9001) [48] for quality in the design and development process have procedures and checks in place to ensure information and data tracking during the design process. They are also required to have validation procedures to check all stages of a design development, together with the necessary control practices to allow change of design content to be tracked through the overall design process.

However there is no guarantee that the procedures and policies required by BS5750 are geared toward efficient and effective product development in a competitive environment, rather that the methods used to organise and control design are self-consistent and that the necessary checks are in place to ensure that the design is traceable. Control over what artifact is designed and exactly how that artifact is designed is outside the scope of BS5750:part 1.

Only 4 of the 18 UK case study companies possessed BS5750:part 1, indicating that control over documentation in the design process was not a priority. This reflected a more troubling attitude toward design held by many design managers, that design is a black-box activity and should not be tampered with for fear of halting the creative process and up-setting their engineers. As a result design engineers were often allowed to free-wheel within the company system, leaving design for manufacture to production engineering as part of an 'over-the-wall' philosophy.

Information Feedback:
Best practice dictates that a design policy should not be “set in concrete.” It should, in fact, be continuously reviewed and modified on the basis of lessons learned from past projects. Almost without exception, however, the companies visited lacked any formal “institutional
memory" of this sort which would easily allow lessons from past experience to be fed back into current practices. The author believes that the establishment of this kind of learning mechanism is vital to product development success though it is acknowledged that costs, both financial and human, are involved in its establishment within a company.

There was one instance, however, of where engineers were in the process of drafting a set of Design Guides to act as a kind of “best practice” manual. At the time of the team's visit, the Guides were taking the form of an 80-route decision tree which was intended to show, among other things, that small changes in design can result in large cost-reductions. In another case, the company had a paper-based system for logging errors which occurred in past projects and which was intended to help engineers avoid making the same mistakes in future.

The generally static nature of such manual systems is, of course, their major weakness. A lot of time and effort is required to gather data on design procedure errors, for example, or on manufacturing problems caused by faulty designs. The data has to be made sense of and then published in a useful format. The documents also need to be continually updated in order for them to be considered a valuable resource.

Another problem with the manual approach to information feedback is illustrated by the fact that, in one case study company, recipients of the documents often simply put them in drawers and ignored them. No attempt was made to complete the feedback loop by, say, initiating a problem discussion session amongst the engineers to ensure they all appreciated the various errors as well as the new procedures.

Major weaknesses were also identified in information feedback both from the shop floor and from field operations to the design office. Particular shortcomings identified in this regard include: information being generated but not used, the existence of large amounts of important information being held in a variety of different locations without anyone knowing what is being held where or, indeed, what value the information is to the company and engineers being denied access to cost information. These examples underline the
critical importance of effective management of engineering data and of the establishment of a single engineering database.

Smithers [49] emphasises, too, that the product creation and manufacture processes are both knowledge intensive activities in as much as a considerable number of sources of knowledge must be drawn upon in order to develop a product which meets the requirements. These processes also generate knowledge which should be made available to anyone who needs it. Unfortunately, there was as little evidence of exploitation of such knowledge as there was of effective feedback of data and information in most of the companies investigated.

4.2.2. Parts and materials selection

To ensure the uniform application of parts and materials by all design engineers, an Approved Parts List must be issued at the start of Full-Scale Development. In addition to providing design engineers with a baseline from which to select parts and materials, the Approved Parts List also serves to introduce discipline into the design process since the use of any non-standard parts or materials requires engineering justification prior to approval [45].

The companies visited demonstrated far more control in the parts and materials selection areas, though here too the research team encountered a number of glaring problems. Many of the companies visited had approved component policies in place and discipline in this area appeared to be good.

This was particularly true in the case of one company which had developed its own computer-based technology selection program which offers a list of components to the engineer. If a component is selected which has anything other than “standard” or “approved” against its entry in the component library, that fact is made visible on the schematic. The program also flags use of commercial grade components with deviations of this nature being reported in a log file for clearance at the appropriate design review.

Poor component selection practice was discovered in a company which admitted giving no encouragement to its design engineers to minimise the parts list. Indeed, the activities of a
value analysis group tended to actually push up component numbers as they attempted to
find ways of taking small amounts of money off the cost of a part without looking at wider
consequences of doing so.

Another company has left the choice of components entirely to its design engineers. They
are allowed to page through a Verospeed catalogue, select a component and have a part
number assigned to that component. The company also admitted that their computer is
unable to cross reference parts in order to identify identical parts stored under different part
numbers, that their standards department has no teeth and that the purchasing department
performs only a service function.

The case study visits also revealed little evidence of design reuse despite the fact that one
company reported £36,000 savings on new tooling for each design reused. Qualifying new
components cost the same firm around £1,000 each.

The examples provided above support the view that since parts and materials selection is an
area where best practice is already well-known, greater design discipline could be instilled
by embedding best practice in a computer-support tool. Such a tool should stand alongside
policies which make it hard, but not impossible, for the designer to introduce non-standard
parts. In addition parts approval and development of company standards should be given
appropriate authority.

4.2.3. Concurrent engineering

Concurrent Engineering links and extends the product design functions beyond individual
departments, beyond the enterprise as a whole, out into the customer and supplier chain. Its
goals are to provide more effective product designs to meet customer needs and quality
expectations, to design products and the manufacturing processes simultaneously, to
improve time-to-market and to simultaneously link producible designs to
high-productivity processes [46].

The application of the Concurrent Engineering approach to product development is
claimed [46] to offer significant benefits in terms of reductions in manufacturing startup
and preproduction costs, in product development cycles and in the number of engineering changes generated. For these reasons, it is the author's view that Concurrent Engineering is best applied to the development of innovative or strategic products. The development of both these product categories involves the taking of considerable risk by the company since many of the component materials and technologies used will be unknown, as will the various manufacturing processes required to realise the end product.

The author views the use of Concurrent Engineering far less appropriate to the development of variant products. In these products, development involves less risk to the company since production will already have evolved fabrication techniques to cope with the design and, therefore, minor changes to the design are unlikely to have a significant impact on the production line. A point shared by one Japanese company who only involved production engineering if a new design necessitated change to the production processes. Designs were carefully assessed for impact on production at all stages in a development project.

However, Concurrent Engineering principles in diluted form, perhaps as team-based design incorporating peer review procedures, can ensure that design and production engineers will work together to ensure the variants employ well-understood component technologies and can be fabricated using existing production facilities.

Appendix 2. Table 5 reveals that the organisations visited are engaged in the development of only a very small number of entirely new products each year. Since most of their design activities are concerned with making incremental improvements to existing product lines it is perhaps not surprising that the research team found only one company which had successfully adopted the CE approach. The remainder were aware of the need to eliminate the traditional sequential approach to product development, the end result of which is a design thrown "over-the-wall" to production, but each had to a greater or lesser degree failed to put the necessary procedures in place. The larger the company, the greater the difficulty appeared to be.

In one extreme case, the company concerned had experienced a "war of attrition" between design and production. Not surprisingly, the latter has lost all confidence in the former! In
another case, the research team were told that the benefits of having a production engineer involved at the front end of the product development process "are not apparent" because "manufacturing has always managed to make it somehow." The same company has a contract bidding success rate of 1:20 yet, if a bid has to be reduced, non-recurring costs such as production engineering support tend to get axed.

For another of the companies visited, the lack of a formal Concurrent Engineering approach provides marketing engineers with opportunities to suggest product solutions which are impossible to manufacture. In fact, they reported one occasion when a design review sequence had been followed for a considerable time before it became clear the product couldn’t be made for the price.

These “horror stories” indicate that there is a long way to go in the U.K. electronics industry before it can out-perform our Far Eastern competitors. The case study visits have also served to reinforce our view that top management commitment is ultimately necessary for successful CE implementation, principally because the adoption of such an approach may require major organisational change.

The strategic implications of Concurrent Engineering:
Concurrent Engineering has important strategic implications and should only be undertaken in the context of the company’s long-term strategic goals. Wilson et al [46] state that Concurrent Engineering relies on a number of tools and techniques, including Early Manufacturing Involvement, Quality Function Deployment [50], Taguchi Methods [51, 52], Design for Manufacture and Assembly. However, it is the author’s view that, while effective use of these techniques may represent critical success factors for Concurrent Engineering implementation, none of them can be used in isolation without causing considerable upstream and downstream problems. They all have organisational and human factor implications which must be considered from a strategic perspective.

Of the companies visited, only one indicated it was using a combination of these techniques, namely Statistical Process Control, Taguchi Methods and design for manufacture and assembly. Only one company said it was using Quality Function Deployment (or House of Quality).
On the other hand, most companies visited had organised their design engineers into multi-disciplinary teams (either skills-, product- or project-based). Only a limited amount of data has been gathered regarding project management methods being employed by UK and European companies, however. One of the automotive electronics companies visited manages its projects using conventional project management methods. The company, which makes no use of the project management tools it has available, undertakes regular progress and development meetings with customers. It also carries out regular deadline checks in the presence of the complete top management team.

No data was collected which indicated that any of the other companies visited managed their projects in anything other than a conventional manner. The use of goal-oriented approaches to project management were never discussed by the interviewees.

4.2.4. Configuration management

Configuration Management is a discipline applying technical and administrative direction and surveillance to identify and document the functional and physical characteristics of a Configuration Item, control changes to those characteristics, and record and report change processing and implementation status [47].

Engineering Change Control, on the other hand, is the process of controlling changes to product form, fit and function.

Configuration management is the process of tracking build states for specific products. Much information pertaining to this task can be obtained from manufacturing planning systems like MRP. However, the work is complicated by changes in the product design and manufacture that alter the bill of materials or revision level of assemblies and circuit boards.

Configuration management for military products requires a higher degree of detail than for commercial products, as component level traceability is an additional requirement making configuration management the method of ensuring that a design built at any time now or in the future can be guaranteed as being both functionally and physically the same as the original approved design.
Some companies view configuration management as the control of variant designs, where partial circuit board population or software options define the different products. One company stated that it was policy to push configuration management as far back into final assembly as possible, where production configuration was mediated through software options to a common electronics hardware product. In this way partial component population of circuit boards common to a range of products together with variant component insertion on the same circuit boards provide a breadth of products tailored to specific customer requirements.

Configuration management is commonly a paper based activity, with the raw data being derived from manufacturing planning and purchasing systems and engineering change control methods. It is also not driven from design, but from purchasing or production engineering.

4.2.5. Engineering Change Control

The success of many companies is heavily influenced by the way in which information is released from design and engineering into manufacturing and by the way in which engineering changes are processed. However, it is also true to say that, the control of engineering change can no longer be left unilaterally to engineering departments [53] since product design influences every part of the organisation, including manufacturing, marketing, purchasing and technical literature.

An effective Engineering Change Control (ECC) system, whether manual or automated, should provide accurate and timely engineering data which should be made available on a company-wide basis. It would help to significantly reduce such problems as:
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- Delays caused by copying and distributing information between departments
- Time spent collecting documents and files from different departments
- Delays caused by information issue and feedback loops between departments
- The possibility that different departments are using different information versions

To a greater or lesser extent, however, all the companies visited were experiencing difficulties managing changes to the form, fit and function of their products.

During the fact-finding interviews, questions about a company's ECC system invariably drew hoots of embarrassed laughter from interviewees who usually confessed that, among other things, their systems were entirely manual and slow to respond.

Only two companies visited had fully-automated ECC systems. Most had manual or partly automated ECC systems. One of the most successful in this area uses Problem Review Requests (PRR) to control change requests. A formal system of feedback, requiring any engineering change note to have a PRR number, handles problems and opportunities. At start of the ECC process, changes are required to have completion dates associated with them which are agreed and signed off, ensuring that checks are completed. A computer-based system, developed in-house using dBase III, is used to track PRRs and is regarded as a powerful tool which has the confidence of the staff who use it.

Another successful company had a completely computer-based ECC system. This had taken as much as 4 years to develop and control principally as a result of major problems with ECN proliferation caused by the company's use of continuous improvement techniques. They currently generate some 800 design-driven ECNs per month but claim to have no deviation or loss of information. The interviewees acknowledged, however, that the proliferation of change requests had been encouraged by the fact that they have managed to control the change process.

In another case, it was learned that, while causes of change can vary widely, current methods of measurement aren't very meaningful, making it difficult for them to interpret
such statistics. They were somewhat embarrassed to admit that they usually manage to get the big things right but make mistakes on the small things because engineers devote too little time to them. For example, in a recent design modification, a circuit board with one IC, one lamp and one switch went through eight revisions to get it right.

In the same company, there was a problem with a component not fitting the hole spacing provided for it, so a change note was raised to alter the hole spacing. Later on the component was found to be too small for the hole spacing, so another change note was raised. The real problem was that purchasing was sourcing the component from two suppliers and the different parts had different hole pitches.

4.2.6. Defect control:

There are several good indicators when an effective defect control programme is functioning. First, visible and meaningful information is posted on the factory floor. There is a distinct sensitivity to trends, as against waiting for statistical "proof" that a problem exists. Predetermined corrective action thresholds have been established and action is being taken based on those thresholds. The corrective action team receives concise data and is able to identify critical areas that need immediate attention [45].

There is no doubt that all the companies visited placed the issue of Quality Assurance high on the list of critical success factors for their respective businesses and all the companies visited indicated they had systems in place for assuring the quality of their finished products. A number of companies indicated they had AQAPS approval, while others either had, or were in the process of getting, BS5750 certification (the British Standards Institute quality standard). Three companies said they had developed their own Quality Assurance approaches and others indicated they were pressing to make employees more responsible for the quality of their own work.

While several companies sought to include suppliers in their Quality Assurance approach, incoming goods inspection is still extensively used, particularly where volumes are low. Use of TQM/Continuous Improvement techniques, Taguchi methods and the Quality Function Deployment approach was disappointingly low, particularly among the smaller
companies visited. Problems are also being experienced getting Quality Assurance metric information back to design. The existence of inadequate circulation controls prevents relevant information getting back to people who may benefit from it.

The fact that quality standards such as AQAPS imposes no requirement on companies to make meaningful use of collected quality-related data is a particularly worrying phenomenon. In one company, no quality reports are generated and nothing meaningful is done with the quality data for this reason. Yet the value of quality metrics lies in the fact that, if analysed properly, they provide the company with rapid feedback of trends in process performance caused by a design fault and resulting in unacceptable scrap and rework rates, for example. Board- and system-level test data can be used to flag a mechanical or electrical design error and detailed field failure data could highlight a supplier quality problem with regard to a particular batch of components.

In this context, computer-based mailing systems for information transfer would ensure that Quality Assurance problems are rapidly brought to the attention of, and understood by, designers, managers and engineers. Only one company visited had such a system. Another company visited did provide a similar paper-based mechanism, but it was not valued highly by the designers and engineers since the information was not readable by anyone outside Quality Assurance. The result was the recipients just filed the reports away without reading them.

4.2.7. Management of design

The management function is often difficult to define and is sometimes regarded as being effective only when the group can operate efficiently without the manager being present. Certainly management is most concerned with the organisation and motivation of people and with project deadlines. It can also be regarded as a facilitator, in communications for example.

Design management in the case study companies was quite variable in its approach. Companies most often had separate design and production engineering groups. Each were likely to be different cost centres.
It was reported from all companies with this organisation that designs were likely to be thrown "over the wall" to production for production engineering. Project delays were commonplace and individuals interviewed could frequently describe projects that had failed due to poor management and communication. For example, one company had been carrying out the circuit design of a product for many months when the team visited their works. During the group interview it became clear that the development team had not considered production test. Furthermore, during the ensuing discussions it became apparent that the product was very likely to be un-testable. This caused a heated debate amongst the works group as this new information came to light.

Perversely design appears to be considered secondary to production in terms of usefulness to many company senior management.

Also, although computer based management tools abound (spread sheets, critical path tools, word processors, electronic mail systems), few if any are integrated into engineering design systems. This separation prevents tight control of design projects where close monitoring of progress, performance and problems is required.

4.2.8. Support for design within the overall business

Although company support can be claimed for design departments, the ease of information exchange between design and purchasing or perhaps marketing or even field service can be quite poor. Case study companies demonstrated this with astounding results, for example one company prevented designers from knowing the real cost of their designs are this was considered to be competitive information and thus withheld. Another company made it impossible for designers to recall old project information and another allowed relatively unskilled marketing engineers to control the product specification process for new designs in the complete absence of engineering designers, resulting in the company's acceptance of projects that were impossible to design or make.

In this context design appears to be used by many companies as a tactical competitive weapon. Design operates in isolation from other groups within the company and is funded on a per project basis.
Special cash injections were noted, however, for investment in CAD tools. But in only three companies of the 18 UK/European companies visited was there any long term policy over CAD tools. Senior management of the remainder viewed CAD as “toys for the boys” – to keep them sweet and to encourage a higher quality intake of new employees, as the company might be seen to be “high tech.”

4.2.9. Support for conceptual design

The early stages of design are still very poorly supported by company management or even designers themselves. It was noted in the case study that design was mostly re-design, with perhaps one design per year (per company) being completely new, but often based on an existing design. Designers often were limited by their own hand, by peer pressure or a perceived time constraint, to rather cursory reviews of product concepts prior to “getting down to the real work of circuit design”.

One company only designed a new product every 2 years, alternate years being taken up by bug fixes on the existing designs. So every 2 years, when the new design cycle was started, the design group saw frenetic activity (quoted by one employee as: “running around like headless chickens as we had forgotten how to design”). This design group did not learn from past failures and also found itself without any consistency in design principle or method in the long term.

Yet the literature abounds in discussions on creativity and innovation [54 and 55 to name but two]. It is surely a human failing to ignore recommendations of good practice (through the use of brain storming, syntectics and other creative techniques) and persist in concentrating on the easier tasks of circuit design.

More is said on this matter in the following chapter on models of design.

4.3. INTERNATIONAL BEST PRACTICE

4.3.1. Introduction

Significantly, neither the US nor the Korean visits uncovered any more advanced design practices and software tool usage than those found in the UK and Europe. On the contrary,
the visits revealed that electronics firms in the US and Korea face the same kinds of problems in effectively managing the product development process as the author discovered in the U.K. and European companies it visited, and which have been reported in detail elsewhere [56].

Of the U.S. organisations visited, only Hewlett Packard in Palo Alto, California clearly demonstrated an advanced approach to design-for-manufacture. HP has developed a real-time process monitoring system for circuit board fabrication that has allowed them to parameterise the PCB fabrication process. The system, which is described more fully later in this chapter, has been built into an expert system model to allow PCB yield and cost estimates to be given to engineers at any point during a design project. In Korea engineers at one large electronics company have traditionally designed “by oscilloscope.” Recently, however, simply reverse engineering Japanese TV and VCR products has made it increasingly difficult for the company to respond to dramatically reduced Japanese product development cycles. The Korean company has belatedly realised that, to survive in business, it must develop its own new product design capability.

The Japanese company visits, on the other hand, demonstrated product design-to-manufacture capabilities which exceeded any the research team had seen elsewhere. In particular, these visits confirmed research team’s view that design must be regarded as a strategic corporate activity, that full automation of the design process should be the eventual goal and that product design can be effectively managed and controlled. Evidence of creativity was discovered in all areas of the product development cycle, but particularly in the management of the cycle across a wide range of projects. It was quite clear, too, that Japanese electronics companies do far more designing than their Western counterparts and have highly developed technological and product engineering infrastructures which operate like learning social systems. The more they design, the better they get.

The companies visited also encourage their (predominantly young) designers to design products they themselves would like to own. Hence, the focus of the design effort is increasingly concerned with the social and lifestyle context within which the products are being used, and social scientists are being consulted at the earliest stages of the design.
process. The visits also confirmed that Japanese electronics firms spend more time developing their product specifications and designing out problems than is customary in the West.

4.3.2. Design Process Management

It has generally been thought, certainly within Western electronics companies, that product design is a creative activity which cannot be managed. It is the author’s view, however, that design is a goal-directed, problem-solving process which must be managed since new product development in the modern competitive context can no longer be undertaken successfully using the previously tolerated, essentially haphazard approaches. It is vital, therefore, that senior executives of electronics companies drive the product development process, including its design aspects, and that they ensure the process is effectively managed.

Indeed, this was one of the key lessons to emerge from the research team’s visits to Japanese electronics companies. At Fujitsu’s Mainframe Division in Kawasaki, for example, an annual business plan is developed by key engineers who understand the impact the product will have on the company’s competitive fortunes. The plan, which is made in consultation with senior management, considers such issues as market trends, the need for the product and product development policy. It lists new products to be developed in that fiscal year, highlighting factors such as product performance, cost and development schedule. Quality aspects are separately defined.

This strategy document is translated into detailed operational requirements appropriate for each level in the organisational hierarchy, the end result being that each department, section and team has its own business plan for that year. Each operational unit is then allowed considerable freedom, in line with Fujitsu’s bottom-up culture which seeks to provide a free atmosphere for engineering activities, to manage its own work and to achieve the goals set out in its business plan. To keep on target, each operational unit has regular discussions on a daily and weekly basis. The entire product development group meets once a month to review progress.
4.3.3. Low staff turnover

While this kind of approach may superficially appear to be unexceptional, it is important to point out that a key factor enabling the Fujitsu Mainframe Division to disseminate its detailed business plans in this manner is its low (<2%) engineering staff turnover. As mentioned earlier, the lifetime employment system adopted by the larger Japanese corporations makes it possible for firms to trust their employees with even the most confidential information, secure in the knowledge that it is unlikely to be "leaked" to competitors. Low staff turnover can increase company effectiveness in a number of other ways, not least because it is possible for those firms to retain hard won engineering experience, which is not usually recorded either in a computer database or on paper, within the company.

In this context, all three Japanese electronics companies visited train staff using on-the-job-training systems using experienced engineering staff to teach preferred engineering techniques to novice engineers, and to pass on design process knowledge. At Fujitsu Mainframe Division, for example, they estimate that it takes one year of On-the-Job-Training to turn a graduate recruit into a reasonably proficient designer, despite the fact that Japanese engineering undergraduates are not generally taught how to use CAD/CAE systems at university.

Similarly, Toshiba places heavy emphasis on educating, training and nurturing its key people and, as part of that process, the company organises conferences for technology executives during which they discuss issues like "the use of computers in factories." Such conferences also provide attendees with important opportunities for "jinmyaku" or networking with colleagues. One result of this internal technology transfer process has been that Toshiba is now selling an air conditioning system using twin fan inverters originally developed in its heavy electronics business. The company also has an organised approach to learning from mistakes, both its own and those of its competitors, and to applying the lessons learned.
4.3.4. The UK and European experience

In both the UK and Europe, on the other hand, design management practices in a number of companies visited fared poorly when set against best practice yardsticks. In one instance, for example, the company had no written account of how its products were being designed, such information having simply become a function of group memory and experience. Even where policy guidelines had been established, however, it was quite clear that their mere existence was no guarantee that they would be applied in a disciplined manner by design engineers, particularly in situations where they were working to unrealistic deadlines.

Best practice also indicates that a design policy should not be “set in concrete,” but should be continuously reviewed and modified on the basis of lessons learned from past projects. Almost without exception, however, the companies visited lacked any formal “institutional memory” of this sort which would easily allow lessons from past experience to be fed back into current practices. While it is undoubtedly true that the incremental improvements in the primary building blocks of the electronics industry will allow many new types of electronics products to become cost-effective to manufacture, it is the author’s belief that the ability of companies to design such products will increasingly depend on their ability to harness and utilise knowledge derived from such past experiences. These experiences might also, in certain circumstances, be termed “wisdom.”

Unfortunately, such distilled long-term interpretation of knowledge is hardly ever retained by the company, but is mostly held within the heads of individuals. Wisdom can also be viewed as that mixture of memories, mostly of the classical engineering kind, which provides the engineer with a “feel” for the technology in question. A good illustration of such “feel” might involve knowing the limits of the functionality of a transistor in ways that are not often documented in design literature. Interestingly enough, while it is clear that wisdom can fail, as all those who possessed electronic valve design technology wisdom can testify, the relevance of such “old style” expertise can re-emerge in response to such modern technological developments as the field-effect transistor, for example. The usefulness of such electronic valve technology design wisdom may decline again in ten years time, however, if quantum effect devices become widely used.
In marked contrast to Japanese practice in this area, the research indicates that a 10% – 20% annual engineering staff turnover is considered an acceptable, even desirable means for Western firms to enhance their design engineering capabilities. In such circumstances, long-term corporate interests may be sacrificed to human resource policies which favour piecemeal skills acquisition, in spite of the fact that the design and manufacture of increasingly complex electronics products places a premium on retaining design knowledge and wisdom within the company.

4.3.5. Design–for–manufacture (DFM)

While the case studies indicated that many UK and European firms are good at parts and materials selection, it was clear that they tend to be poor at understanding the implications of parts and materials selection, early in the design, upon final manufacturing costs and constraints. In contrast, the author discovered at least one US electronics manufacturer which demonstrated a well developed understanding of these issues. In order to maintain competitiveness in world markets, Hewlett Packard (HP) has had to develop a detailed understanding of the relationship between design and manufacturing. The company has developed its own printed circuit board (PCB) design support tool, known as the Board Construction Advisor (BCA), which uses an expert system approach to automate the calculation of yields from early stages in the design process. An important consequence of HPs use of the BCA tool has been the removal of product cost ownership from the domain of production engineering. That responsibility now resides within the design group.

The tool incorporates knowledge derived from PCB yield curve statistics and measurements taken over a number of years. Its effectiveness also stems from the company’s detailed knowledge of PCB circuit performance, design density, thermal properties, complexity, assembly, test repair, field support and relative cost, data for which have been systematically extracted from CAM databases of actual designs [57]. Based upon an in–house design–for–manufacture manual containing, among other relevant information, design equations relating to such factors as electrical performance and PCB impedances, the BCA tool makes it possible for HP engineers to predict PCB yields and costs from as early as two months into a project.
During conceptual design, the BCA tool can advise engineers regarding the impact of size, density and technology on yield and performance. Later on in the product development path, as the design is refined in its detail prior to prototype construction, the BCA (given appropriate circuit netlists) can provide an extremely accurate picture of fabrication costs and process yields resulting from specified electrical capacitance, resistance and impedance goals.

4.3.6. Concurrent Engineering

The UK and European companies visited are engaged in the development of only a very small number of entirely new products each year. Since most of their design activities are concerned with making incremental improvements to existing product lines it is perhaps not surprising that the research team found only one company which had successfully adopted the concurrent engineering approach. The remainder were aware of the need to eliminate the traditional sequential approach to product development, the end result of which is a design thrown "over-the-wall" to production, but each had to a greater or lesser degree failed to put the necessary procedures in place. The larger the company, the greater the difficulty.

Again, in another of the companies visited, the lack of a formal concurrent engineering approach has provided marketing engineers with opportunities to suggest product solutions which are impossible to manufacture. In fact, the company reported an occasion when a design review sequence had been followed for a considerable time before it became clear the product couldn’t be made for the price.

From a Japanese perspective, Fujitsu Mainframe Division’s overall approach to managing its product development activities emphasises the management of projects, not departments. In any event, for Japanese companies the concept of the department has much “fuzzier” connotations than is traditionally the case in the West.

Project management at Fujitsu is accomplished using matrix structures with the vertical structure comprising Division, Departments, Sections and Teams. Projects cut horizontally through this structure, utilising personnel across departments as necessary. As Figure 7
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below illustrates, each manager manages his own organisation, and many jobs are related to the different projects which are managed across that organisation. The engineering department has overall control in a horizontal direction while the organisation, which may be involved in several different projects, occupies the vertical dimension.

![Diagram of Project Management at Fujitsu Mainframe Division](image)

**Figure 7: Project Management at Fujitsu Mainframe Division**

"Oblique" communication channels, such as socialising with ones former workmates from another department or going out drinking with suppliers, are considered an important mechanism both for gathering new product ideas and for maintaining the harmony of the product development team. It is taken for granted that the achievement of high quality products and timely delivery to customers can only be achieved using multi-disciplinary teams whose composition is shown in Figure 8 below. At Sony’s Semiconductor Division, too, little distinction is made between the various functional responsibilities engaged on a project. They simply organise and coordinate the people and resources required to achieve a particular target, and, in that sense, the concept of Concurrent Engineering is viewed as an artificial one.
Overall control of Fujitsu Mainframe Division’s entire portfolio of development projects is accomplished by its several engineering departments, with each engineering department involved in one or two large projects. However, while the manager in charge of the Mainframe Division is kept informed regarding progress of all ongoing projects, the managers of each engineering department retain effective day-to-day control of the projects. The effectiveness of this approach is demonstrated by the fact that, to date the company has experienced no significant product failures and, in the period 1990-1991, it reports that 97% of all new mainframe projects were delivered on time.

![Figure 8: Concurrent Engineering at Fujitsu Mainframe Division](image)

This supports some recent academic work by The Institute for Research on Learning showing that people learn more swiftly and so are more effective when they belong to overlapping communities [58].

The comparison of international electronics product design practice presented in Table 3 below highlights a number of key lessons for UK and European electronics companies which have been reported in [59, 60 and 61] and which can be summarised as follows. Firstly, the product design process must be effectively managed. This should be accomplished using matrix organisational structures and multi-disciplinary teams and
should ensure that all relevant staff are made fully aware of their own roles and responsibilities in that process.

<table>
<thead>
<tr>
<th>Category</th>
<th>Country</th>
<th>JAPAN</th>
<th>EUROPE</th>
<th>UNITED STATES</th>
</tr>
</thead>
<tbody>
<tr>
<td>DESIGN MANAGEMENT</td>
<td></td>
<td>Multi-organisation in all companies</td>
<td>Strongly organised along</td>
<td>Strong departmental</td>
</tr>
<tr>
<td></td>
<td></td>
<td>visited, multi-disciplinary in-house</td>
<td>departmental lines some</td>
<td>organisation supported</td>
</tr>
<tr>
<td>INDIRECT VS DIRECT EMPLOYEE RATIO</td>
<td>80:20 with 75% of</td>
<td>30:70 with 10% graduates</td>
<td>40:60 with 30:40%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>support staff at</td>
<td>graduates or Masters degree level</td>
<td>graduates</td>
<td></td>
</tr>
<tr>
<td>TRAINING</td>
<td></td>
<td>Strong philosophy re-training: OIT</td>
<td>Very mixed approaches;</td>
<td>Very mixed approaches;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>common; basic design skills acquired</td>
<td>no apprenticeships for</td>
<td>no apprenticeships for</td>
</tr>
<tr>
<td></td>
<td></td>
<td>through apprenticeships</td>
<td>basic skills; some evidence of</td>
<td>basic skills; tendency to buy in</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>buying in skills</td>
<td>skills and to quickly dis-</td>
</tr>
<tr>
<td>DESIGN STAFF TURNOVER</td>
<td></td>
<td>&lt;2% no key staff turnover</td>
<td>10% - 20%, including key staff</td>
<td>10% - 20%, including key staff</td>
</tr>
<tr>
<td>CORPORATE ATTITUDE TO DESIGN</td>
<td>Design regarded as one of a series of strategic activities</td>
<td>Generally design given low priority, especially in regards to investment</td>
<td>Mixed response, some took a strategic view, others gave design a lower priority</td>
<td></td>
</tr>
<tr>
<td>DESIGN-FOR-MANUFACTURE</td>
<td>DFM is the prevalent approach</td>
<td>Widely varying some DFM</td>
<td>Widely varying; some DFM</td>
<td></td>
</tr>
<tr>
<td>DESIGN TOOLS</td>
<td>2nd or 3rd generation in-house tools; some bought-in</td>
<td>Almost entirely bought-in</td>
<td>Almost entirely bought-in</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Comparison of international product design practice

Secondly, it is vital, given the complexity of modern electronics products, that engineering knowledge and "wisdom" should be retained within the company, in a form which is easy to access and utilise. Thirdly, UK and European electronics engineering companies should significantly raise the profiles of their design departments, particularly with regards to investment and training. Finally, every effort should be made to develop design infrastructures which are resilient to both current and future changes in such factors as the nature, scope and volume of the design tasks being carried out.

4.4. SUMMARY

This chapter has raised a number of points about international best practices in the design/development process of electronics products. These may be contrasted to the poor practices identified in U.K. industry. It is the author's view that a number of these problems may be reduced in magnitude or even removed from the design environment by changes in
work practices and by additions to computer support tools currently employed in the design processes.

It very quickly became clear, however, that the mere existence of such policy guidelines could not guarantee that they would be applied in a disciplined manner by design engineers, particularly in situations where they were working to unrealistic deadlines. Examples of violated design policies include simulation not done for lack of time, customers being allowed to talk changes into specifications, product specifications not being checked for consistency and standards being considered last because of pressure to get the product to the marketplace.

The fact that many of the design and production engineers interviewed appeared to spend a significant amount of time involved in high-stress "firefighting" indicates that companies need to understand the causes of such dysfunctional activities and to develop appropriate policies and procedures for minimising their occurrence.

A summary of the important points is given below:

- **Design Policy**
  Design policies should not be 'set in concrete' they should evolve by learning from past experiences. Static systems will fail to adapt to changing market or technology conditions. Formal methods of assessing and improving the design cycle time must be instituted. Companies must be learning systems.

- **Parts and materials**
  The selection of parts and materials during the design of a product must be carefully controlled. The procedures for control, approval, collation and referencing of parts within a company must be consistent (and easy to use) across the company.

- **Concurrent engineering**
  Concurrent engineering can only work in an organisation structure that does not inhibit the free flow of information within it. The information must, however, be controlled and
tracked in respect of its generation, accuracy and analysis. Electronic mail and integrated computer based documentation systems may be a solution.

• Configuration management
Companies that are able to design and build electronics products with fully automated change control and configuration management systems, are able to implement a policy of continuous change on the product design and manufacturing processes: to their competitive advantage. Engineering change control can effectively be mediated by computer.

• Management of design
Design management in the case study companies was quite variable in its approach. Companies most often had separate design and production engineering groups. Each were likely to be different cost centres. Designs were often engineered for product after they were designed.

Also, although computer based management tools abound (spread sheets, critical path tools, word processors, electronic mail systems), few if any are integrated into engineering design systems. This separation prevents tight control of design projects where close monitoring of progress, performance and problems is required.

• Support for design within the overall business
Design appears to be used by many companies as a tactical competitive weapon. Design operates in isolation from other groups within the company and is funded on a per project basis. Information dissemination and acquisition by design groups to other departments was poor.

• Support for conceptual design
The early stages of design are still very poorly supported by company management or even designers themselves. It was noted in the case study that design was mostly re-design, with perhaps one design per year (per company) being completely new, but often based on an
existing design. Designers often were limited to rather cursory reviews of product concepts prior to “getting down to the real work of circuit design”.

• Lessons from International best practice

World class performing companies highlight the need for well controlled and effective design processes as a pre-requisite for CAD supported design. In these companies design is regarded as strategic in both the increased scope of design and in the volume of designs undertaken. Significantly low staff turn-over provides a natural mechanism for design archiving and design recall. In addition effective design for manufacture in all of its manifestations is a primary goal. This has been achieved, in part, through the development of in-house CAD tools and the customisation of third party tools to suit the needs of design and production staff.

Design can be effectively managed and controlled.

4.5. REFERENCES FOR CHAPTER 4.


CHAPTER 5. MODELS OF DESIGN

5.1. INTRODUCTION

In order to create a CAD functional specification one needs first to understand the processes being carried out by engineers who design electronic products. To understand design one needs to model the activities involved in design and their precedents. This definition of the design process so obtained may then be used to form part of the specification of the CAD functional specification. This chapter reviews existing models of design in this context, chapter 6. follows where a new model for design is presented.

Electronic engineering design is complex, involves both humans and their computer support tools and is the subject of much academic research (cf: Pugh and Morley 1988 [62], Coyne et al [63], Culverhouse et al, 1991 [64] and scholarly works in, for example, IEEE DAC [65], ICED [66] and other engineering conferences). Unlike some areas of design, electronics engineering is not a mature domain, but rather a fast developing area where technological change is rapid.

Since the turn of the century designers of electrical circuits have had to understand and use several different physical properties of materials, from electro-magnetics, through hot emission vacuum valves to semiconductor bipolar transistors and field effect switching technology. Electronics circuit designers have had to develop electronic circuits during these periods of change and a number of design practices have developed over the years to support these activities.

In contrast, the motor car has benefited from a dominant design (the internal combustion engine) and new products have tended to be in terms of motor car styling or in providing new features through developments in electronics products, for example electronic ignition or anti-lock braking systems. Thus, although electronics designers only have one dominant physical effect to work with (the conduction of charge carriers through a medium), they are hampered by evolutionary and stepwise changes in the underlying technology. The efficient use of time and knowledge during the electronics design process is therefore a
particularly important factor in design cycle time and design technique and design support in electronics engineering should be understood to allow computer support tools aiding this process to be developed.

However, most work on engineering design to date has focussed on understanding the activities involved in mechanical engineering design (for example, Popplestone et al [67], Pahl & Beitz [68]), Cross [69] and Hubka [70]), and has generally centred on understanding the way in which engineers manipulate that technology, rather than comprehending the way in which engineers manipulate that technology, although Ullman [71] and Ball [72] (reported in [83]) have undertaken empirical studies on this latter question in the separate domains of mechanical and electronic engineering respectively.

A literature review of electronic engineering design research seems to indicate most work is progressing on automatic synthesis of electronic circuits by computer programme, rather than understanding the design process itself. Thus over the past ten years, research has centred on detailed circuit layout and simulation, resulting in a number of commercial tools providing specific circuit simulation and layout capabilities, for example: the systems offered by Mentor Graphics, Racal Redac, Valid Logic, Intergraph and Cadence.

Recent advances in the capabilities of these tool sets now allow an engineer to enter a circuit schematic diagram into a computer, simulate the activities of the devices in the network so created, and place and route the circuits in order to fabricate a circuit board, a hybrid circuit device or an integrated circuit. Data on thermal emissions from each component in the design allows thermal modelling of both the circuit board and the local environment it is designed to operate in. Reliability calculations may also be performed automatically on these results.

More recently, circuit synthesis tools promise to save digital engineers from having to develop detailed circuit connectivities, engineers are only required to specify the initial Boolean expression of the desired logic circuit; logic creation and layout for the integrated circuit being completed automatically. Although computer aided design (CAD) is still some way off being able to automatically synthesize digital circuits from customer
requirements, hardware definition languages like ELLA and VHDL can now be used to understand the issues and problems of conceptual design support by computer for digital electronic circuits.

Unfortunately computer support for analogue engineering has not progressed at such a blistering pace, due perhaps to the additional complexities imposed on a design by the inherent low noise immunities of analog circuits. This additional sensitivity of analogue circuits means that a physical layout of a circuit has a significant effect on the function of that circuit.

So, a plethora of CAD tools now exist to aid specific parts of the engineering design process. Unfortunately, a suite of computer support tools does not guarantee an efficient and speedy design process, nor does it ensure new products can be made in a timely manner. The case study review of twenty-seven companies around the world engaged in electronics product design (Hughes et al [73], Culverhouse et al [74]), indicates that although CAD tools are being sold as solutions to engineering design problems, they are not solving the major problems in engineering design; the more intractable problems are due to management and communication problems within companies. So, then, in order for CAD tools to improve the design cycle time they must support engineering management and communication functions in addition to the existing and specific technological processes in order to achieve this. It would, therefore, seem sensible to study the activities of the generic design process, in addition to the detail of technology support tools to further the support necessary for engineering designers.

5.2. MODELS OF ENGINEERING DESIGN

Gero [75] refers to Routine Design, Innovative Design and Creative Design in a recent discussion of artificial intelligence techniques supporting the design activity. Routine design is, in this definition, the selection and refinement of a design prototype. Design prototypes are retrieved and selected, producing instances. Instance refinement is carried out in two ways, by pruning the set of variables to the application set and by changing the values of the applicable set of variables using available knowledge. Innovative design is,
then, design prototype-instance refinement, but using an adaptation of some of the knowledge concerning the applicable ranges of variable types. Creative design uses new variables, producing new types and extends the state space of possible designs.

Henderson and Clark [76] discuss innovation with respect to the impact on components and the linkages between them. The resulting four element matrix provides four innovation categories, incremental, architectural, modular and radical innovation. Incremental innovation refines and extends an existing design, improvement occurs in individual components, but the core concepts and linkages remain the same. Radical innovation establishes new core concepts, which are linked together in a new way. Modular innovation changes the core concepts, without altering the overall structure; for example, replacing analog electronics with digital electronics. Architectural innovation modifies the linkages, but leaves the core concepts and components essentially unchanged.

Yoshikawa [77] states that design is mapped from functional space to attribute space, using one of 4 design methods, (i) one to one correspondence – the design process is a choice of existing solutions, (ii) Calculation model – all attributes have numerical values and it is possible to calculate the solution(area) from specifications mathematically, (iii) Production model – a number of generally valid production rules can be applied to transform specifications into a solution or (iv) Paradigm model – the designer finds a solution which seems to satisfy some of the specifications and then modifies (by exchange of parts) for better and better performance, until all the specifications are met. He has computerised approaches 3 and 4, and also demonstrated their operation on simple problems.

Nakazawa [78] maintains the axiom: the design that has minimum information content of the system is the most optimal design. He has developed two theorems, (a) in a good design, the independence of functional requirements is maintained and (b) Total design is superior to additional design and combination design.

Black [79] refers to four types of design work in the mechanical engineering context: Innovative design, Adaptive design, Variant design and Order execution. Black states that innovative design is concerned with elaborating an original solution for a product, adaptive
design is concerned with adapting a known product to a changed task, variant design involves modification of the size or arrangements of an existing product, and order execution requires minimal design during the completion of an order.

The German VDI 2221 standard for engineering design, resulting from significant work by Pahl & Beitz [68], only addresses one type of design process, assuming implicitly that all aspects of design variants and innovations are logically the same. Thus, the single design track forces each design to be progressed from a creative concept, its alternative representations, a selection of the optimal design and finally the detailed design of the optimal choice. Each step in the process is carefully defined as are the types of decision that should be made and the information generated at each stage. The work focuses on embodiment design to highlight the problems facing the mechanical engineer at this important stage in the process of design.

Of the design models discussed above only the VDI 2221 standard and Black's model attend to the demands and pressures of actual engineering design in an industrial setting. For example, the VDI standard requires a logical decomposition of problem from initial task to preparation of production instructions in a seven stage sequential process, in a strictly top-down manner. Cross [80] is critical of this process model as it is problem oriented rather than solution oriented. Although a focus on the problem and its decomposition into sub-problems may well be a sensible technique given that Quality Functional Deployment (QFD) [81], and more recent developments by Hauser and Clausing [82], appear to be successful methods of translating the customer requirements into engineering solutions and is used by a number of world leading companies engaged in engineering product design and manufacture.

Black's model is difficult to implement directly in the electronics sector of engineering, since his variant design (affecting the size and/or arrangement of aspects of a design) has no direct equivalent in electronics. Also, Black ignores the long term evolutionary needs of a company, which should result in investment in research that may not have direct product development as a goal. Such strategic research must form part of a balanced company portfolio in product research and development.
Models of Design

Approaching the design process from a different viewpoint, Ball [72] and Ullman [71] have studied the activities of electronic and mechanical engineers, respectively, during actual design tasks, using psychological study techniques. Ball states: "at each stage of design, then, the expert engineer is applying an iterative technique in which (1) problems relevant to a particular design level are defined and subsequently prioritised in order of perceived salience and (2) solutions for each of these subproblems are developed in turn and integrated into an overall design solution. What is particularly interesting about the expert engineer’s design approach, however, is that subproblems, once identified, are tackled in a top-down, breadth-first manner (see especially Ball’s findings [72] relating to the design methods of professional company engineers). The breadth-first approach means that the designer develops solutions to subproblems at one complete level of design abstraction before then iterating these solutions through to a more concrete level of design detail. This method is generally agreed to be very useful for accommodating the interdependencies that generally exist between sub-solutions for an overall design problem.” Ullman offers a similar dissection of the mechanical engineers design problem solving technique; a congruence that provides a strong indication that engineering design skills are similar across the two design disciplines of mechanical and electronic engineering.

However, in addition to being creative, innovative and structured in the application of techniques to the design tasks, designs must be made to a dead line and to budget. A new product design must fit into the marketing strategy of a company and ensure the continual development of ‘rising stars’ for the company product portfolio. Likewise, a company will not wish to expend time, energy or money above limits determined by financial constraints and competitive advantage. In reality, a company design project must satisfy important financial and manpower criteria as well as exceeding a customer requirements specification in order to be successful. In fact the financial and manpower constraints of a company may well dictate the way in which a customer specification is developed into a product. None of the above models account for this in their attempts to define engineering design. In addition, a strategic consideration of design must be to ensure that effort placed
upon a design project is commensurate with product competition, existing company products and at minimal long term cost to the company.

A sensible definition of engineering design is, therefore, one which attempts to minimise the costs associated with a project life, given the needs of the engineer and the creative aspects of engineering design. Thus the author proposes a four path design tree, tailored to company and engineering needs, rather than just idealised engineering needs.

5.2.1. New Knowledge And Design

All of the companies surveyed [in 73] showed little adherence to any of these models. Indeed, the case study interviews support Baker et al [83], who demonstrated that engineers tend to employ satisficing strategies to generate solutions to the problems given, rather than using structured techniques recommended by Pahl and Beitz, for example. This is not surprising, since engineering design is often time limited and pressure is often on engineers to find solutions quickly, given limited resources. This supports the notion that the company design engineer is in fact an "administrative man", a game player first suggested by Simon in 1960 [84]. An administrative man recognises that he has limited knowledge, personal prejudices, loosely defined targets and knows that he cannot conceive or comprehend all the possible outcomes resulting from each stage in the decision making process. Administrative man makes the Pahl and Beitz model of design, supported by BS7000 and DIN 2221 and recommended by the educator Chaplin [85], to be of limited value in reality. The theoretical notion of studying the principles, searching for an optimal solution and then implementing it is not feasible for most companies. Rather, what is found (in [83]) are time and knowledge constrained engineers attempting to modify existing solutions to fit new or modified requirements, to the best of their abilities.

The concept of new knowledge is linked implicitly with the personnel involved in a product design; since an engineer lacking information and knowledge of a particular aspect of a design will either fail in the specific design task, or develop a less than satisfactory implementation or be delayed as the relevant knowledge is solicited and assimilated.
Attempting to measure this potential delay or failure by assessing a crude percentage information change may not be sufficient, since an identifiable change in available information does not provide any clues toward the ability of a company engineers' ability to utilise new information. It is an ability to assimilate and understand new knowledge that is important.

This understanding is, in fact, the core of engineering principles: an engineer understands how to use materials and what their physical limitations are, the well known "engineers' feel" for the materials and devices of technology. At present there are no clear guides in measuring this ability except to assess, on an individual basis, the number of specific functions of a product specification that an engineer regards as new or unfamiliar. This will be discussed in more detail.

Newness of information may also be implicated in mistake making and project delay, as an understanding of the limitations and correct utilisation of this information may be lacking in the individuals involved in the design. Information is partially relevant to the degree of difficulty of a design, since the availability of information at critical points in the design is a factor affecting the critical path of a project.

5.3. COGNITIVE MODELS OF DESIGN

An important distinction in models of design is the separation between company and human models. So far in this thesis only engineering models have been described and reviewed. However, it should be recognised that the company process of design is accomplished by people and as such it is necessary to understand their individual and group interactions and processes.

There is a wealth of cognitive models of problem solving and human reasoning in the literature, for example readings in Cognitive Psychology by West [86]. However the bulk of the academic study in this area has been restricted to situations where the amount of knowledge necessary to complete an experimental task has been small compared to real-world problem solving tasks, so called domain independent tasks.
There are a lack of studies on domain specific problem solving and reasoning. Although research into this area emerged in the late 1960's with work by Eastman [87] on space planning tasks common in engineering and architecture. In addition there has been little investigation into cognitive processes in engineers working in the domain of electronics engineering. Although Ullman et al [71] and Jefferies et al [88] have used protocol analysis to study mechanical engineering and software engineering respectively the author is aware of only Colgan et al [89] and Ball (reported in [72, 83 and 90]) within the field of electronics engineering. Colgan, however, is more concerned with improving feedback to engineering designers who are involved in very specific technological design activities in analogue circuit designs.

Ball studied both expert electronics designers (professionals working in electronics companies) and novices (second year and final year undergraduate students). He generated problem behaviour graphs from Think Aloud (TA) traces gained during protocol analysis studies on these designers engaged in, constrained but real, design tasks. It seems that experts and novices alike design in an iterative goal directed manner. They appear to follow a personal design schema that gives them a basic strategy for design. Within this schema problems are decomposed into sub-problems (sub-goals), then solutions sought and decisions made; this is applied iteratively until the problem is solved. Experts generally follow a top-down breadth-first route through this problem/solution space, whereas novices follow a top-down depth-first route.

These observations, based on engineers problem solving in knowledge rich domains (ie. real-world problem solving), suggest that because experts search in a breadth first manner they can attend to the linkages between problems and their respective solutions at each level within this hierarchy, so generating a more optimal solution to the overall problem; whereas novices seek detailed technological answers to their high-level questions ie. always seeking direct technological solutions to problems. This is supported by Ullman et al and Jefferies et al in other domains.

This makes sense, for experts will already have an internalised knowledge (their personal experience) from which to draw pre-existing lower level problem/solution schemas from.
Figure 9 shows a trivial example of a possible problem/solution space for the design of a pencil. From this it can be seen that an expert might run through the design space breadth-first, enabling the trade-offs and constraints between the body, lead, shape and life time of the pencil to be assessed without having to perform detailed technical searches and analyses first, this does not preclude depth first forays in search of specific information or knowledge, but the predominant breadth-first approach of the expert minimises the chance of making errors in a design at points where the different sub-solutions meet within any layer in the hierarchical solution space. For example an expert in the field of pencil design would probably know the strength's of commonly used pencil body materials, in contrast to a novice who may have to derive the specific strengths of specific materials from first principles or by an information search.

![Hierarchical Problem/Solution Space for Pencil Design](image.png)

**Figure 9: An example hierarchical problem/solution space for the design of a pencil**

Referring to figure 9 again, an expert will be able to define satisfactory solutions for the pencil body, lead, shape and lifetime given his or her prior knowledge of the strengths of suitable materials, possible colours and the likely shapes of existing pencils for example. And a novice, lacking this prior knowledge, will have to carry out detailed investigations into each of these matters. The attention to each of these sub-goals in isolation makes it more difficult for a novice designer to cope with the inter-dependencies between different...
part of the hierarchy. So the chances of an expert designing a pencil with a very strong body but one that cannot be gripped in the hand are minimal, but the chances would be higher for a novice. This is domain dependent, so a novice may well be an engineer familiar with (and expert in) a different technology.

5.3.1. Reasoning and problem solving.

The psychological literature presents a number theories on reasoning and problem solving, the most relevant to this discussion appears to be mental modelling. Again a number of differing views of mental modelling are represented in the literature for example Thorndyke [91] and Johnson-Laird [92]. Essentially they develop the notions of mental models as frameworks for either (a) recognising and encoding new information into pre-existing categories or (b) building new models based upon the retrieval of existing models. These appear to represent rather static structures, and Borgman [93] extends this to a more dynamic structure that can hold both procedural (schema) and declarative knowledge (existing models). Borgman suggests that mental models are useful for making predictions and inferences about the world (analogical reasoning) rather than just enabling a reaction to a new situation. This interpretation has been applied by De Cleer and Brown [94] to suggest that engineers reasoning about engineering systems could simulate the behaviour of components in a system using mental models. In theory this allows an engineer to compare and evaluate different designs by some cognitive simulation process. This capability is intuitively obvious to engineers.

This is domain independent to the extent that the skill involved in mental modelling is acquired with experience that is not necessarily domain specific.

5.4. SUMMARY

This chapter has presented a number of models of the design process, from both the engineering and company aspect as well as from the human cognitive point of view. Looking at the engineering and company models of design it is clear that the models attend to very specific features of what is a very complex situation. Only Black and VDI 2221
Models of Design

attend to the problems found in electronics product engineering and development. The remainder focus on more specific parts of the design process or specific types of design.

The human cognitive issues on design are as significant a contribution to the design literature as are company models of designs, but have been ignored by many in the pursuit of design methodologies. This has been to the exclusion of a more fundamental comprehension of the nature of design in engineering, a topic introduced by Hubka in 1984 [95].

The descriptions constructed in this chapter add to the overall picture of engineering design developed in the previous chapter on engineering practice and the role of computer support tools. In particular it is important to note the following points:

• CAD tools

CAD tools are not solving the major problems in engineering design, the more intractable problems are due to management and communication problems within companies. So, then, in order for CAD tools to improve the design cycle time they must support engineering management and communication functions in addition to the existing and specific technological processes in order to achieve this.

• Quality functional deployment

A focus on the problem and its decomposition into sub-problems may well be a sensible technique given that Quality Functional Deployment (QFD) and more recent developments by Hauser and Clausing appear to be successful methods of translating the customer requirements into engineering solutions and is used by a number of world leading companies engaged in engineering product design and manufacture.

• Administrative man

The company design engineer is in fact an “administrative man” who recognises that he has limited knowledge, personal prejudices, loosely defined targets and knows that he cannot conceive or comprehend all the possible outcomes resulting from each stage in the decision
making process. Administrative man makes the Pahl and Beitz model of design, supported by BS7000 and DIN 2221 to be of limited value in reality.

- Human creativity

Engineering personnel may be classified according to their cognitive skills in both specific and non-specific ways. Their mental modelling and reasoning ability may improve with experience in a domain independent manner, yet their skill and creativity may be related to the depth of their knowledge of specific subject areas. Knowledge of which is retained in schemas trees whose structure and cross-linkages are crucial to domain specific reasoning ability. Engineers may be expert or novice at both of these capabilities. This will affect their faculty for creativity.

A recent survey of 656 electronics engineers [96] in the U.S.A showed only a small decline in the proportion of engineers that view creativity as the top-most factor in job satisfaction. In 1988 65% of respondents placed this top, whereas a repeat survey in 1992 showed 58% of electronics engineers felt this was the most important feature of their employment job satisfaction.

The survey result indicates that most engineers are still seeking job satisfaction by being creative. Yet as demonstrated in this thesis unwarranted creativity or innovation may present too great a risk for a company to sanction for all designs within its portfolio.

5.5. REFERENCES FOR CHAPTER 5.


Models of Design


[77] Yoshikawa, H. General design theory and a CAD system. IFIP: Man-machine Comm. in CAD/CAM, North Holland, Amsterdam, 1983


Models of Design


CHAPTER 6. A NEW MODEL OF DESIGN

6.1. INTRODUCTION

This chapter develops a new model of design that attends to the product design process in the electronics industry. It is built upon the earlier literature review of existing models of the design process and it also reflects aspects of design best practice.

The chapter is structured to present an overview of the model, followed by a more detailed discussion of the key elements of the model. This is followed by a discussion of metrics ancillary to the model that facilitate a selection process that is a major feature of the new model.

6.2. DESIGN IS NOT JUST TECHNOLOGY

The models presented in the previous chapter define and develop activities concerned with the technology of design practice. It may be seen that these are all limited in their industrial application by their failure to explicitly link design with the commercial demands of manufacturing and product development. Unfortunately this is a significant short-coming as Pugh notes in his monograph entitled “Total Design” [97].

Pugh recognises that technical design cannot occur in isolation from commerce in a company. Even design for manufacture (an often cited example of advanced design practice) requires commercial input to constrain its activities. Essentially Pugh views design as a company wide activity. It embraces marketing, sales, legal, finance, stock control, manufacturing and design. His monograph demonstrates, through the use of examples, that successful products can be developed with lower risk if the development team is cogniscent of the constraints imposed on a design by the customer and by the commercial needs of a company as well as the more obvious manufacturing constraints.

Although the case-study work carried out for this project supports Pugh’s model in this respect, it is clear that more has to be done to improve practical design. Unfortunately Pugh only reviews the issues from a distance and does not attempt to tackle any of the outstanding
problems raised in this thesis concerning communications, constraints and documentation control. In particular the effect of CAD tools and word processor usage on these processes must be considered.

The model developed in this thesis attempts to address these issues by building upon Pugh’s work in a number of novel ways.

Firstly, Pugh recognised that information control is of great value, but he fails to define methods of handling the documentation and information explosion facing companies at the present and in the future. A technique based on books, called Product Books, is developed here in an attempt to solve this problem.

Secondly, in order to control the people active in a company’s product development teams a technique is developed that partitions designs into several categories. Designs thus partitioned no longer suffer equal amounts of design effort and creativity, implied in the models of engineering design discussed earlier. Rather effort is channelled into each design according to its novelty and complexity to the design teams and to the expected amount of change experienced by the manufacturing teams.

Both concepts are developed below, but are presented in more detail as an activity flow diagram in a generic model of the electronic product development process in appendix 3. The model follows the concept of Total Design (after Pugh) but presents a more detailed set of activities and their linkages for the electronics design process in particular.

As may be seen from an overview of the new model, shown in Figure 10 below, the model follows the 5 step path from customer to product. This corresponds to Pugh’s 5 step plan from Market, Specification, Concept and Detail design to Manufacture for mechanical product development plans. However, the activities defined in the new model as shown as activities integrated throughout the company. there is no division between marketing and design engineering. It is assumed that team-based design is pre-existent and that the arbitrary divisions separating design, engineering and product marketing (for example) do not affect the operation of product development teams.
Each activity has been categorised according to the cognitive nature of the task, whether it be creative, analytic or neither (figure 11 shows the adopted notation). The approach adopted is based upon a number of widely used systems modelling methodologies, including the European Computer Manufacturers Association flow charting standard [98].
The detail of phase 1 (product concept) is shown below in figure 12 and depicts the steps involved in obtaining and validating the customer’s requirements to evaluating the market potential of the new product and finally to generating an in-house product specification.

The design process provides a mechanism for auditing the design via a series of five Release Gates, each of which is conducted by a project-independent Product Release Committee. Additional ‘internal’ gates are also provided. These gates are referred to as:

1. Initial Screen
2. Preliminary Assessment
3. Product Definition and Pre-development Business Analysis
4. Circuit review (internal review)
5. Post-layout review (internal review)
6. Pre-test Review
7. Pre-production Review
Figure 12: Generate Product Concepts

1. Customer
   Modify CPR

2. Customer product requirements (CPR)

3. Unstructured CPR
   Handled by Strategic Design Team
   Does company wish to bid for project?

4. First-cut solutions

5. RELEASE GATE 1: Initial Screen
   Test:
   - Market attractiveness
   - Market acceptance of new product
   Activities may include:
   - Discussions with key customers
   - Small sample phone surveys
   - QFD analysis

6. Hold until assessment complete

7. Customer Reaction/feedback

8. Preliminary technical analysis
   Including:
   - Does proposed product fit with internal functional strengths?

9. Preliminary market analysis
   CPR

10. Crass product commercial requirements specification (CRS)
    Specify:
    - Possible engineering solutions
    - Commercial targets
    - Financial targets and project funding
    - Staffing, project resources, organization of responsibilities etc.
    - Including issues like test (minimum requirements for customer acceptance)
    - Define engineering costs
    - In line with company strategy, policy & objectives

11. CPS
    Crass
    CRS

12. OK?
    No
    C
    CRS failed?
    No
    CPR failed?
    No
    No
    B

13. Analyse cause of rejection
    Yes
    CRS

14. Who is involved?
    What kinds of knowledge should be made available to the team?
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Figure 13: Generate Product Solutions

Generate Product Solutions

- Preliminary Assessment Report
- CPS
- No Go
- RELEASE GATE 2: Preliminary Assessment
- Go

Product Book 1
- Release CPS

Product Book 2
- Formulate Initial Product Concepts
- Establish most important functions required in design
- Group into structures

- Test Concept in Market
- Perform Competitive Analysis
- Analyse Product Concepts
- Analyse Product Concepts (Product Book 2)
- OK?
- Analyse Solutions
- Behavioural Solutions
- Analyse Solutions
- Reject concepts & solution sets that are not feasible

- Behavioural model?
- Analyse Solutions (Product Book 2)

- Conduct
- Behavioural Solutions

- Analyse Solutions
- Mismatch
- Yes

- Continue

- Requirements
  Requirements:
  Marketing
  Production
  Design
  Purchasing
  Involves:
  Preliminary market assessment
  Preliminary technical assessment
  Uses some financial criteria

- Stop

1. Handle by
2. Marketing
3. Production
4. Design
5. Purchasing
6. Marketing
7. Initial assumption
8. Preliminary audit
9. Critical

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Figure 14: Develop product

1. Analyse Solutions
   - Configure & analyse vs existing products
   - Existing vs proposed product report
   - Rough cut capacity plan
   - Solution wrong?

2. Analysis
   - Modified PDP/TPS
   - Select product development path (PDP)
   - Critical Path Document (CPD)
   - PDP/TPS wrong?

3. Modify PDP/TPS
   - TPS
   - PDP
   - Critical Path Document (CPD)

4. TPS/PDP
   - Hold until assessment complete
   - RELEASE GATE 3: Project definition & pre-development business analysis
   - No Go: Analyse problems
   - Go

5. Establish enlarged project team
   - Develop sensitive marketing plan

6. TMP
   - Project team
   - Do selected PDP

7. Product Book 2
   - Product Book 3
   - Selected PDP
   - Do PDP (A)
   - Do PDP (B)
   - Do PDP (C)
   - Do PDP (D)

8. Repeat Order
   - Variant Design
   - Innovative Design
   - Strategic Design

Pre-development business analysis report

Form: Detail Design Team
(A) Production ltd, design function
(B) Production/Design ltd
(C) Design ltd, assign production
(D) Research and design ltd, assign production

R&D team

Strategic Design Team

Customer Team

Sustainability Team

Customer Team

Electronics, Mechanics, Electronics and Software may proceed on different PDPs.
The gates each provide the company with an opportunity to formally evaluate the evolving product design in a systematic and thoroughly documented manner. Their purpose is not to monitor the progress of the project. Thus, before development is allowed to proceed further, the design must satisfy a set of audit criteria laid down for each Release Gate. Provision is also made for internal reviews, where current members of the product development team are required to check the design quality in a formal (rather than ad-hoc) manner. Reports are required for both internal reviews and for release gates. A fuller definition of the product release gates is shown in appendix 4, starting on page 354.

Further product definition is obtained during the "generate product" solutions phase of design. During this stage the putative product is analysed for competitive advantage and also test marketed. The product concepts are then re-defined in terms of desired functions and behaviours, which are subsequently critically reviewed, as depicted in Figure 13. Products that are developed by modification of existing products may not have to undergo all these checks and analyses. A product design is then critically compared to the existing product portfolio, a technical product specification is defined and accompanied by a product development path (see Figure 14). Release gate 3 allows the product to be formally assessed prior to any major budget spend or commitment by the company. Once through this gate the product starts the development process that is traditionally regarded by designers as "design", consisting primarily of circuit development, prototyping and testing.

Product development then follows one of four paths according to whether it is defined as a Repeat Order design, a Variant design, an Innovative design or a Strategic design.

6.3. FOUR DESIGN ROUTES

By considering each design project in terms of the amount of new knowledge anticipated in the design, required either by design or production engineers, provides a more useful categorisation than Black et al, Henderson & Clark, Gero and Pahl & Beitz. Important in this model is the understanding that new or novel company knowledge implies risk and difficulty to a company. Although Henderson and Clark discuss this in their paper and specifically categorise innovation in terms of new knowledge, they do not place it in the
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cost of manufacturing and design capability within a company. Yet the success of a company in being able to manufacture such designed products is an important measure of the viability of that company. This is the four path model of design, which is described in more detail below.

Starting from the simple premise that a company engaged in engineering design and manufacture profits solely from the existing products it is selling, one can observe that any cost embodied in developing a new product will reduce the company profitability, until one presumes the new product is being manufactured and is selling well.

![Figure 15 Typical product life cycle (by project expenditure)](image)

In addition, companies must hold strategic plans of new product development that enable them to compete profitably in the long term, in the markets they have chosen to offer products to. The classical product life cycle must be reviewed when planning a new product, but the amount of risk, which may be equated to percent new company knowledge must be assessed as well. Figure 15 describes the classical curves for product profit/loss over the life of the product. The normal marketing approach is to determine when to launch product B, so that the company can maintain or increase market share with its developing product range. However, if product B is developed without any real consideration for actual product development time, the launch date may be delayed. It has come to the authors attention that, on a number of occasions, products have been late to market because the project inception was not sufficiently early to meet desired marketing strategy, given the degree of difficulty of the project (from [73]). This does not mean that with hind sight the
project should have been started earlier than it was, rather that the amount of effort, the degree of support were set incorrectly.

Indeed the cost of getting a product to market six months late has been shown to be extremely high in a recent survey [99]. A problem borne out by Technophone, where the delay in introducing a new cell-net telephone to market six months late was approaching £0.5 million [100].

It would therefore seem sensible to view the design of new products in this wider company context. By partitioning company design according to the novelty (or risk) it is possible to differentiate design into 4 distinct classes or paths, each defined to provide design management that is tuned to the needs of the type of design in progress. The four design paths allow repeat orders, variant design, innovative design and strategic design to be observed explicitly by designers and management alike. The spectrum of possible designs may be represented by a graph, see figure 16, plotting percentage of new knowledge needed to complete a design on each axis. The two dimensions allow new knowledge to be
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accounted, in both design engineering and production engineering. The graph shows the spectrum of possibilities, rather than absolute definitions of each category and thus the divisions between the different design paths should be taken as dependant on particular circumstances, rather than hard and fast percentages. For the purposes of illustration, the descriptions given below refer to percentage new knowledge. These percentages should not be too strictly interpreted.

6.3.1. Repeat Order design

A new product could be a company repeat order design if there is zero (or near zero) new knowledge required to complete the product in either design or manufacturing. Repeat Order designs typically (see figure 17) involve the following functions:

- No extra design or production effort, just build more of the previously designed order.
- Cost reduction by Design and Production for parts reduction, for example modify design for ease of assembly or for increased reliability, using established design and/or production techniques.
- Design and manufacturing fault detection and correction by iterative learning.
- Optimisation of manufacturing processes that impact on the design of the product.

Theoretically, a repeat order would require no new knowledge it would just vary in volume of production run. However in reality tooling changes, refinements in manufacturing techniques and component changes could impact on this criterion to take the design from a repeat order (with appropriate timescales and costs intimated) to a variant design (on a longer assumed timescale and costs), without management or even the engineers themselves appreciating the time over-run caused by the changes. In this way unanticipated change can undermine even the best controlled production facility.

A programme of continuous refinement for repeat orders, perhaps aimed at reducing manufacturing costs, can generate large numbers of engineering change notes, potentially
causing catastrophe. Catastrophe that may be avoided by ensuring the procedures and practices are already in use on the shop floor and in design to handle this anticipated change. For example, Hitachi (UK) Ltd [101] handle over 800 ECNs per month per product, many are raised as cost reduction exercises on the production line. Hitachi (UK) control this potentially chaotic situation with a well structured, computer mediated, engineering change note system. Uncontrolled engineering change, in these circumstances, could change a repeat order design into a strategic design!

A repeat order design for an existing product does not always require any design engineering time to be expended. But, it is often the case that designs change over time, either through cost engineering exercises or through the discovery of a fault requiring a circuit revision to correct. Both require the time of a design engineer. The first since a component change introduced by production engineering or even purchasing should be assessed and have the approval of the original design team prior to implementation of the change. The recent case study, by Hughes, Culverhouse and Bennett [102], has uncovered a number of examples of production problems caused by this category of change: For example, in a recent design modification, a circuit board with one IC, one lamp and one switch went through eight revisions before getting it right.
6.3.2. Variant Design

A variant design is indicated, for example, if from one percent to about twenty percent new knowledge is required in either design or production engineering. Variant designs are the most common category of design, and should involve a higher proportion of joint development than for repeat orders between design and production engineering. The aims of the variant design (see figure 18) may be achieved, through one or more of the following operations:

- Incremental innovation by extension of existing product.
- Refinement of existing technology usage.
- Apply modified manufacturing technology, allowing variant re-design (finer lithography, for example, allows higher chip packing density or new solder technology requires different pc boards layouts for solder traps)

Additionally, within the company context, portions of a product may require different design paths to be allocated. For example, a systems design or a software configured product may already have pre-existing sub-sections, to which new extensions are added, making a repeat order for the existing portions and a variant or innovative design path for the new sections.

Figure 18 Variant Design Path
Systems design may require parts of existing products to be re-used in new designs and therefore only require making again. It may well be the configuration of such building blocks that is new and therefore will require all the preceding stages of this design process to check and evaluate the problems of the new concept. Also, with software technology tending to replace hardware and mechanical modules in products giving a new flexibility to a design; it is now possible to have a completely new product function, but employing existing mechanics and electronics; requiring only software changes to implement the new function.

Variant design in electronic engineering should be supported by existing know-how within a company and only extend it by small increments, enabling a company to follow an evolutionary development path. Such a path will enable product developments to change over a period of time, perhaps tracking market trends or incremental changes in technology. For example, a company specialising in digital process control equipment can tailor their product developments to improvements in packing density, power consumption and processing speed brought about by the advances in digital integrated circuit fabrication (see, for example, [103]). Such a company might see improvement in printed circuit board packing, reductions in power supply requirements and improvements in numerical processing performance of their circuitry. The developments will extend their design engineers’ knowledge in terms of these incremental performance figures in that they will appreciate aspects of circuit layout techniques demanded of the higher circuit operating frequencies, but they are unlikely to have to grasp unfamiliar basic principles of a new type of technology; for example to understand principles of analogue signal processing or to master completely new mathematical or algorithmic principles (such as neural networks or expert systems).

Designs in this category are more likely to have a smaller revision history during development than innovative or strategic designs; for in theory all the expertise required to develop a new variant product is held within a company and the use of this knowledge should reasonably well rehearsed in the professional engineers involved.
The boundaries of variant design are limitless and depend upon the nature of the underlying technology. If the technology is likely to be stable for a number of years, as digital logic has been and will continue to be for at least another five to ten years, then product developments can evolve by tracking advances in the underlying device physics. However, in a competitive world, other boundaries can appear. Where, for example, a competitor company develops a analogue neural network processor (with significant advantages of resilience to noise and with no process characterisation) that offers the market a completely new type of product to solve their problems. A company, developing variant products based on up to 20% modification of existing designs (as the author defines above) as their evolutionary path, may have its market removed by a competing company offering radically new technological enhancements to the customer base. The only way to avoid this event, given the speed of technological change, is to have innovative and strategic design development activities running in parallel to the variant track.

Out of the eighteen companies in the casestudy, eight stated that at least 40% of their designs were design variants, four companies had more than 40% pcb redesigns and only three said that at least 40% of their designs were completely new. Of the eleven companies that were able to provide information on their design categories, three stated they only engaged in variant design and seven regarded variant design as their main occupation. The remaining companies could not provide the necessary information on their design activities.

6.3.3. Innovative Design

An innovative design is defined as requiring about twenty to fifty percent new knowledge in design or production engineering, see figure 19. This higher proportion of new knowledge allows radically new designs to be developed using by applying one or more of the following techniques:

- Innovation by new combination of features from existing products.

- New use of technology on existing solutions, for example: convert analogue circuits to equivalent digital circuits.
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- Apply new manufacturing technology, for example; where surface mount technology has not been used in the company.

However, design innovations in this category are likely to be achieved through the use of new knowledge and know-how. Henderson and Clark discuss in some detail four different types of innovation. Incremental, architectural, modular and radical innovation are grouped together as classes in a matrix whose axes are core concepts and linkages between core concepts and components. Incremental innovation is said to reinforce the core concepts and leave unchanged the linkages. Thus, in terms of existing design expertise, incremental innovation may be classified as one driving force in developing variant designs, which are discussed above.

![Diagram of the Innovative Design Path](image)

**Figure 19 Innovative Design Path**

Modular innovation places more demands upon company engineers, as they are required to extend their know-how and skills to cover new ground. For example, a recognition that electronic signal processing may advantageously be performed using digital signal processing techniques instead of analogue signal processing techniques would require the know-how to be bought in either by training or by hiring new design staff. The latter is more common in the western nations, whilst the former is still practised successfully in Japan. Either way, knowledge has to be acquired and applied to the new set of problems created by the demands of the innovative development. Importantly, the new information will have to be assimilated and developed as a working knowledge of the new principles of operation.
The engineers embarking on this new product development will not have any prior experience to help them avoid pitfalls and inevitably mistakes will be made.

The impact of the recognition that a particular concept requires modular innovation to be carried out within a company is two fold. Firstly, the design group will have to be inculcated with novel information and will have to develop a ‘feel’ for the way in which the principles may be used and, importantly, the limitations of the theories, i.e where the application of the technology stops. Secondly, the impact of the design innovations must be assessed on the manufacture of the product. Taking a seemingly simple case, that of changing a design from analogue to its equivalent digital circuitry. The change will affect the way in which the printed wiring board is developed and populated with components, as the physical shape of the digital components may be different and require changes to the assembly processes. Production circuit testing will alter considerably, since voltages and currents are no longer meaningful, but voltage patterns in time (binary numbers) have instead become significant.

Architectural innovation, according to Henderson and Clark, is more subtle since many of the component parts of a putative design may already be available to engineers within a company. However, architectural innovation still seeks to utilise existing information and knowledge in a company and as such remains an innovative design category in the current categorisation discussed in this paper, dogma and limited company skills, however, may prevent new combinations of technology being put together in novel ways.

6.3.4. Strategic Design

Strategic designs cover the remaining portion of the continuum with over fifty percent new knowledge being applied to the problems and their solutions, see figure 20. A strategic design is often regarded as the domain of a company research group, a special section that normally does not have the pressures of commercial time scales explicitly tied to development work. The remit of such groups often requires the development of new basic principles of operation, that are defined and developed as below:-
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- Understand new basic physical principles.
- Explore limits of operation of new principles.
- Define manufacturing tolerances of new principles.
- Develop demonstrator embodying new principles.

The purpose of strategic design is to extend the design and production knowledge base of a company. It's goals are therefore seen to be different from the other three paths of design. Classically engineering research and development have not been tied to particular commercial product development programmes, but instead tied to demonstrator products that are then handed over to development and production engineering to turn the prototype into a production engineered design.

This lack of familiarity with commercial development requirements and procedures, and an all too frequent physical separation of strategic development staff from the 'cutting edge' of manufacturing in a company can lead to a mis-understanding of the role of a strategic development engineer, both in the eyes of the development and production engineers and the research engineers themselves. This leads to communication barriers being formed between the groups and to the 'passing the buck' of problems that should have been solved in strategic development, rather than in production engineering. Thus, the
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author suggests strategic design should embody novel electronics design with the development of any necessary manufacturing principles. Therefore strategic design, as with repeat order, variant and innovative design, should involve design and production engineering experts.

In fact, a number of large companies attempt to address these problems by requiring their research engineers to accompany the strategic design through the remainder of the design process, helping to smooth the way to a product as well as learning aspects of engineering to tolerances, testing issues and other manufacturing requirements.

6.4. CHOOSING A DESIGN PATH

There are several implications of a multi-path design process model that relate to designers and their management. Firstly, for designers each of the four paths places different constraints on the range of possible solutions that are acceptable. For example, a project that is a design repeat order cannot employ innovative techniques as solutions to any outstanding engineering problems. If, indeed, such techniques are suggested then a decision to move the design phase of the project from a repeat order status to a variant design status (or innovative status) may have to be made. Likewise, a variant design cannot involve the application of significant new techniques, suggesting an innovative design, or even be only a minor modification in which case the design may well be a repeat order rather than a variant design. Secondly, an electronics product is likely to be complex and resulting from the application of the skill of many domain experts from marketing engineers, electronics and mechanical engineers, to production and test engineers. With digital circuit technology developments being at the forefront of electronics many new products are engineered with considerable effort being expended in software development. A new design, therefore, may well be split into modules that are taken from requirements to final design in each of these areas of engineering. Thus, a design may have components of digital and analog engineering, components of mechanism and materials engineering and components of production and test engineering. It is possible that such a design may be regarded as repeat order for the electronics and materials, variant design for the
mechanisms and production engineering and an innovative design for the software and test engineering components.

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Design review gates
Initial screen

Technical Product Specification Document

Customer Requirements
Conceptual Design
identify salient problems, search for appropriate solutions & impact on company make explicit specification tasks assess % new knowledge in design & production
choose development route

Activity
understand
innovate
analyze
criticize
select design effort

PATH: Repeat Order Variant Innovative Strategic Design

Embody Design
Embodiment Design
Embodiment Design

evaluate engineering change requests
development of circuit or production process

develop clear functional production procedure critical review
develop clear function production procedure critical review

Circuit layout gates
Test/Manufacturing gates

Detail Design
Detail Design
Detail Design

modify final assembly instructions
correct parts list and other documents

validate final assembly instructions
parts lists and other documents

integrate assemblies
parts lists and other documents

integrate assemblies
parts lists and other documents

verify and then make

Figure 21 Overview of the Four Path Product Design Sequence

The higher the risk, the greater the possibility of delays to the critical path of a project and the concomitant increased financial costs. PERT charts and other critical path techniques are designed to quantify the risk of a project. A design manager constructing such an assessment is required to break a project into small chunks, assign time, manpower and budget to each portion. Expert engineers controlling the project portions are asked to estimate the degree of difficulty and estimated time to complete their section of the design. This is often done in an informal way, but utilising that engineers professional judgement based upon prior experience.
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In order that the four alternative design path model, presented above, may be applied to real engineering problems it is necessary to provide a means of aiding the decision as to which path a design or part of design should be undertaken. A simple metric is proposed by the author that places a figure on the complexity of a design. The rationale is that by measuring aspects of the design task in hand, an estimate of the complexity of the project may be obtained. It is important to ensure that the metric may be derived with ease, so encouraging design management in industry to adopt the technique. A formal measure of design difficulty can then be refined in an iterative manner, employing hindsight of actual designs whose complexity was estimated using the design complexity metric.

It is the authors assertion that design complexity consists of two separable components, Design Magnitude and Design Novelty. Design magnitude is a simple measure of the size of the task related to the personnel charged with completing the task and can be estimated by assessing the ‘degrees of freedom’ of the design or part of design, which may be estimated as the sum total number of functions each prospective component possesses together with the number of functions in the design specification. This figure has to be scaled by the prior experience of the engineering staff, in terms of the number of similar designs carried out by the assigned engineering team, together with the number of similar design performed by other company engineers.

Design novelty is a function of the rate of change of the design specification (since fast evolving designs add complexity to the design task) added to the number of specific design functions that are unfamiliar or new to the engineering team; this is scaled by the experience of the designers. As novice designers will still be mastering the technology and perhaps will not have a wide base of knowledge to draw upon to cope with the design changes and their possible solutions. A recency effect on the design magnitude, in proportion to the time passed since a similar design (for a variant design for example) was undertaken is likely but has not been made explicit in the author’s model described in equation 1, below.

Given that electronic engineering designs take many forms and can cover several magnitudes of scale of task, the proposed metric of design complexity is required to handle designs of differing sizes and differing implementation technologies. This is achieved by
assuming that the measures of design magnitude and design novelty are assessed with specific consideration of the engineering skills and experience of the team to be engaged on the project, a reasonable assertion since companies tend to operate in market niches they possess the skills to compete in.

The design complexity figure of merit obtained from this provides an indicator of the type of design support required to carry out the design task.

\[
Design\ Complexity = \frac{(A + B)}{(C + mD)} \cdot \frac{((1 + F)(1 + G))}{H}
\]

**eqn. 1**

design magnitude \quad design\ novelty

Where

- **A** is the sum total number of functions of each device in the circuit,
- **B** is the number of functions of the desired circuit
- **C** is the number of similar designs done by the engineer tasked with the design (% prior knowledge. Additionally if no similar designs have been done, but an engineer attended a relevant course to acquire 1–50% know–how and thus a value for \(D\) of 0.01 to 0.50
- **D** is is the number of similar designs performed by company engineers
- **F** is the current rate of change of the design requirements (for example: revisions per calendar month, i.e. \(\partial A + \partial B\))
- **G** is the number of functions (in \(A\) and \(B\)) new to the designer(s)
- **H** is the experience of the proposed designer(s) (in years).

setting \(m=0.8\), since knowledge residing in other company individuals is not accessible in the same way as from the individual involved. It is probably proportional to size of company too.

The left hand side of equation 1 is the magnitude of the design, right hand side is the novelty of the design, making complexity a factor of the measure of novelty, scaled by the magnitude of a design.
SOME EXAMPLES:

1. A small circuit board has three components, a switch, a resistor and a lamp. A=3, B=1, D=5, E=5, F=1, G=0, H=5. The design complexity is therefore \((3+1)/(5+4.0)*((1+1)*(1+0)/5) = 0.18\) (design magnitude of 0.4, novelty of 0.4). **A repeat order design task**

2. Another circuit is expected to contain a novel IC, a battery, a lamp, a resistor and a switch. A=10, B=3, D=0, E=1, F=1, G=5, H=5. The design complexity is therefore \((10+1)/(0+0.8)*((1+1)*(1+5)/5) = 33\). (design magnitude of 14, novelty of 2.5). **A variant design task**

3. Another circuit is larger, and expected to have A=(32+7+32+5+5), B=4, D=1, E=0, F=0, G=40, H=7. The design complexity is therefore \((83+4)/(1+0)*((1+0)*(1+40)/7) = 509\). (design magnitude 87, novelty 5.9). **A variant design task**

4. Another circuit is an example of converting analog to digital circuitry and has been calculated to have A=(33+4+15+10+6+9), B=6, D=0.05, E=0, F=5, G=78, H=7. The design complexity is therefore \((78+6)/(0.05+0)*((1+5)*(1+78)/7) = 112,320\). (design magnitude 1,680, novelty 68). **A strategic design task**

5. Another circuit has A=(33+4+15+10+6+9), B=6, D=0.5, E=0.5, F=5, G=36, H=7. The design complexity is therefore \(((78+6)*6)/(0.5+0.5)*((1+5)*(1+36)/7) = 2,664\). (design magnitude 84, novelty 31.8). **An innovative design task**

Additionally, the design complexity figure of merit must be calculated for each engineering department involved in the design work. Once this has been done the graph in figure 16 may be read, enabling the commensurate funding, manpower, timescales and other details to be set for the project, given prior experience in assessing the needs for each type of design.

The actual thresholds between types of design are only meaningful within a company, for the measures are related to the type of business a company is engaged in. For example, company A may have a project that has a design complexity of 1,000 and a novelty of 45
and is regarded within the company as an innovative design. If the work is to be sub-contracted out, the sub-contractor may have different values for parameters D, E, G and H causing a different design magnitude and novelty to be calculated. Such factors may make the design simply a repeat order or a variant design to the sub-contractor, rather than an innovative design; giving the main contractor good reason to sub-contract the design work.

Design complexity provides a measure, for the first time, of the effort likely to be required to complete a design. The manning levels and time allocation for a design, however, also need to be approximated. Equation 2., below, describes the notional yield of a design exercise to aid this task. It is calculated from the complexity of the design task together with estimates of project time allocation and staffing levels.

\[
\text{yield} = \left(\frac{\text{time}}{\text{complexity}}\right) \cdot (k \cdot (\text{people} - \ln(\text{people})))
\]

\text{eqn. 2}

task size \quad personnel complexity

where, \(k\) is a personnel rating factor for historical design performance

The scaling factor, \(k\), is a measure of performance based upon historical design achievements, given the type of project normally undertaken within a company.

FOR EXAMPLE (using the same examples as for design complexity above and assuming \(k=1\)):

1. A small circuit board has three components, a switch, a resistor and a lamp. The design complexity is 0.18. With 1 person taking 1 day, the yield is \(1/0.18 \cdot (1-0) = 5.56\).

2. Another circuit is expected to contain a novel IC, a battery, a lamp, a resistor and a switch. The design complexity is therefore 33. With a time of 14 days, the yield is \(14/33 \cdot (1-0) = 0.42\).
3. Another circuit is larger. The design complexity is therefore 509. With a time of 30 days and 2 designers, the yield is \( \frac{30}{509} \times 2 = 0.12 \).

4. Another circuit is an example of converting analog to digital circuitry. The design complexity of 112,320 with a design magnitude of 10,080 and a novelty of 68. With a time of 360 days and 4 engineers, the yield is \( \frac{360}{112,320} \times 4 = 0.01 \).

5. Another circuit has a design complexity of 2,664. With a time of 150 days and with 4 engineers, the yield is \( \frac{150}{2664} \times 4 = 0.22 \).

As with the design complexity figure of merit, yield is only meaningful when estimated within a particular company's expertise and support structures.

6.4.1. Information theory

The mathematical expression for design magnitude may be seen to relate to the design evaluation metric by Nakazawa and Suh \([104]\), where information theory (from Shannon) is employed to derive a measure of design quality when evaluating a set of design alternatives.

Taking the description of design evaluation by Nakazawa and Suh the aim is to maximise the overlap between the information held in a system and that necessary for the design.

Following Shannon,

\[ I = \ln \frac{1}{P_a}, \]

where the Information \( I \) is related to \( P_a \) the probability of event 'a' occurring. For example: \( 2.9 = \ln \frac{1}{0.05} \) and \( 0.6 = \ln \frac{1}{0.5} \), ie, the more unlikely the event is, the higher the information content necessary.

Thus a design is chosen with lowest information content. This relates to my expression of complexity, where prior knowledge by engineers and company reduces the design risk and equates to variables \( D \) and \( E \) in my equation 1. The authors metric is a refinement that is applicable to electronics engineering, where the prime goal of the designer is the design of function with defined effects. So although designers may need additional technological or physical information to complete a design, it is the enumeration of product functions that
can most easily be completed by company engineers and thus are most accessible to a review of their novelty to specific company design staff as part of a formal review of design complexity.

Since the information related to an event will be high if company engineers have not experienced that event before, it is likely that they will require more information in order to completely describe it.

6.5. LIMITATIONS

There are a number of potential implementation problems with the generic design process model that might limit its usefulness in industry.

(a) It must be appreciated that being generic the model may not represent the precise flow of activities held to be of value in every company. However, it does layout a comprehensive set of functions that need to be considered during the product development process. The precise timing of each activity in reality will depend on the nature of the design in each company.

(b) It should also be noted that the mere existence of an activity in the generic model does not imply either a time or a personnel cost in carrying out that activity. Rather these costs are expected to be proportional to the magnitude and complexity of the design and manufacturing tasks being tackled.

(c) Percentage new knowledge to design engineers may be difficult to solicit from engineers unused to introspective thinking of their own abilities. A solution might be to develop a personal “schema” tree of past projects, together with listings of circuit design types and past failures. But, again, past failures are likely to be emotive issues when first discussed with engineering staff.

(d) This model imposes four categories of design, when it is likely that designs fit a continuum of possibilities of change to production and new knowledge in design. The author defends this stance by proposing that the act of labelling a design as one of four types
has more benefit to a company (discussed in chapter 7) than the previous wide spectrum view point of design.

(e) And finally an assumption of controlled technological change (ie. controlled innovation) is central to this model. This may not be sensible for product development in nascent markets or when using nascent technologies. However both of these areas fit into the model at the level of innovative or strategic project with concomitant project costs and timescales.

Obviously the design capabilities of a company relate directly to the nature and psychology of its employees. It is hoped that the researches carried out by the author now make allowance for these human factors within the design process.

6.6. SUMMARY

A new definition of engineering design is proposed, which attempts to minimise the costs associated with a project, given the needs of the engineer and the creative aspects of engineering design. Thus the author proposes a four path design tree, tailored to company and engineering needs, rather than just idealised engineering needs. This has been reported in [105].

- Design model
  A new model of design has been presented. It describes the activities that electronics engineers must undertake during the electronics product development process. The model is generic and may be applied to any area within electronics engineering. The model highlights the information exchanges and personnel interactions between design and other departments of a company, including production, test, purchasing, marketing and finance.

  The model also defines a product documentation standard as an integral part of the design process, called the Product Book. This is defined in the following chapter.

- Assessment gates
  These gates provide a company with an opportunity to formally evaluate the evolving product design in a systematic and thoroughly documented manner. Their purpose is not to
monitor the progress of the project. Reports are required for both internal reviews and for release gates.

CAD tools may now synchronise their activities with these gates to provide additional design methodology management.

- Four paths
  The model views the design of new products in a wider company context. By partitioning company design into a number of avenues, or design paths, the effects of new knowledge in a company design portfolio may be minimised. In this way is is possible to provide design management that is tuned to the needs of the type of design in progress. The four design paths allow repeat orders, variant design, innovative design and strategic design to be observed explicitly by designers and management alike.

- Constraining designers
  The Four path model now provides a mechanism for limiting the amount of work undertaken on any particular design project. It may be applied to both company personnel and company computers. Constraints can now be specified in a consistent manner that prevent complete re-designs occurring when minor modifications were expected. These constraints can also be applied to on-line documents to provide a warning when a constraint is violated.

- New knowledge
  The spectrum of possible designs may be represented by a graph, see figure 16, plotting percentage of new knowledge needed to complete a design on each axis. The two dimensions allow new knowledge to be accounted, in both design engineering and production engineering.

- Design complexity metrics
  An aid to the management of the design process is also introduced, allowing real engineering problems to be measured in terms of likely new knowledge requirements and
A New Model of Design

staff design experience forming a metric called design complexity. Design complexity is necessary to provide a means of aiding the decision as to which path a design or part of design should be undertaken. A simple metric is proposed by the author that places a figure on the complexity of a design. Design complexity consists of two separable components, design magnitude and design novelty. A further metric is developed called design yield, a notional figure allowing manpower to be estimated from design complexity. This together with design complexity should allow design management to assess design capacity and capabilities in a rigorous way.

6.7. REFERENCES FOR CHAPTER 6.


[100] Personal communication with Mr. Ian Ashworth, Design Manager, Technophone 1991.


[103] Chairman's annual report, INTEL Corp., 1990


CHAPTER 7. PRODUCT DOCUMENTATION

7.1. INTRODUCTION

Engineering project administration can best be achieved by keeping documentation to the minimum. A system of documentation should nevertheless be established, particularly in companies which concurrently undertake a number of different projects which need to be controlled continuously. To enable the progress of a project to be controlled, the system should provide records of objectives, progress and achievement. It must also provide evidence of why and how a particular activity was undertaken (ie. decision points). In the event of a customer's request that a previous order be repeated or that the product be changed slightly before being produced in volume, these records will play a key role in ensuring that the design to manufacture cycle is kept as short and cost-effective as possible.

Hence, a company's document preparation system is of considerable importance in the process of electronics product design. Significantly, however, current practice shows that a large proportion of the process is manual and also that designs are essentially paper-based. So, if computer support tools are to be successfully integrated with existing systems, one must be able to interface to existing methods and existing archive formats to ensure simple linkages between people, manual methods, paper documentation and computers.

As a technology, paper has been an enormous success. Since its development thousands of years ago, it has proved to have a wide range of benefits. In particular, paper is long lasting, when stacked flat it is fire resistant, it may be read by several people at once, it may be written on for purposes of annotation, it is light weight and does not require electricity to operate. In recent times, however, the ability of computer based tools to create large amounts of data and information that requires archiving has caused considerable concern. Reliance on computer storage media has almost become standard practice but this approach is not without its problems since computer storage media technology, though rapidly evolving and providing higher densities of storage, lacks long term standards.
7.2. PRODUCT BOOKS

Company product design information can be viewed as a series of three ‘electronic’ product books, each holding aspects of the developing product for future reference. Each book has contents, chapters and indices. The product book structure may be applied hierarchically to complex electronics systems, so that each sub-system has its own product book set.

The set of books generated during the project constitute the Product Encyclopedia. Over time, a Product Development Library will be established comprising the accumulated product encyclopaedias. The following three sections briefly describe each of the three product books.

Product Book 1: Product Book 1 describes the potential product from the customer viewpoint as well as from the company commercial point of view. It is made up of the Customer Product Requirement (CPR) document and the product Commercial Requirements Specification (CRS).

The CPR should contain an unambiguous requirements definition which overcomes any difficulties caused by differences in specification language used. It is for this reason that the accuracy of decomposition of the specification into marketing, purchasing, engineering and production aspects needs to be checked, and requirements prioritised according to customer importance.

Customer acceptance and test requirements must also be defined in the CPR. On the other hand, the CRS translate the customer’s product requirements, as defined and agreed in the CPR, into an internally understood specification which the company can use as the basis for proceeding with actual product development.

Specifically, Product Book 1 should include a concise rationalisation of the product’s purpose, both from the company and the customer viewpoints. It should include such factors as desired market positioning, target market, desired lifecycle, cost and such high level technical aspects as product variant strategy. This rationalisation, or “product
philosophy,” is essential to the long-term success of the product since development projects which are undertaken without such philosophical underpinnings can easily become unmanageable, exemplified by Lawson [106].

Book 1 may hold the early structured analyses of customer needs in, for example, quality functional deployment (QFD). It is certainly feasible to extend QFD throughout the design process, so book 2 and book 3 may also contain QFD charts charting the links from customer to product design in an explicit fashion.

**Product Book 2:** Product Book 2 contains details of possible implementation strategies, together with evaluations of their respective merits and describes a recommended set of solutions, both market-tested initial product concepts and behavioural solutions, to the requirements specified in the CRS. A strategy for production test must also be described.

This book holds the Product Concepts Behavioural Solutions document (PCBS) and accompanying constrains data. It results in the development of the Technical Product Specification (TPS) which is held in Product Book 3.

**Product Book 3:** Product Book 3 describes the actual product. It comprises a Technical Product Specification which defines the product’s concepts, its functional structure, the circuits and their specific signal timings and interactions. This book also defines the product assembly and test strategy and contains a refined estimate of engineering costs.

The contents of Product Book 3 must be updated as a result of feedback from field engineering and sales/marketing. Examples of this kind of feedback include field failures, product maintenance problems and customer response, both favourable and unfavourable. Any engineering change notes generated as a result of this feedback should be managed according to an effective change control regime.
This book holds the following documents: Technical Product Specification (TPS), Product Development Path document (PDP), the Product Concepts Behaviours Functions and Circuits document (PCBFC), change control notes and manufacturing constraints, as well as circuit netlists, component lists and assembly instructions.

All three books exist as initially only as templates, however as the product development path unfolds more and more information and data will be written to the appropriate product book either manually by company personnel or automatically by CAD/CAM or ECN system.

### 7.2.1. Value of product book concept

The value of the product book approach to the disparate documents mentioned in Section 9.2.2.2. of the functional specification is that specific information, say marketing data, will always be held in book 1 of a product’s database. This consistency across products simplifies human cross-referencing and filing when information or data is sought from the books. Additional books hold company engineering data, which detail manufacturing and other constraints together with component libraries, as well as theoretical and practical reference literature (supplied by publishers of “electronic books”).

Computer databases are invaluable aids to engineers, however they have a significant fault. The information they hold can only be accessed through the use of specialised computer programmes that understand the structure of the databases. The manner in which the information is accessed and displayed is not always intuitive to the human and thus represents a possible source of error and certainly of hindrance if training is required prior to the use of such databases.

For this reason it is suggested that design databases (including component information) be structured in a more natural way, that of books; with chapters, sections, headings, tables of contents and indices. This allows all the a priori human knowledge and skill of reading to be applied to the computer database, so (being HCI technical) the mental model of the database formed by the user is already formed by years of experience of reading books.
To fully realise the full potential of company documentation it is recommended each product book be an active document. Therefore the books must be structured in ways that allow automatic computer access to the information stored within them, as well as for easy reference by people. Each set of key parameters of a design would have to be embedded in the electronic document for human and machine access.

\section*{7.2.2. Engineering databases and books}

Structuring company information of particular products into books allows people to access information about the products in a familiar way. To ensure that information stored in these books is, and continues to be, useful a mechanism must be instituted to ensure all data and information is kept up to date.

Apart from direct copying of data from the appropriate engineering files and tables, the normal method of updating such data is to embed references to the data in the documents, as most integrated design systems provide for circuit diagrams embedding at present. Unfortunately, issue control is difficult to organise for both these methods. The first fails as human intervention is required to place the new data in the correct places in the company information product book, the second fails as the amount of information embedded in the company archive document grows and results in a complex web of pointers and cross references as data from engineering, production, purchasing, test and service are integrated into the company book on the product, which results in horrendous data consistency and archive problems.

The technique suggested here is to use company product books as the complete engineering database for each product. This results in a combined database that is tangible to people, since, in addition to the inclusion of more advanced referencing techniques such as hyperlinks and structured browsers into the documentation, it is book structured with contents pages and indices.

Thus, in summary, a design exists in its entirety in one logical (if not physical) place within the computer system. Product book 1 holds a product's philosophy and from both customer and company viewpoint. Product books 2 and 3 hold the conceptual design and the
technical design information. Schematic editor tools create design circuits and place results directly into an evolving company book.

Copies or references to the circuit schematics may be mailed electronically to other personnel, but the up to date version is always embedded in a company book in chapter 1. Layouts of circuits on circuit boards are always in chapter 5 and definitions of interfaces will always be in chapters 2 and 3, making it easier for staff to remember where specific information is, making navigation around what are likely to very large databases more consistent for people.

7.2.3. Book evolution:

Chapter 1 of the design book contains the design functionality and descriptions of the product function at several stages of development. From a practical viewpoint, a circuit schematic diagram is only released to be part of the book when it has approval at an appropriate assessment gate in a company's control structure.

The company control gates, used as formal assessment points of the developing design, are also amenable to computer support. This is discussed in detail in appendix 3.

7.2.4. Book operation:

A new product design may be a Repeat Order design or a Variant design of an existing product or it may be Innovative or Strategic in respect of existing design capabilities and product portfolios of a company.

Trade-offs, constraints, cross-checks and costs are recorded in the relevant book in a structured manner. Templates for each book may be defined to conform to in-house company standards of documentation. Each template will define the chapter and section headings for each book, together with the sub-sections that contain the references to actual costs, constraints and checks. A complete set of production constraints and cross checks would be required for a fully operational documentation system, and it is certainly anticipated that these would be readily available from production engineering and other sources.
Chapters have folded sections (cf. INMOS transputer development kit folding editor) to facilitate different viewpoints of information. For example, quality assurance data would form part of a product book, as would the analysed data. The tabular displays for engineering, design, accounting and other parties interesting in reading the quality information would be able to access their specific data from folds in the document. The effect of folding the document in selected places is to reduce the “cognitive overload” on the reader by hiding information not specifically salient to them.

7.2.5. Product book chapters

It is central to the product book philosophy that design decisions and design constraints of a product development are retained within the appropriate product books for future reference.

Concept phase:
Product Book 1 describes the potential product from the customer viewpoint as well as from the company commercial point of view.

The detail of this product book is not described in this thesis.

Design phase:
Product book 2 describes conceptual knowledge. The Conceptual Product Book (electrical) consists of 18 chapters, each of which details an aspect of the electrical function, its operating conditions and its manufacturing constraints and cross checks. These chapters define the Product Concepts Behavioural Solutions (PCBS) and accompanying constraints data.

Even though this book contains the early stages of a design it is important to appreciate that manufacturing, test and other non-design issues are important, even at this stage. To reflect this, a number of slots in the structured book are dedicated to decisions that have to be made in relation to the fabrication and testing of the design. Only Chapter 1 of the book is directly concerned with the product’s function.
The fabrication and design factors which are taken into account are depicted in table 4 below:

| 1. Functionality            | 11. Health & Safety          |
| 2. External Interfaces      | 12. Cost (financial)         |
| 3. Internal Interfaces      | 13. Timescales (personnel & actual), including project gates |
| 4. Field maintenance        | 14. Quality issues           |
| 5. Physical Interface       | 15. Mechanical Engineering   |
| 7. Test strategy            | 17. Risks (identifiable)     |
| 9. Environmental            |                                |
| 10. Standards               |                                |

Table 4: Chapter structure of Product Books 2 and 3

This structure is shown in a design example in Appendix 4. Items 1, 2 and 3 above are replicated for electronic, mechanical and software design in the manner shown in Figure 22 below.

**Product Book 3 – Technical phase:**
This product book uses the same templates as the Conceptual Product Book, above, but the level of detail differs since the Technical Product Specification Book holds data and information relating to the embodiment and detail stages of design. This book is also the logical place for templates that check the design to manufacture interface for consistency of
manufacturing information and for ensuring testability and assembly issues at circuit layout stage. Please refer to Appendix 3 where a detailed example is provided.

**Data books and reference materials**
A wealth of information exists about the engineering capabilities of a company and the processes employed in the design and manufacturing parts of its business. Much of this information and knowledge must be held in a computer database for easy reference by engineers and their computer support tools, during the development of a product and its documentation. The information is of a very specific nature, but should include design information together with manufacturing and other constraints. On-line published design material is also necessary to provide a font of knowledge for engineering reference.

### 7.3. SUMMARY

Product books are presented as a way of controlling information capture, archive and recall for a developing product. They place the emphasis on product description rather than circuit diagram as definition of the design, its testing and its assembly. This is made explicit to the design engineer through the mandatory use of product books during the development phases of the product. The value of the circuit diagram as a description of the product is reduced by ensuring that a design’s schematic diagrams are captured using a desktop publishing tool rather than a circuit diagram editor, thus integrating note making, annotation and diagramming.

- **Product books**
  Product books now provide a single (and uniform) repository for company documentation and information. Book are structured in analogous ways to traditional paper based books, but provide additional ‘active’ capabilities, for example: dynamic consistency checking, automatic version control and viewpoint control (to hide sections of books where they are not needed, where technical information is not required – in say marketing).

### 7.4. REFERENCES FOR CHAPTER 7.

CHAPTER 8. VALUE OF THE 4 PATH MODEL AND COMPANY DESIGN BEST PRACTICE TO DESIGN

8.1. INTRODUCTION

The preceding chapter developed a model of engineering design. It is the intention of this chapter to define the ways in which the author's model can best benefit electronics product development. This will be also be linked in with elements of best practice that were discussed in chapter 4 to provide a more complete picture of the ways in which industrial best practice and innovations in design modelling can help the lot of designers in industry.

There are five sections to this chapter, each addressing issues that effect different parts of a company. So section 8.2. deals with the value to designers themselves, section 8.3. deals with the value to design managers, section 8.4. deals with the value to CAD tool management and CAD data management, section 8.5. covers issues that affect the company as a whole and the final section deals with the links between the four path model and international best practice.

8.2. VALUE TO DESIGNERS

There are three points of value of the design model to designers. The first is that designers, who are perhaps more used to categorising designs as either routine or novel, will now formally allocate design tasks to one of the four categories. This ensures that designs traditionally regarded as minor changes (and perhaps undertaken by production engineering personnel) are now labelled as design work and may be undertaken by personnel who follow design policy to an agreed quality standard (in accordance with BS5750:part 1 – ISO9001 – for example). This means that designers can regard all design jobs as their responsibility, including re-work and change note requests. They can, therefore, adopt specific procedures appropriate to the level of design, again in accordance with in-house and external quality standards.

Design management suffer a dilemma: how to get the right type of innovation into a design and yet prevent innovation in designs that do not require it. Traditionally this problem is
attacked by implicit control by the design engineers themselves. Additional control is applied by tacit request of their management, who prefer to assume that designers will “do their best” to meet the project specifications whilst fully comprehending the constraining factors. That is: by treating design as a black box activity and hoping that peer review and group pressures can generate the necessary controls.

For example, a variant design is likely to be market or customer driven in its specification of function. Such a design will have a considerable overlap with an existing design and will not therefore require a substantial amount of innovation by the design team. It will be constrained by production capabilities, since a variant design is also likely to be manufactured by an existing production line (as determined by a company financial and strategic analysis). In turn this will limit the circuit board packing density and new component selection processes early on in the design process, and therefore limit a designers creativity. Thus control can be exerted on design innovation.

So, then, repeat order design and variant designs are unlikely to require access to new knowledge or information, but perhaps just involve the re-application of existing design knowledge in an already defined manner. This limits any information seeking necessary to complete these types of design job, since in theory the information and knowledge should be immediately accessible to the design team members, perhaps as pre-existing internalised design case histories (accessed through analogical reasoning) and rule based knowledge (accessed through design schemas) built up over years of experience. This discourages designers from being overly creative in a repeat order or variant design and possibly causing excessive on-costs in production as a result of their flights of fancy.

The generic design process model describes the activities that must be carried out during the design process. Although this is not meant to be a prescriptive company specific model, a similar activity model that is company specific should be constructed prior by historical analysis of company procedures and by review of best practices. The model does, however, highlight the role design has to play in a company setting. In this context it is suggested that the generic model be employed as an educational tool for training design engineering staff.
8.3. VALUE TO DESIGN MANAGEMENT

Design management require methods of assessing designer progress, productivity and success on a project by project basis. The information generated by these assessments can be used to provide feedback as part of a control loop during the process of design; to engineers themselves and also as part of a programme of refinement of design management practice. Classically, methods are applied that involve using PERT and Gantt charts for critical path definition together with post-design reviews to assess delivery deadlines and design quality. This is often augmented by direct consultation with design engineers in respect of design complexity, but this can be prone to post-hoc rationalisation of previous project time scales and degrees of difficulty.

By segmenting design into four major categories design managers can begin to compare projects of similar complexity for design time, cost and manpower. The equations for design complexity and design yield should allow design management to place formal metrics on each design (based upon retrospective application of these design metrics on previous projects). Designs at all levels of magnitude, from complete systems to new single circuit board designs should then be amenable to evaluation by this method, by a hierarchical application of design complexity and design yield at all stages of the design process, from conceptual design through to detail design.

The four path model aids design management by also being explicit in defining the nature of any specific design task in terms of the ancillary support required during particular phases of a development programme. For example by allowing management to institute specific creativity techniques (brain-storming or synetics for example) appropriate to the design type, ie. none required for Repeat order design or for Variant design (assuming Variant design is market driven), and additionally recognising that specialist skills may be necessary for Innovative and Strategic designs.

The discussions on mental models helps here and suggests that procedural knowledge (held as schemas) are applied by novices at some task. However experts somehow internalise this schema knowledge and support it with case studies to provide additional analogical
reasoning to bear on the problem. This has some relevance to this thesis in a consideration of innovation in novice and expert designers. Expert designers are more familiar with their domain than novices by the amount of internalised procedural knowledge (schemas) and declarative knowledge (case histories) in their personal mental model of their professional domain.

It is likely that their schematic knowledge will be richly cross-linked with interdependencies that have become defined by experience, for example by knowing that a pencil’s body material will affect the ergonomics of the pencil’s shape (and thus is constrained by the shape of the pencil too). Their abilities to step outside of the limits of their mental models could become restricted if an expert’s learning abilities are decreased, making innovation more difficult. Especially if they are unused to seeking new domain or world knowledge to fill gaps in their personal mental models.

However, novices who will have only partial schemas and relatively few case histories within their mental models and thus routinely involved in the processes of discovery as they expand their personal mental models, will be more disposed to being innovative. The problem then arises of – how to prevent innovation – to satisfy the demands of repeat order designs and variant designs, where innovation is being suppressed in a controlled way in an attempt to ensure that a design is easily manufacturable (and to specifiable yield) by the existing production processes. West [107] sheds some light on this by showing that control of group vision, participant safety, commitment to excellence and support for innovation are important factors in innovation and are open to manipulation.

Eventually design managers will have a sufficient historical basis upon which to sort designs, chosen in relation to risk to production and to new knowledge required by ones engineers. At this point design management will be able to characterise their design group’s capabilities and establish an optimal mix of designs based upon the expertise of their designers and on the capabilities of their production lines.

Strategic planning for future products and future company goals are then possible by planning changes to the mix of the design portfolio and by controlled growth of the design
teams to fit the new knowledge requires predicted for the future. This should (through time) provide improvements in the conceptual design phase and design route selection process.

A side effect of applying the design complexity metric is that a detailed database of design personnel’s knowledge, as defined (for the needs of the metric) by the different types of function they have personal knowledge of, provides a method of constructing an explicit knowledge base directory for company designers. So, then, the effects on company design capability by staff retirement and staff turnover can be quantified in terms of lost design capability.

Creativity as a problem can occur in may forms (in fact the control of creativity has just been discussed above) but during conceptual design it has been shown by Pahl and Beitz and others that the creation of alternative design concepts as solutions to the initial set of requirements is a sensible goal to attain. However, the creation of alternative solutions during conceptual design is surprisingly difficult for electronics engineers. Balls study of electronic engineers showed that it is often the first solution to be elicited that is most likely to be adopted as the only solution to a problem and that other potential solutions are quickly discounted without proper evaluation or even effort.

Evans [108] shows that confirmation bias in mental reasoning prevents real alternatives being created by a single person as they tend to concentrate on supporting evidence for their existing theories or hypotheses, even if those theories have been shown to be flawed, rather than attempting to generate new theories. This is exemplified by Wason in 1960 with an experiment that has come to known as the “2–4–6 problem” [109]. The effect of this can be shown using a Venn diagram, in figure 23., where the possible solution space is shown as a large ellipse and a designers solution search spaces as a set of smaller dotted ellipses.
By deliberately forcing brainstorming sessions on design staff at appropriate points in a design one can minimise the effects of human bias in the generation of solutions. Within the four path process of design these sessions would be utilised in the early stages of innovative and strategic designs, but are unlikely to be needed during repeat order or variant designs. This allows human effort to be directed to where it is needed most.

The generic model also provides design management with a systematic method for assessing design progress and quality. Designs may now be assessed at a number of design group reviews (internal reviews) and company reviews (assessment gates). These gates may be implemented as part of a company’s information technology strategy.

Product books provide a rich formal mechanism for design archive, design information recall and a method for constraining designs, designers and their CAD tools. They also map into computer support systems with ease. Product books also act as a structured engineering design database that may be used throughout a company in a uniform manner, that is by having a consistent structure from project to project.

8.4. VALUE TO DESIGN CAD TOOL USERS AND MANAGEMENT

CAD tools have developed to provide point solutions to well defined design problems. In a sense they now provide islands of automation within a company’s design process, where say design circuit board layout is routed automatically, or bills of materials are extracted from design drawings automatically, or digital logic circuits are synthesized by machine from detailed specifications. However few CAD tools constrain the generation of their output in order to satisfy company constraining factors. So, for example, it is easy to use a
CAD drawing package to draw an electronic circuit that is impossible to test, or to use a layout package to generate a design that will be very costly to fabricate.

The value of the four path model of design to the control of CAD tools lies in the model's alignment with production constraints. So that a repeat order design should make use of as much of an existing design's production processes as possible. In this way designs can be constrained in cost terms before they have been designed. The link with CAD tools is that the tools themselves can impose these constraints on the design engineers during interactive sessions with any design tool. The problem can be illustrated by consideration of a repeat order design.

A Repeat Order Design Example

A design engineer must make some wiring changes to an existing design to satisfy an engineering change note request.

Ordinarily, that designer will make the modifications based upon his or her deep understanding of the functional and physical aspects of the circuit in question. This may entail re-laying out a part of a circuit board, this is likely to be done by editing a schematic diagram and then feeding this new diagram into a printed circuit board layout tool. The layout tool will generate a new printed circuit board that should satisfy all the internal and external requirements on tooling holes, test fixtures and other fittings, as well as generating a new set of assembly sequence listings for auto-assembly pick and place machine (and so on).

The product authorisation process demanded by BS5750: part 1 (ISO9001) only requires that the design changes are fully documented and go through an approval process and are signed off. So, a circuit board with only a small wiring change has not only potentially been completely re-routed, but there is no guarantee that production engineering can still make and assemble the revised design. Indeed since a new set of circuit layout interactions have been created by the new layout there is no guarantee that the circuit will still operate as desired.
Now, if the CAD tool knows that a design is a repeat order, then it can potentially prevent the designer from altering anything on the original circuit drawing that would affect production, for example by preventing component changes to the circuit. Also the circuit layout phase could be similarly constrained by ensuring that the original tooling holes and test points are all exactly in the same places in the new revised design as they were in the original design. Then the approval process could guarantee that the changes would have a minimal impact on production. In fact the changes could be listed and evaluated by a change control panel as part of the final approval process.

8.4.1. CAD Tool constraints on designers

Listed below are the limitations a CAD tool should impose on a design according to the type of design being undertaken. Breaking any one of these rules would automatically schedule a review process to assess the impact of the change and subsequent authorisation.

(a) Repeat order designs would be explicitly limited by production features of a product, such as:

i. no tooling changes to circuit layouts,
ii. no component position changes,
iii. no component type changes,
iv. no component value changes,
v. no net wire changes to layout,
vi. no text screen changes to layout,
vii. no change to circuit tests,
viii. no change to circuit inspections

(b) Variant design would be less constrained, being limited only by production tooling features, such as:

i. no tooling changes
ii. no assembly changes
iii. no new field service techniques
iv. no new test structures required (ie. bed of nails)
v. sub-set of components not changed,
vi. sub-set of net wires that do not change

(c) An Innovative design would be unlikely to be constrained by existing production tooling, but would be limited by current production technology features. This would then
minimise the cost of changes to production imposed by a design, but still retain a certain flexibility of production that would probably require the application of concurrent engineering techniques to minimise prototype iterations and delay in introducing the product to market. So a designer could alter the packing density of a circuit layout by adding buried via holes to a printed circuit board design knowing that this would directly affect the yield of the production processes for that circuit board, but safe in the knowledge that the use of buried vias had been approved for the design work being undertaken. The types of constraint applicable to innovative designs could be the control of:

i. printed circuit board buried vias
ii. printed circuit board conducting layers
iii. printed circuit board wire net widths

(d) Strategic or Long term designs, involving the acquisition of new knowledge by engineering staff may radically alter the methods and processes needed to produce the design. In these cases it is likely that a strategic design would not be limited by existing internal factors such as existing production facilities, but be limited by the existence of long term factors external to the company, such as:

i. Electro–magnetic compatibility
ii. Product operating environment
iii. International standards for design, quality and the environment.

These constraints may, in principle, be checked for consistency with a design as it is progressing. So, a CAD database may hold these definitions of constraint and dynamically check them against an evolving repeat order design, variant design, innovative design or strategic design. The limitation is that the application of pattern matching techniques for say checking for violations against the number of “via holes” in a printed circuit board is a much simpler process than checking a design against an environmental standard.

Such a set of constraints should be held in a company's computer documentation of a design, and can therefore be checked automatically for consistency as a design is evolving. This directly effects the nature of text editors and desktop publishing systems that support the engineering design process.

The product books provide a natural method of integrating design knowledge, often held in disparate sites in a company, including design documentation and schematic diagrams,
parts lists, stores lists, purchasing lists, bills of materials, production constraints, production assembly notes, customer requirements, conceptual decisions and engineering change control systems.

Design gates provide a means of managing design methodology and CAD tool usage, as does tracking of a company specific model of the generic design process.

8.5. THE VALUE OF THE MODEL TO A COMPANY

The four path model defines the expected adherence to pre-defined production and other constraints for any particular design ie: Repeat order or Variant designs should be close to 100% defined by an existing product, making only Innovative and Strategic designs less that 100% defined and thus risky.

A problem still exists, however. That of a design that is ostensibly exactly the same as a previous design, but with one small design specification change. It is possible that some design specification changes will force the design beyond its technological limits, ie. it will fail to meet the specifications or will be unreliable. The metric of design complexity attempts to catch this type of design problem by demanding design engineers review their own past experiences of limiting factors on a design and thus to decide whether a particular functional specification will be novel to them in this respect. This may then convert a variant design into an innovative design provided the engineering team themselves are rigourous enough to notice the problem. Although this rather seems like the existing scenario in design offices, the major difference is that the addition of a formal assessment of risk using the metric of complexity at least prompts design engineering staff to make these judgements explicitly at an early stage in the design process.

Currently design decisions affecting production are made at points of necessity rather than points of timeliness, ie. just prior to internal or external assessment gates. However, for many designs (repeat order or variant designs) almost all of the constraints affecting them, that are arising from the choice of production processes, will already have been defined. So, for example, a complete list of production decisions, involving say the limitations of
vapour phase soldering on a design, will have been written down and will be available to
company design engineers (and also embedded in their CAD tool systems).

Therefore new designs in these categories can, in theory, be checked against this
information as they evolve. Decisions being made at specific points in time as the necessary
information becomes available. Previous decisions (from previous designs) may be
re-applied to a current design if the designs are similar or they are to be fabricated using the
same production processes. So automatic decision making can at least recall these decisions
and check them against the defined knowledge of the current design, as a means of checking
whether the earlier decision is potentially valid for this new design.

In addition, the four path model explicitly defines the usefulness of personal, company or
world information, knowledge or data to specific categories of design. So the four path
model can act as a controlling mechanism for intelligent indexing within a computer based
information system. This can potentially restrict the presentation of information to that
deemed relevant to the type of design being undertaken, and thus reducing the likelihood of
cognitive overload of individuals using such a CAD information provider.

Decision making processes within a company can also benefit from adoption of a 4 path
design strategy. The value here is that designs are now being regarded by the development
engineers as 'similar', or 'the same as' previous designs (for repeat order and variant
designs). Thus previous decisions could in principle be re-used to make short cuts in the
design process of a new product, by saving design time, component selection time,
production assessment time and so on. However, rather than stating that sub–circuits held in
a recipe book of electronic circuits should be used where possible, to short–cut the
development process, the savings are now made by identifying decisions of previous
designs that are useful and applicable to a new design. The key difference is that the
re–usable circuits resulting from acceptance of an old decision are already documented
with their usefulness in context, whereas sub–circuit libraries are essentially context free
and perhaps more difficult for an engineer to associate with and thus to use.

The four path model also provides additional company documentation to design databases,
whether they be paper or computer based. The checks and constraints that accompany the
definition of a repeat order or say a variant design may be embedded in design documents. These may be electronically checked for consistency.

Best Practice demonstrates the need for a strategic outlook by senior management when planning a company’s design function. Investing in CAD tools just to keep engineering staff amused is not good practice, they need to be set in a plan for overall company development, and with planned product portfolios.

Management of the design process is desirable and necessary. Product assessment gates in concert with the design metrics discussed above can provide a uniform method of tracking both personnel and project progress. A deeper understanding of ones company’s knowledge base (held in ones employees) is gained in the process. This, in turn, can provide an understanding of the limitations of ones staff and thus company capability.

8.5.1. An extension to the model

The four path model also has a significant role to play in the wider context of product design in a company. The value can be seen from an extension of the two axis model, where currently percent change to production is plotted against percent new knowledge to design as a means of choosing a design path. The new extension is to add percent change to customer base as the third dimension on the graph. This has an interesting effect on choice of product development path, since a company can now relate other internal groupings, such as marketing and field service, to the design process.

A new customer base has a significant effect on design, since the functions required by a new customer base will not be fully understood. In fact growth into new market areas can be very risky and needs to be controlled in some way to ensure that the design and manufacturing capabilities of a company are adequate for any new ventures and strategies are needed to assess and cope with this risk (Roberts et al.[110] and Buur [111] for example).

The use of the product to a new customer could well be unknown and thus risky in terms of achieving or exceeding customer requirements and thus customer satisfaction. This allows
a company to relate customer/marketing effort to design effort, through the controlled practice of Quality Functional Deployment (QFD). QFD allows routine extraction of pertinent information about customer needs and maps them into engineering specifications. In this context, a repeat order will have a set of QFD charts associated with its early customer design phases, the potential for a new customer base for this product means that a new set of QFD charts would have to be constructed. These charts can then be compared to the existing ones for the product. If there are any differences between the two chart sets then the next step is to assess which design path is appropriate to the new design for the new customer base.

Figure 24. Four company design paths

Figure 24. depicts the relationship between production change, design knowledge and customer base. It may be observed that a new customer base can force a design that was previously regarded as a repeat order design into a variant, an innovative or even a strategic design. The change in emphasis is linked directly to a company’s knowledge of the needs of the new customer base. By attending to this, one may hope that a better match between design functionality and new market needs can be attained and a concomitant reduction in company risk attained.
8.6. IMPLICATIONS FOR BEST PRACTICE

All of the benefits described above directly effect design best practice to a company implementing the four path model of design. The four path model describes a generic design policy within which existing design procedures can exist, but whose application is now constrained by the type of design required.

The specific controls of CAD tools provide additional checks for conformance with design policy with a company and could be viewed as a logical extension of the controls and checks ISO9001 imposes on design as part of a company's framework of quality assurance.

In addition, the parts and materials selection control imposed by repeat order and variant designs in the four path model conforms to international best practice as part of a stock minimisation exercise, where part variations between products are explicitly minimised by design engineers for repeat order and variant designs.

Engineering change control procedures are not affected by the four path model directly, since the essence of ECN administration is in rapid information acquisition and dissemination from and to the minimum number of staff necessary to carry out and approve the changes.

Design for manufacture (in all of its guises, design for test, assembly, etc) is an important principle and is very salient to the four path model of design. The reason is obvious, since one axis of the four path selection process is the effect on manufacturing of a putative design. So, the four path model is in fact a design for manufacture technique and if used properly can constrain designs to be produceable at an early stage in a products development. In addition, the it can be used proactively to define designs that will force change on the production processes, presumably as part of the construction of a portfolio of design types and as part of a company's strategic outlook on design.

The link with production is that for repeat order designs and variant designs much of the production processes will be the same as for an existing design. Therefore, in principle, it should be possible to apply those existing production decisions and constraints to the new
products. It should also be possible to constrain designers for these types of product, so that most of the production engineering on a repeat order design or variant design can be done prior to completion of the designs. For example, a production decision to use reflow soldering for all components directly effects the range of parts a design engineer can use; so too does the accuracy and repeatability of printed circuit wiring manufacture on the packing density of parts on electronic boards. It can thus be seen that (for repeat order and variant) design is a well constrained problem.

Indeed as part of a quality assurance programme in a well found production facility all constraining factors will be defined and tolerated for each job in production. This same data and information can be utilised by designers to ensure their designs are manufacturable.

8.7. SUMMARY

This chapter has discussed the ways in which the generic model of design, in context with industrial best practice in electronics product design, can help design personnel, their management, the control of CAD tools during the design process and the impact of adoption of the model on a company. It has introduced an additional axis to the four path model as a link into controlling company effort into new customer bases.

The new process model specifically supports management of the design process by providing means of assessing project risk and by controlling the design process according to project complexity and magnitude to both design and production engineering.

Assessment gates provide a means of tracking a project's progress. Design product books provide an integrating focus for design data, information and knowledge, as well as giving a way of tying production constraints on a design into an evolving design. Product books also allow management information to be stored (and accessed) with design diagrams and documents, so allowing management tools to access salient design data automatically.

Many of the features developed here are directly applicable to the way in which CAD tools can be used and controlled. The next chapter defines the functions necessary to achieve this
as part of a functional specification for a next generation CAD toolset. The application of these features to CAD tools will then enable CAD tools to respond to company demands upon design and not just technological requirements.

8.8. REFERENCES FOR CHAPTER 8.


CHAPTER 9. A FUNCTIONAL SPECIFICATION OF AN ELECTRONICS DESIGN SUPPORT TOOLSET

9.1. Introduction

This chapter presents a functional specification for a CAD toolset framework based upon the preceding chapters of this thesis; a study of the nature of problems and successes in product design in the industry today and a new model of the design process. The functional specification is not a detailed technological specification of the next generation of design tools. Rather it is concerned with identifying new areas of support which will enable EDA tools to sustain best design practice and facilitate improved management, operations and support of the design function.

Many of the problems being experienced in the electronics industry today are caused by failings in document control, information access and a lack of concern with design for manufacture. Hence, this functional specification is not concerned with such underlying CAD tool technology developments as software interaction response times, MIPS rating of computing machines, descriptions of fast maze routing algorithms and techniques for mixed digital and analogue simulation. It does, however, describe the functions necessary for improved design control, for structuring decisions related to the manufacture of circuits at appropriate points in design and for handling document preparation that have been derived from consideration of the four path model of design and from international best practices in electronics product design.

9.1.1. The functional specification

Rezevski defines the functional specification (FS) of a system as a model of the expected, externally observable behaviour of that system [112]. When, for example, an information system is being developed for a company, the process usually begins with an investigation of the existing information system. This is invariably followed by a requirements analysis
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defining “what” the proposed system should be capable of doing and establishing how the current system should be changed to meet those requirements. An FS is then devised, based on this analysis, which details exactly “how” the information system is to perform.

Hence, the purpose of a FS is to provide sufficient information for system designers to design the system, for system vendors to produce a system quotation and for system clients to assess whether or not the system meets their requirements. The approach to the development of an FS here differs from this view only in so far as it is targeted at CAD tool users rather than the vendors of such software tools. In particular, the aim is to provide a design support system which can be applied to any electronics company wishing to enhance its product design capability.

Sufficient detail will be provided to enable users of CAD tools to understand how to apply design best practice and to support best practice with appropriate design tools. The specification explicitly focuses on providing electronics designers with the levels of support required to produce good electronics product designs which are “right first time”. A good design, in this context, is one which meets customer cost, quality and functionality requirements and which, ultimately, is easy to manufacture and to maintain.

9.1.2. Functions from requirements

Business needs relating to the design of electronics products have been analysed in the preceding chapters and recommendations for Best Practice have been derived. The requirements developed in the preceding chapters have been structured according to their effect on the (a) management of design, (b) design operations and (c) support for the design process.

Figure 25 shows a logical architecture for the designers toolkit. The functional specification is based upon this architecture and described below. It is necessarily structured from the viewpoint of the design process rather than from the company perspective used in Chapter 7. Thus, although there are three layers in the hierarchy, they now consist of existing CAD technology support tools (eg. digital engineering tools, microwave engineering tools), the EDT toolset and the design infrastructure.
Reference to existing CAD technology support allows the author to show how existing tools, where appropriate, may exist within the EDT framework. For example, Section 9.3 provides links into existing digital logic engineering tools.

The specification of the design support tool framework is composed of two elements which are termed “core” and “optional”. Specifically, a framework has been identified of a future generation electronics designers’ toolset, the key elements of which are an inter-personnel communications capability, a design documentation control system and a method of ensuring consistency between an evolving design and the manufacturing and other tolerances applied to its manufacture in volume. This toolset is placed into best practice context discussed in Chapter 5 by encouraging design control and effective management of the design process using the Four Path model of design to minimise risk. The following “core” or essential elements of the FS are addressed in Section 9.2:

- Enhanced human–computer interface (HCI)
- Document preparation system (DPS)
• Project management

• Inter–personnel communication/Meetings scheduler

• Design Information and knowledge management

• Design Control (Engineering release and change control)

• Decision support tools

• Design constraints and consistency checking

• Mailing system

These sections provide a common support framework for the company product design process. More specialist tasks for technology design support are regarded as optional, by the author, since the core business of electronics product design only requires design integration and documentation, design control and institutional learning as the strategic design capability. The technical aspects of design are more than adequately carried out by designers and their technology CAD tools and so are optional to the framework.

The “optional” elements of the design tool framework, discussed in Section 9.3. below, specify design tools used for specific design tasks. These optional tools, shown in the shaded areas of Figure 25 above, are not described in this functional specification in any detail, but are placed here to indicate the manner in which point solution CAD tools interact with the core modules in the toolset.

Circuit capture, simulation and layout are the traditional CAD/CAE design tools of electronics engineering and are treated as optional design routes within this framework. This has been done since specific tracks, for example microwave design, small signal design, digital design, and even enclosure design or mechanism design, are product specific and not generic requirements. Only the digital electronic engineering track will be discussed in this thesis, where specific tool functions will be developed in relation to the core elements of the CAD framework.
On an infrastructural level, the functional specification covers best practice in the following areas in Section 9.4:

- Technology support
- Organisation for effective design
- Human resource maximisation

This is appended to the functional specification in order to clarify the fact that the toolset is used within an organisation. This latter section was prepared by Mr. Jan Bennett as part of the EDT project.

In addition, two product development examples are shown as walk-throughs of the recommended Four Path design model for a Repeat Order design task and a Variant Design task (in Appendix 4.). A small example software system highlighting implementation techniques of the product book concept is also described at the end of Appendix 4.
9.1.3. Design support tool environment

9.1.3.1. Overview

The EDT functional specification describes an environment in which existing CAD tools may be integrated. Various data and management structures are specified that specifically provide support for design communication, design control and design management, for example. Company infrastructures are also discussed where appropriate (see section 9.4. for details). However, the underlying computer hardware, software operating systems and related products are regarded as necessary and lower-level than the EDT specification. It is assumed that the reader is familiar with such detail and is able to understand the concepts discussed within the functional specification detailed in sections 9.2., 9.3. and 9.4. of this chapter. Figure 26 shows the relationship. A brief review of hardware and software matters is presented here to set the scene for the following discussions.

The design toolset environment proposed in this functional specification operates on top of the following platforms.

- Design support toolset hardware platforms.
- Design support toolset software platforms.
- Communications and standards.

9.1.3.2. Hardware platform

The research revealed that many different hardware platforms were in operation supporting electronics design and manufacture in industry. The requirement arising from this situation may be fulfilled by specifying that hardware purchased for use in electronics product design must be capable of being networked to Manufacturing Automation Protocol (MAP) and the Technical Office Protocol (TOP) standards using OSI protocols. It is appreciated that the cost of implementation may be high and that in these circumstances simpler systems may prove sufficient, but the reduced functionality must be recognised.
Networking computer resources seems to offer the most flexible approach to company computer integration, given the current rapid evolution of computing hardware. It is therefore recommended that a network of computing devices is developed, linking design and production engineers together, and linking these to administration. A high volume of electronic usage of these networks may dictate the separation into smaller local area nets with bridges linking an entire factory together. A company wide directory of people, their responsibilities and their electronic addresses must be made available to network users.

The local disk space and RAM allocation in each computer must be sufficient to support all required application programmes. Currently word processing and spread sheet software for PCs can operate satisfactorily with 8Mbyte of physical RAM under the Windows environment. Other design tools may necessitate the purchase of upto 64Mbyte of RAM.

A key feature of the support environment is the quality of the human computer interface. It is therefore recommend that all computing machines should be at least SVGA standard (DOS machines) or Open Windows (Unix machines) to support the display of high resolution colour images (1024 by 1024 by 8 bits), graphs and design information where appropriate. Although it should be noted that human interface standards are still a moot point and at the present time only a draft standard (ISO 9241) is available as a reference.

The costs of individual machines may be controlled by specific purchase of additional RAM and local disk for computer running graphics based applications. Network file servers can also reduce unit costs for distributed computing resources. One or two specific network nodes should be identified as archive nodes, allowing copies of all design, engineering and other information specific to particular designs to be archived using long term storage media. It is recommended (discussed below in Section 9.2.7., Design Control) that released designs be archived in both machine (Write Once, Read Many – WORM – optical discs recommended) and paper versions once a design has been released.

9.1.3.3. Software platform

The above hardware platforms must be capable of supporting either a precursor to POSIX/Open Windows or the DOS/Windows operating environment. The layered OSI
network protocols must be available using Novell net or similar for IBM PCs or using IEEE 802 standard for UNIX workstations.

Network printer drivers and other peripheral support should be available and X.400/X.500 electronic mail should be available.

The main criterion to be considered is the future compatibility and expansion of the software platform to accommodate new applications packages. Hence the adherence to internationally recognised standards.

9.1.3.4. CAD tool interfaces and standards

As is clear from CAD tool requirements and also from the authors review of problems in industry, the compatibility of CAD tools from different vendors is of paramount importance. Fortunately a number of authorities in the U.S and Europe are working toward a set of common interfaces and procedures that will allow engineering companies the freedom to purchase CAD tools from multiple vendors whilst still maintaining data exchange techniques (including neutral formats), programme portability between hardware platforms and common procedural interfaces for CAD tool usage.

The CAD Frameworks Initiative (CFI) work on software standards for CAD tools provides specific CAD tool development guidelines for the standardisation of calling interfaces for tools, databases and library components, applications tool compatibility, tool configuration, activity logging, design methodology management and user interfaces. The procedures defined by CFI and STEP should be available in any CAD/CAE tool (where appropriate) and adherence to these standards should be an important criteria in any CAD tool evaluation. It should be noted that CFI, JESSI and STEP are still early in their development programmes.

Note: In the following specification elements of specification are *italisised* for emphasis
The fact that the user's view of a computer-based system is conditioned chiefly by experience with its interface consequently the overall effectiveness of modern computer systems can be undermined by deficiencies in human computer interface (HCI) design. In such circumstances, it is common for users to compensate for poor design with extra effort, though there are limits to how well users can adapt to unfriendly interfaces. The cumulative negative effect is likely to be system failure with disgruntled users resorting to parallel manual systems or even to sabotage.

Designers of information systems face considerable pressure from users, as well as from such regulatory authorities as the UK’s Health and Safety Executive, to improve the usability of their systems. Standards have an important role to play in improving information system usability and, over the past seven years, a technical subcommittee (TC159 SC4) of the International Standards Organisation (ISO) has been responsible for
developing HCI standards on the ergonomics requirements for work with Visual Display Terminals (VDT) – ISO 9241. ISO 9241 [113] addresses VDT hardware as well as software ergonomics.

Notwithstanding the attachment of dates to the current status of the various parts of ISO 9241, only parts 1, 2, 3, 4 and 14 of the standard are available in June 1992, and then only as Draft International Standards. Furthermore, it appears unlikely that Parts 5 through 13 will be unavailable, even in draft form, before the end of 1992.

Nevertheless, for the purposes of this functional specification, the HCI design of an electronics design support toolset must, as far as is possible, conform to ISO 9241.

As part of the human computer interface, design tools must maintain operational visibility. That is rules employed and decisions made by CAD tools must be made explicitly in a manner in which people are able to comprehend. This is discussed in section 3 with respect to existing digital design CAD tools.
Engineering project administration can best be achieved by keeping documentation to the minimum. A **system** of documentation should nevertheless be established, particularly in companies which concurrently undertake a number of different projects which need to be controlled continuously. To enable the progress of a project to be controlled, the system should provide records of objectives, progress and achievement. It must also provide evidence of why and how a particular activity was undertaken. In the event of a customers request that a previous order be repeated or that the product be changed slightly before being produced in volume, these records will play a key role in ensuring that the design to manufacture cycle is kept as short and cost-effective as possible.

Section 9.2.6. (page 186) on design database structure and management specifies the actual structure of product information database using the term product books. This section only develops the specification of the document preparation system used to create and manipulate product books.
9.2.2.1. Product Books

Company product design information must be viewed as a series of three ‘electronic’ product books, each holding aspects of the developing product for future reference. Each book has contents, chapters and indices. Appendices are used to track the appropriate chapters ensuring that critiques and updates are locally available to the reader. Any chapter longer than 5,000 words must be accompanied by a summary at the beginning of the chapter. This may be enforced by software checks on the length of a chapter.

The product book structure may be applied hierarchically to complex electronics systems, so that each sub-system has its own product book set.

The set of books generated during the project constitute the Product Encyclopedia. Over time, a Product Development Library will be established comprising the accumulated product encyclopaedias. The following three sections briefly describe each of the three product books.

**Product Book 1:** Product Book 1 describes the potential product from the customer viewpoint as well as from the company commercial point of view. It is made up of the Customer Product Requirement (CPR) document and the product Commercial Requirements Specification (CRS).

The CPR should contain an unambiguous requirements definition which overcomes any difficulties caused by differences in specification language used. It is for this reason that the accuracy of decomposition of the specification into marketing, purchasing, engineering and production aspects needs to be checked, and requirements prioritised according to customer importance.

Customer acceptance and test requirements must also be defined in the CPR. On the other hand, the CRS translate the customer’s product requirements, as defined and agreed in the CPR, into an internally understood specification which the company can use as the basis for proceeding with actual product development.

Specifically, Product Book 1 should include a concise rationalisation of the product’s purpose, both from the company and the customer viewpoints. It should include such
factors as desired market positioning, target market, desired lifecycle, cost and such high level technical aspects as product variant strategy. This rationalisation, or product philosophy," is essential to the long-term success of the product since development projects which are undertaken without such philosophical underpinnings can easily become unmanageable.

Book 1 may hold the early structured analyses of customer needs in, for example, quality functional deployment (QFD). It is certainly feasible to extend QFD throughout the design process, so book 2 and book 3 may also contain QFD charts charting the links from customer to product design in an explicit fashion.

**Product Book 2:** Product Book 2 must contain details of possible implementation strategies, together with evaluations of their respective merits and describes a recommended set of solutions, both market-tested initial product concepts and behavioural solutions, to the requirements specified in the CRS. A strategy for production test must also be described.

**Product Book 3:** Product Book 3 must describe the actual product. It comprises a Technical Product Specification which defines the product's concepts, its functional structure, the circuits and their specific signal timings and interactions. This book also defines the product assembly and test strategy and contains a refined estimate of engineering costs.

The contents of Product Book 3 must be updated as a result of feedback from field engineering and sales/marketing. Examples of this kind of feedback include field failures, product maintenance problems and customer response, both favourable and unfavourable. Any engineering change notes generated as a result of this feedback should be managed according to an effective change control regime.

All three books exist as initially only as templates, however as the product development path unfolds more and more information and data will be written to the appropriate product book.

**Value:** The value of the product book approach to the disparate documents mentioned overleaf in Section 9.2.2.2. is that specific information, say marketing data, will always be
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held in book 1 of a product's database. This consistency across products simplifies human cross-referencing and filing when information or data is sought from the books. Additional books hold company engineering data, which detail manufacturing and other constraints together with component libraries, as well as theoretical and practical reference literature (supplied by publishers of “electronic books”).

9.2.2.2. Documentation under DPS control

All the following documents must be incorporated under DPS revision and access controlled to ensure that crucial company information is authored and revised to company standards in the product book structure, as recommended above. Each document described below should exist as a template within the product book scheme described above.

Although the product book approach is described in this functional specification, a list of documents normally associated with a product are given below as means of linking existing systems in to this one.

Marketing:
The brief normally defines the project problem and contains the specified solution. It usually contains a definition of the business problem together with necessary details relating to client organisation, the market and to activities of the principal competitors. It also contains the design brief and a breakdown of the work programme detailing elements of work, who does what and who is responsible to the client organisation and elsewhere, resources allocated, deadlines and associated budgets.

The project proposal relates to the initiation of the project and is usually submitted to the Board of the company where the project involves major capital outlay. In more minor projects, it will be presented to the responsible manager.

Examples of the kinds of information which should be included in the proposal document include:

- Project title
- The name of the department principally involved
• The objectives set and expected benefits

• Other criteria against which success or otherwise of the project will be judged

• Start and completion dates

• Outputs per stage (deliverables)

• Resource allocations

• Total budgets required now and at specified periods later on

When approval is given for the project to commence, it should be allocated a reference number. All material and documentation relating to that project should bear that number. This includes the Job File and Progress Reports.

**Sales documents:**
Product specification documents

**Purchasing:**
Main and alternative sources of supply

Cost of components

**Design:**
Design specification (including unwanted or side-effects if possible)

Design circuits

Design layout (including maintenance issues)

Design engineering log books

**Production:**
Production schedules

Bills of materials

Manufacturing and assembly instructions
Engineering change notes/Problem notification reports

Quality assurance statistics

9.2.2.3. Document archiving

Computer archival standards are a matter of international debate. However, since the purpose of design archiving is to recall those designs at appropriate times in the future in order to reuse the information they contain, a standard format is required which ensures long-term guaranteed readability to company personnel. In such circumstances, archiving in an idiosyncratic database format is not useful.

The archive format should be as simple as possible. Furthermore, in light of advances in data storage technology which have removed the need for data compression, information should be written in ASCII or to ODA or SGML (electronic office document standards), for example, including ASCII formatting and structural control data. This would modify the archiving structure of machine readable data into an archive structure which was both man- and machine-readable.

A further requirement is to ensure that the archive data is in some structured form. Circuit schematics, layouts and plotted drawings for example should be held in an agreed electronic format (defined by CFI or STEP for example).

Textual data such as the bill of materials (BOM) or production schedules, should be held in the same format as they would be used within the company. In this way, computer readable format comes to resemble the human readable, filing cabinet paper archiving system format.

This unified view of archive material would also allow for existing paper designs and information to be easily optically scanned using OCR software to a prescribed format (for example to CCITT G4, as required in STEP). Designs could be backed-up as secondary archives on paper or micro-fiche and at some later date scanned back into the computer-based information system ready for use.
The major difficulty with such an approach would be that documents containing drawings, diagrams and pictures would need to store such pictorial information in a human readable manner. This issue has still to be resolved.

9.2.2.4. Interfaces to other word processor formats

A document preparation system must be capable of reading and writing in a representative set of current standard tools such as RTF, ODA, Word for Windows, Amipro, Wordperfect.

This would allow a mix-and-match within a company, enabling it to use existing wordprocessing skills and investment in conjunction with the new design system.

The document preparation system must be capable of reading and writing in RTF and other popular applications such as Lotus 123, and Excel.

Additional interface capabilities are necessary to collect data and information generated by spreadsheets in management, design, engineering and quality control.

9.2.2.5. Document statistics

Word count must be available, as other statistics on each document (creation date, last modified for example).

9.2.2.6. Release controls

The first pages of any documents must explicitly indicate release dates and document version numbers. Hence, the DPS must enable users to create such dates and numbers easily, modification must be handled automatically or by special authority.

All document components should contain:

- Date and author stamp.
• **Release date**

• **Version number**

• **Author on paragraph-by-paragraph basis**

• **Author change controlled by automatic hiding of original paragraphs**

Although the above functions are required it should be noted that it is also mandatory for edit access to these functions be prevented. This includes the ability of users to alter the date and time of particular computers to suit their purposes.

Automatic revision bars are necessary as a method of highlighting changed sections of documents, notably altered paragraphs, words and graphics images, and are thus invaluable to document control.

*The ability for a document to to be tracked as part of an engineering change request.*

*Allow editing of documents by a group of people.*

Document structure allows different people to create/modify specific chapters/sections of documents. Therefore chapter critique may be written by different author to chapter contents author.

This function is an aspect of work flow automation, and is discussed in Section 9.2.5.4. (page 184).

*The ability to automatically archive documents to a specific directory as “name.released.type-of-release.date.” This constitutes the company memory of a design (please refer to the Product Book example for further details on the suggested structure of such archived documents in appendix 4.).*

*The listing of directories by name, release, type-of-release or date.*

*The ability to index archived documents, as a means of facilitating company access to archival data and designs. This includes indexing and contents pages and auto-indexing of key words and phrases within and across documents.*
The ability to search product books for key words and phrases and construct a document index based upon the positions of these words and phrases in each document.

Manual indexing can be a tedious, it can be simplified by using an intelligent indexing scheme that runs through a document discarding all except significant nouns and verbs. These can then be manually edited to remove unwanted references.

Generation tables of contents for documents.

It is normal for documents to have contents pages that are derived from section headings within the document itself. The indenting and emboldening can be controlled by templates to simplify the task.

9.2.2.7. Templates

Existing templates should be entered into the DPS and used for all new document creation and archiving. Please refer to section 9.2.6.2. (page 190) for further details on templates.

Company templates for clusters of documents as well for release and version control, allowing group changes for say, all design drawings.

Enforced summaries for documents over 5,000 words (includes chapters if they exceed the size too).

Drawings must be created with company labels, logos and change control information embedded in them.

Documents must also have these items held within them as non-deleteable items.

Templates must have Title, Author, Version, Date created, Date printed, Release date and file location reference (for human access to computer location of data).

The computer filing system must handle the long file names necessary for these documents, which can exceed 128 characters.
9.2.2.8. Mailer support

*Mail book, chapter or marked range*, see Section 9.2.5. (page 179) for further details.

*Read-only (for information).*

*Read/write overlay (for comment and ‘red-penning’) text.*

*Read/full write (for changing) via electronic mail.*

9.2.2.9. Viewpoints

*The ability to mark specific portions of a document for distribution to specific categories of company personnel by the mail system.*

This facility allows, for example, parts of a complete quality assurance document containing manufacturing statistics to be distributed to selected design and production personnel. Each category of personnel will already be defined within the electronic mailing system and by tagging each component of the document (table, paragraph, section, etc) with the appropriate personnel category allows the DPS (in concert with the mailing system) to send the appropriate precis to the correct people.

9.2.2.10. Hypertext and Multimedia

*DPS should allow hypertext button creation and coloured overlays of text (one specific for comments and sideline-notes).*

*The DPS should allow the use of inclusion of hypertext and multi-media into documents.*

Although at present neither hypertext nor multi-media information can be printed onto paper easily, there are situations where hypertext may be of value to on-line manuals. The inclusion of speech, hypertext and visual moving imagery could provide important information for, say, field service.
Must be capable of reviewing, editing and creating documents that contain video, sound and animations.

9.2.2.11. Technical authoring

Design documentation is the reference material for design and production engineering staff. It is also the source text for technical authors tasked with developing user and maintenance guides. As such multi-media interfaces, change control and other functions must be available to the author.

In house standard formats for documentation must be specifiable in the form of templates.

Spell checkers must provide UK. English dictionary and thesaurus, as well as the ability to add extra words oneself as an extension of the dictionary.

Additional facilities include the ability to check the syntax of the document, using 'engineering' grammatical rules. Hence, checking for “not a sentence” or “too many 's” for example would reduce the nonsensical results of “wordprocessor-ese” and allow documents to adhere to a company style and grammar.

9.2.2.12. Active documents

Must be capable of executing embedded code in text like MATHCAD and supporting the concept of active documents and hypertext.

The function library available within active documents will be mathematical expressions (arithmetic & algebraic), circuit function and graphics. This functionality will allow circuit simulations to be carried out in a document, by activating a circuit diagram.

Code execution can save on disk archive space, by storing only the specification of an action, rather than the results of the action itself.
It is clear from Best Practice that senior executives of electronics companies must put in place effective project management capabilities in order to support detailed planning, the measurement of performance in relation to the plan, the rapid reporting of any deviations from the plan, the communication of planning and performance information to all parties involved and the identification of objectives and the highlighting of important operations leading to these objectives.

9.2.3.1. Multi-project tracking

Allocate and track personnel and equipment to particular projects in a company wide manner.

So, mixes of mechanical, electronic and production engineering personnel for example, including their skill bases, may be allocated to particular phases of projects. Critical paths for personnel across a portfolio of projects allows the type of knowledge being placed in
projects are particular points in time to be tracked for project delay and cost impact. In this context personnel, it is suggested, may be defined as being expert, theoretician (book expert) or novice at the identifiable categories of design routinely undertaken in a company. This facilitates the computer mediated evaluation of the metrics of design complexity for each project.

Support interactive project management by monitoring and controlling activities associated with each stage of the engineering project lifecycle, namely:

- Concept
- Planning
- Implementation
- Termination

A project's critical path model, derived from planning (above), must be kept up to date using feedback from the actual progress of the design as measured at each project assessment gate (defined in appendix 4.).

The ability to specify assessment gates within a CAD framework.

Concept:
Projects in their conception stage are generally not properly specified, their scope is not stabilised, the interested parties have typically not found a consensus of views, implementation methods have normally not been decided and parts of the project may need further R&D [114].

Planning:
The project management tool must support the management of the design project by facilitating the project manager's planning activities. These include:

Implementation:
Detail design

Procurement and construction
Commissioning

Operate and maintain

**Termination:**
Upon termination of a project all management predictions created and updated during a project must be compared to the final figures, to close the feedback loop for management control purposes.

### 9.2.3.2. Management functions

The toolset must support a variety of management control functions. These include:

- Control of human and material resources
- Scope control
- Financial control
- Time management
- Quality control
- Communications
- Risk management

**Control of human and material resources:**
Ensuring the optimisation of equipment and personnel usage is an important aspect of project planning and is referred to as resource levelling.

The project management tool should provide a resource levelling capability.

**Diary:**
Store, as a history, all human resource details on a per project basis, together with a post-hoc rationalisation of the final outcome of the project for reference in later projects.
**Scope control:**
Scope control involves such project management techniques as the work breakdown structure, user sign-off, work authorisation procedures, scope status reporting and specific project close-out analysis.

*The toolset must support the determination of engineering project scope by facilitating the above activities. It must also enable those responsible for overseeing project progress to sign off the various stages electronically.*

**Financial control:**
The project management tool should support thorough financial analysis of each project using appropriate analysis techniques. Such financial analysis should consider the effects of delays and cost escalation from internal and external sources. Comparison between cost predictions and actual expenditure would provide warning of an over-spend.

**Time management:**
Engineering projects have time and costs associated with each activity. However, the fact that such projects tend to be discrete, non-recurring events means that their time and cost elements can only ever be estimates. Hence, there is a need for data derived from a series of monitors of the progress of a project.

*Where small projects are being undertaken, the project management tool should enable project managers to automatically generate Bar/Gantt charts. For larger projects, Network Analysis techniques such as Critical Path Analysis (CPA) or Programme Evaluation and Review Technique (PERT) should be supported. The computer-based network analysis system should be able to check the logic in the network. It should also be able to identify activities not connected to two events, more than one activity connected to the same events, loops and dangles.*

*Support multiple starts and finishes and should utilise time checks at each project gate to confirm actual progress of programme of work. This can obviously be linked to work flow automation.*

**Quality control:**
Measurements of project development quality can only be made by assessing on a day to day basis the number of design iterations and design decisions carried out by the project
team. Although this is not a normal part of design monitoring in the UK, the control of
design can only be accomplished by monitoring the processes involved.

Design iterations are relatively easy to track if CAD tools are used to develop the
electronics circuitry, although careful discussion of progress with engineering staff can also
be effective.

It should be noted that the measurements of design quality should only be made in a positive
light, since the very act of monitoring what many people view as a creative process may
cause management problems if not handled carefully.

A programme of continuous improvement within product design is essential. Therefore
formal methods of feedback from the process of design to the individual engineers involved
in that process is essential.

To this end the following examples of process feedback must be provided:

• Number of faults in circuits designed (at alpha release)

• Design time

• Design complexity

• Robustness of design

• Production yield of design

• Production assembly/test costs/time of design (complexity)

• Sales volumes of design

• Field returns and failure listings

• Design on time and budget at each project assessment gate

The electronic mail system may be used to place the data with the correct engineer and
additionally the data must be held in an appendix of product book 3 as an archive of
designer performance and design quality.
Communications:
The essence of good management is a moot point, but effective communication with ones staff must surely be a significant factor.

Electronic mail systems can replace paper based memos provided the mailer also has a comprehensive filing system. The Interleaf desktop (an electronic publishing system from Interleaf UK.) has excellent desktop graphics icons. The hierarchy of cabinets, drawers, files and documents provide a rich and natural interaction for “electronic paper memos” and other documents. This style of human computer interface for the electronic communications and mailing system is discussed in Section 9.2.5. (page 179) below.

Risk management:
Provide electronic sign-off at specific product development gates.

Update the project critical paths models (PERT charts) directly from date and time information relating to electronic sign-offs.

Highlight specific PERT chart boxes with Engineering Change Notes as they arise, according to the point of effect of the change note.

Explicitly label and categorise design projects (or parts of design projects) according to the Four Path model of design (refer to requirements chapter for further details).

Assess project complexity metric in a hierarchical manner for each aspect of a new project, based upon historical records.

See Appendix 4. for details of design gates in the generic design process.

9.2.4. Meeting scheduler

Meetings have assumed added significance in the field of electronics product design, as companies recognise the potential for reducing cycle–time using concurrent engineering methods. Such methods rely heavily on the use of multi-disciplinary product development teams.
Functional Specification

It is quite possible for engineering staff to be involved in more than one project at a time and an electronic meetings scheduler would provide a mechanism for optimising meeting times across a group. Such systems are common in commercial email systems, and the IBM PROFS package, for example, allows manual date selection and automatic diary checking of all personnel involved in the potential meeting.

*The minimum functionality of such systems required as part of the support framework for engineering design are:*-

- **Meetings time and date selection**
- **The provision of no-go dates and times**
- **Automatic consultation of personal on-line diaries and updating thereof**
- **Usage of pre-defined meetings lists partitioned as obligatory or optional attendance**

**On-line diary:**

*Memos are passed to personnel using system mailer.*

*Provides personal diary plus expert system scheduler for company wide meetings co-ordination.*

*Two year rolling diary include membership details of each committee, design team and matrix structure professional organisation.*

*Allows meetings to be specified by authorised individuals and also allows individuals to prevent meetings at specific times if required.*

*Meetings and diary function available to all company personnel, including assembly staff (enables tracking of meetings and personnel at all levels in a company)*

*Ability to set up meetings based on seniority, thus company directors may set up a meetings with any company personnel. But a design team leader cannot do the reverse and include*
director as an obligation, just as a request. The person setting meetings up is recorded in mail message automatically.

9.2.5. Mailing system

![Diagram of mailing system]

9.2.5.1. Inter-personnel communications

Whilst recognising the continuing importance of person-to-person communications in the context of a multi-disciplinary, team-based approach to electronics product design, it is clear that increases in both company size and product complexity demand improved communications capabilities. This is particularly true in situations where team members are based at different locations within a company site or even in geographically different locations.

*Human communication is so important to engineering design that a CAD framework with electronic communications as a core module within the framework is proposed.*
The philosophy is simple. Any program within the framework can access an electronic mailboard, sending and receiving data to and from other applications packages within the CAD framework.

*The mailer system may take any file format, for example:*

- Word processor text/spreadsheet
- Schematic diagram
- Simulation results
- Solid model

*When reading mail, the user invokes the mailing system which, in turn, must invoke the same application program used to create that message*

In this way, a detailed simulation screen might be sent as a message to an engineer, who would read it using the appropriate simulator package. Having made any necessary modifications or attached appropriate comments, the engineer might use the result as the basis of a reply message. The key to the success of this approach lies in the fact that any utility will have an internal menu that allows mail to be sent and received without forcing an engineer to exit the application program he/she is currently using.

Furthermore, the research revealed that most companies operate paper-based control and information systems in which computers are employed in the creation of documents. These are then communicated to the appropriate personnel, read by them and then archived in a manual filing system. Although paper-based filing systems have a number of advantages, recent developments in office automation systems now allow efficient computer-based filing systems with advanced facilities such as version control and automatic updating of document releases, together with a more natural user interface that utilises graphical icons for filing cabinet/drawer/folder/document to represent the directory structure in a computer document storage system.
In such circumstances, it seems appropriate to archive engineering and company information in computer storage systems while, at the same time, allowing document recipients to exercise a choice regarding the manner in which they read the information.

Such a system would support a *create anywhere, print locally* (for reading) philosophy.

Finally, an important aspect of discussing engineering issues in meetings is that a considerable amount of information can be exchanged with little effort. Critique of designs undertaken in this way, as either a peer review exercise or formal review, is an important activity in engineering design. The provision of these documents through electronic means would allow similar discussions to take place without the convening of a meeting. It is however important to be able to obtain feedback from such discussions and therefore electronic red-penning of documents as part of the feedback processes should be provided by a CAD framework; allowing a schematic or textual document to be corrected or modified by highlighting the problematic sections.

As discussed above a company which uses computer support tools should logically have them networked, to allow the transfer of information between the personnel using the computers, rather than using paper based transfer techniques (the internal mail system).

*Electronic versions of the internal mail system must be employed if design control and engineering change notes are to be effective.*

It is now reasonable to expect that an engineer developing a circuit schematic diagram can email the diagram to the production or layout engineer for comment. Obviously, to use such a system within a controlled release environment a number of additional features must be supported by the mailing system and also by the application packages, to ensure the company revision control of drawings is not confused and so on. These issues will be discussed below.

**9.2.5.2. Maller function**

*MAIL messages may be created in any utility, the MAILER just sends the data and records when the data has been read (which it sends back to the sender for confirmation).*
When reading mail, the user invokes the MAILER, but MAILER invokes the same programme the mail message was created with. Therefore a detailed simulation screen may be sent as a message to an engineer, who would read it using the simulator package itself. The engineer may wish to modify the message (error correction perhaps), forming the reply to sender; providing a sophisticated information messaging system.

This turns the traditional iconic interface on its head, since any utility will have an internal menu that allows mail, without exiting the program itself and therefore not having to terminate an application in order to just send a mail message to someone.

**Copy or point:**
An emniler must have the option of either sending a copy of the message or sending a pointer to the message to the recipient. The reason is that mail messages in whatever format they have been created would normally be copied and sent. So, for example, a schematic diagram will be copied and sent from the design engineer to the production engineer. However, if the production engineer was required to modify part of the diagram, or comment on the diagram, or even take control of the evolution of the diagram from that point, a more sophisticated emailer is necessary.

*Three modes of operation are required:*

- **If data is for reading only,** send copy OR mark email as read only and send pointer to original data (to minimise network transfer loading and data storage).

- **If data is for comment** do above and then tag original data as expecting a reply. When reply arrives, mail user and overlay comments on original data as read-only information. Options may then be to paste into original data all or selected parts of the reply.

- **If data is for use by recipient,** as part of a work flow mechanisation of data transfer then pass pointer to data to recipient and mark data as read only by sender if required.

**Modification as a reply:**
Replies must be co-ordinated with the originating messages. The emailer must keep record in the structure of the email message itself the source of the original data, to allow the new
data (the reply to the reply!) to be overlaid upon the existing data. Cut, paste and other insert functions may then be applied to update the original data, together with a note that the original has been updated.

If the document processing system is used to generate the messages and also to handle the storage and integration (optional) of the replies, then version control may also be applied to the users mail. For example, if a reply is incorporated into an original message by the original sender then the new text of the message will still retain a tag, telling the machine who wrote the new text and when it was added to the message. This is a fairly simple task, since a small data record can be kept with every paragraph in every document to hold this type of information, a principle common in many current commercial document preparation systems. A revision bar can also be used to highlight the changed or commented text.

A frequent mode of communication will be to reply to the original message, the reply constituting a comment on the original email message. The new reply being overlaid upon the original data to enable the original data sender to view the comments and take the appropriate action.

A typical dialogue would allow a production engineer to graphically circle a problem area on a circuit board, the accompanying text or even the spoken word communicates the problem and possibly a potential solution to the layout engineer, who can then modify the layout to fix the problem. The entire conversation would have taken place using the CAD layout tools and could have taken place across different geographical continents.

The emailer must also tag the message being transferred with a record of which application package created the data, so allowing the recipient to automatically call the correct application package for reading the received message.

9.2.5.3. Formats

The emailer must be capable of handling all word processor text, including all format and control data. Tags for each document or word processor output should signify the creating
application, enabling the same software package to be invoked by the emailer when the recipient reads the message.

The ability to email schematic diagrams from any part of a design process to another person on the network is an important and efficient means of communicating problems and progress to personnel in a company. This may even form part of the company policy on raising problem or change notes.

Examples of mailer communication formats include:

- Simulation results
- Word processor text
- Schematic diagrams
- Wire frame model of circuit board
- Spread sheet
- Defined standard for emailer application tags

### 9.2.5.4. Work flow automation

The flow of work around an office is normally controlled by company policies, procedures and practices. In a CAD environment it is possible for some of these to be embedded in the computing network itself, this is known as work flow automation.

Work flow automation may be constructed using the emailer system, allowing diagrams, documents and bill of materials and other company information to be transferred in a prescribed manner.

Material may be transferred upon "electronic signature" of an authorised person and may be copied to other personnel using predefined distribution lists. Upon transfer it would be normal to transfer writing permissions as well to the recipient, leaving the originator with read only access.
The following two functions are required:

- Construct a work flow from an organisational flow chart

- Authorise transfer along flow chart to next stage (including recipient acknowledgement and management notification)

Material may be transferred upon “electronic signature” of an authorised person and may be copied to personnel using predefined distribution lists\(^1\).

Upon transfer it would be normal to transfer writing permission to the recipient as well, leaving the originator with read-only access. Hence adjustment of read-write permission should take place according to an organisational rules list.

For security and tracking of progress a history of work flow for particular projects must be maintained.

9.2.5.5. Using the maller

All company personnel are available by mail, and are split into groups by section and responsibility. MAILER has on-line directory cross referenced by name, location, job title and project and computer logon name.

The user invokes the MAILER to read mail, but MAILER invokes the same programme the mail message was created with. Therefore a detailed simulation screen may be sent as a message to an engineer, who would read it using the simulator package itself. The engineer may wish to modify the message (error correction perhaps), forming the reply to sender; providing a sophisticated information messaging system.

A history log for each sender correlates message sending with recipient read date, and allowing a “read-by date” or “urgency date” to be specified too. Allowing the reader to prioritise their incoming mail.

\(^1\)An example: Fred is designer, Joe is layout engineer. Fred gets design (job no. M) signed off, computer system sets pointers up to job M for Joe and automatically notifies Joe that job M has arrived for his attention. Computer tracking of designs throughout a company (as work in progress) can also provide salient management information.
Received mail may be indexed by name, job title, project or sender location.

Mail may be cut and pasted from any utility for mail creation, or design information update (ie. bi-directional).

**Voice mail:**
Voice data compression techniques now make it possible to send voice mail over computer networks. The ability to handle this in a similar manner to written email is important, although red-penning of the spoken word would of course be difficult.

A minimum ability to store and replay telephone messages of up to two minutes in length is thought to be adequate.

The tagging of documents with speech, allowing paragraphs or diagrams to hold the spoken word.

### 9.2.6. Design databases

A particular strategy for design database management is not recommended. However any system developed must have proper access controls to ensure data cannot be corrupted.
Proper archiving and retrieval controls are also necessary to prevent users from altering designs that are under "release control" for production. This should avoid the situation where a design engineer releases a circuit to production engineering and yet continues to develop it without renaming the version they are working on, so generating two versions of the circuit both having the same reference name.

It is considered appropriate to discuss the design document database structure in this section since the author takes a wider view of design information than is traditionally the case. That all design notes and circuits should be included in the database and thus in the design archive.

9.2.6.1. Structure – electronic books

Computer databases are invaluable aids to engineers, however they have a significant fault. The information they hold can only be accessed through the use of specialised computer programmes that understand the structure of the databases. The manner in which the information is accessed and displayed is not always intuitive to the human and thus represents a possible source of error and certainly of hindrance if training is required prior to the use of such databases.

For this reason it is suggested that design databases (including component information) be structured in a more natural way, that of books; with chapters, sections, headings, tables of contents and indices. This allows all the human prior knowledge and skill of reading to be applied to the computer database, so (being HCI technical) the mental model of the database formed by the user is already formed by years of experience of reading books.

To fully realise the full potential of company documentation it is recommended each product book be an active document. Therefore the books are structured in ways that allow automatic computer access to the information stored within them, as well as for easy reference by people.

Each set of key parameters of a design must be embedded in the electronic document for human and machine access.
To facilitate electronic access to the data a cross-reference table embedded in the document is maintained.

**Engineering databases and books**

Structuring company information of particular products into books allows people to access information about the products in a familiar way. To ensure that information stored in these books is, and continues to be, useful a mechanism must be instituted to ensure all data and information is kept up to date.

Apart from direct copying of data from the appropriate engineering files and tables, the normal method of updating such data is to embed references to the data in the documents, as most integrated design systems provide for circuit diagrams embedding at present. Unfortunately, issue control is difficult to organise for both these methods. The first fails as human intervention is required to place the new data in the correct places in the company information product book, the second fails as the amount of information embedded in the company archive document grows and results in a complex web of pointers and cross references as data from engineering, production, purchasing, test and service are integrated into the company book on the product, which results in horrendous data consistency and archive problems.

The technique developed here is to use company product books as the engineering database for each product. This results in a combined database that is tangible to people, since, in addition to the inclusion of more advanced referencing techniques such as hyperlinks and structured browsers into the documentation, it is book structured with contents pages and indices.

Thus, in summary, a design exists in its entirety in one logical (if not physical) place within the computer system. Product book 1 holds a product’s philosophy and from both customer and company viewpoint (as discussed in Section 9.2.2., page 161). Product books 2 and 3 hold the conceptual design and the technical design information. Schematic editor tools create design circuits and place results directly into an evolving company book.

Copies or references to the circuit schematics may be mailed electronically to other personnel, but the up to date version is always embedded in a company book in chapter 1.
Layouts of circuits on circuit boards are always in chapter 5 and definitions of interfaces will always be in chapters 2 and 3, making it easier for staff to remember where specific information is, making navigation around what are likely to very large databases more consistent for people.

**Book evolution:**

*Chapter 1 of the design book must contain the design functionality and descriptions of the product function at several stages of development. From a practical viewpoint, a circuit schematic diagram can only released to be part of the book when it has approval at an appropriate assessment gate in a company's control structure.*

*The company control gates, used as formal assessment points of the developing design, must also be embedded in the computer support framework. This is discussed in detail in appendix 4.*

**Book operation:**

*A new product design may be a Repeat Order or a Variant Design of an existing product or it may be Innovative or Strategic in respect of existing design capabilities and product portfolios of a company.*

*Trade-offs, constraints, cross-checks and costs are recorded in the relevant book in a structured manner. Templates for each book may be defined to conform to in-house company standards of documentation.*

*Each template will define the chapter and section headings for each book, together with the sub-sections that contain the references to actual costs, constraints and checks. A complete set of production constraints and cross checks would be required for a fully operational documentation system, and it is certainly anticipated that these would be readily available from production engineering and other sources.*
Chapters have folded sections (cf. INMOS transputer development kit folding editor) to facilitate different viewpoints of information. For example, quality assurance data would form part of a product book, as would the analysed data. The tabular displays for engineering, design, accounting and other parties interested in reading the quality information would be able to access their specific data from folds in the document. The effect of folding the document in selected places is to reduce the “cognitive overload” on the reader by hiding information not specifically salient to them.

9.2.6.2. Product books

It is central to the product book philosophy that design decisions and design constraints of a product development are retained within the appropriate product books for future reference. These may well be hidden from normal view under the folding editor scheme.

Concept phase:
Product Book I must describe the potential product from the customer viewpoint as well as from the company commercial point of view. It is made up of the Customer Product Requirement (CPR) document and the product Commercial Requirements Specification (CRS).

The detail of this product book is not described in this thesis.

Design phase:
The Product Book (electrical) consists of 18 chapters, each of which details an aspect of the conceptual electrical function, its operating conditions and its manufacturing constraints and cross checks.

Even though this book contains the early stages of a design it is important to appreciate that manufacturing, test and other non-design issues are important, even at this stage. To reflect this, a number of slots in the structured book are dedicated to decisions that have to be made in relation to the fabrication and testing of the design. Only Chapter 1 of the book is directly concerned with the product’s function.

The fabrication and design factors which are taken into account include:
1. Functionality
2. External Interfaces
3. Internal Interfaces
4. Field maintenance
5. Physical Interface
6. Design Validation Criteria
7. Test strategy
8. Power Supply
9. Environmental
10. Standards
11. Health & Safety
12. Cost (financial)
13. Timescales (personnel & actual), including project gates
14. Quality issues
15. Mechanical Engineering
16. Manufacturing
17. Risks (identifiable)
18. Technical Documentation (user manual, field maintenance, etc)

This structure is shown in a design example in Appendix 4. Items a, b, and c above are replicated for electronic, mechanical and software design in the manner shown in Figure 27 below.

**Technical phase:**

This product book (book 3) uses the same templates as the Conceptual Product Book (book 2), above, but the level of detail differs since the Technical Product Specification Book holds data and information relating to the embodiment and detail stages of design. This book is also the logical place for templates that check the design to manufacture interface for consistency of manufacturing information and for ensuring testability and assembly issues at circuit layout stage. Please refer to Appendix 4, where a detailed example is provided.
The following checks are examples of those which should be carried out at circuit layout stage:

**Production checks:**

1. Height cross checks
2. Position sensitive components
3. Min/max tracking and special requirements for non-std layout (a) high voltage isolation zones, (b) small signal zones, (c) rf zones, high EMF zones
4. Support points for boards
5. Allow via holes, buried vias – YES/NO
6. Number of layers (min,max)
7. Peelable solder masking – YES/NO
8. Build strategy – single/double sided population – YES/NO
9. Define procedure for non-std build
10. Which sides are test points
11. Define silk screen masks showing (a) version, (b) name, (c) components position and orientation, (d)
12. Rules of screen layers – if automatic assembly try and use copper layers instead for version and name
13. Identify & tag CAD parts that are not BOM parts
14. Pcb panelisation details
Quality assurance

The following quality assurance checks are examples of those which should be carried out at circuit layout stage:

- Highlight shortest life components
- Assess evolving circuits for production yield
- Assess evolving mechanics for production yield
- Ensure production calibration equipment accuracy exceeds production calibration requirements

9.2.6.3. Data books and reference materials

A wealth of information exists about the engineering capabilities of a company and the processes employed in the design and manufacturing parts of its business. Much of this information and knowledge must be held in a computer database for easy reference by engineers and their computer support tools, during the development of a product and its documentation.

The information is of a very specific nature, but must include design information together with manufacturing and other constraints. Sections 9.2.8. (page 201) deals with engineering constraints in more detail and section 9.3. (page 212) relates this to design for manufacture in digital logic electronics.

Product books should exist for each of these areas, defining for example approved components and manufacturing rules. A small example of this is shown in appendix 4.

On-line published design material is also necessary to provide a font of knowledge for engineering reference.
Electronics product design is complex and involves the application of a wide diversity of human skills over extended periods of time. Control of this process is also complex. Currently designs are tracked in haphazard ways, for example the Bill Of Materials (BOM) of a design may be rigourously monitored, yet the number of circuit board iterations ignored; also the time a design engineer books to a project is rigourously controlled, yet interactions with production engineering are not encouraged encouraged nor monitored.

Design decisions must be recorded as a matter of course.

A CAD framework must support a number of design control functions. These are described below.

9.2.7.1. Four design routes:

The functions required here are:
• **The explicit control of CAD library access according to which path the design is progressing under (Repeat, Variant, Innovative, Strategic).**

• **The ability of design engineering CAD tools to constrain editing of drawings and notes according to explicit instructions held in an ECN.**

A product design may be constrained by the company in terms of cost and manpower available to design and production engineer it. Such a design may be categorised as Repeat Order, Variant Design, Innovative Design or Strategic Design. It is appropriate to monitor a Repeat Order design to prevent it from being changed beyond company expectations of minor re-works for cost reduction or tool change minimisation, for example.

Hence, a Repeat Order design will only allow changes to a design as explicitly defined by an ECN, unless approval is obtained to do otherwise. A Variant Design can not employ un-approved parts; the design database will be monitored to ensure that neither the BOM, nor the net list does not change significantly. An Innovative Design is allowed to employ a proportion of un-approved components but this proportion will be signalled to production engineering automatically. No limits are placed on a Strategic Design.

*An important aspect of design control is the control of computer tool utilisation by engineering staff. Two functions are required here:*

• **The recommended sequence of tool usage. For example, the circuit compiler may only be called after a design circuit schematic has been electrically rule checked and naming convention rule checked (see workflow automation below).**

• **Ensuring that the circuit schematic editor is not used on a design after that design has, for example, been released for layout engineering. This prevents design engineers from modifying controlled release drawings without the explicit approval of a responsible authority.**

9.2.7.2. Work flow automation:

*Tracking of job execution as the design progresses is required. Critical path models of the design process may then be updated automatically.*
This task is essentially one of electronic mailing of job data and information, therefore please refer to section 9.2.5.4. (page 184) where this is discussed in more detail.

9.2.7.3. Engineering change and design audit

Functions require list of participants, list of authorities, list of actors (people authorised to carry out the changes), knowledge of the design process (to select appropriate point for making change) and tracking of changes.

A prime concern of change control management is the ability to capture problem reports immediately they arise, to assess the engineering changes necessary to solve the problem and to expedite the changes in a rapid but controlled manner. The automatic updating of all version numbers and associated tracking systems is mandatory.

Engineering Change Notes (ECN) arise from many sources in production, test or perhaps field service. The problems that caused each ECN to be raised should be reviewed by appropriate personnel, the changes they recommend or require must be traceable from the point of change to the remainder of the production path. Most ECN systems are paper based at present. Paper based systems can suffer from saturation if the numbers of change notes raised reaches a threshold.

Computer based change notes, with the accompanying problem reporting notes may be implemented using electronic mail. Specific checks and distribution lists are also required, as are electronic sign-offs prior to action of the necessary changes. It is then a relatively simple matter to feed a management information tool with information regarding number of change notes, type of problem and so on. Computer based version control becomes the means of tracking the changes.

This should be implemented for any design where a build has been authorised whether it be a prototype or a full production build.
9.2.7.4. Problem capture tracking

All engineering change notes arise from the identification of a problem. The tracking of problems and their solutions is important. However, it is equally important to record in the design database the changes made to that product as a result of a problem as well as recording the problem itself. These two aspects to the database allow a historical review of past problems (together with solutions) and also a review of changes made to a product design. The first provides training material for design engineers, the latter forms the basis of a system of computer-based circuit board tracking that allows field service to apply the correct procedures to repair and maintenance of the product regardless of the revision history of the product.

9.2.7.5. Version control

All company documents must be version controlled. The recommended conventions are that internal documents are point versioned, that is fractions to the right of the decimal point, and external released versions are alpha-numeric version controlled in the required manner for production release control tracking.

Additional tags are required for tracking of author and date of creation/change and recent editing, as well as the ability to inhibit specific changes to selected documents.

9.2.7.6. Security of information

Computer file access permissions must fit to company project groupings of personnel:

- Owner,
- Project team,
- Company department

Detailed access permissions allow read/write/modify/comment modes of access. Access for reading and writing alone are not a sufficient means of control of security of documents in a company setting.
Encryption may be necessary.

9.2.7.7. Design information manipulation

An on-line encyclopedia accessing theoretical and practical information on circuit design, including on-line books, selected publications and company originated notes and reports is required to provide rapid access to design knowledge, information and data. All existing designs are also on-line and accessible through this system. Since access to information is one of the critical paths in a design, it is important to provide all necessary information at the touch of a button (or two!).

It is expected that a design information system would be constructed as part of the DPS (document preparation system) and thus provide a uniformity of access of information regardless of its source within a company.

Implementation issues include the following:

- Menu structure
- Information base format
- Uniform data retrieval allows cut & paste of retrieved information into current evolving design.
- DFM manual on-line
- Common component design curves
- PCB design curves
- Mathematical formulae
- Parts registry, including retrieval of parts already designed

DFM manual:

All manufacturing knowledge and information that effects decisions made by design engineers must be held on-line within the product book scheme.
See sections 9.2.8.4. and 9.3.4. for further details on manufacturing constraint information and design for manufacture.

9.2.7.8. Decision support

Although many types of expert or knowledge based assistance of industrial product design are discussed in research seminars as suitable methods for decision support, few systems are robust enough to warrant running as on-line support for design and production engineers engaged in electronics product development.

It is certainly Hewlett Packard's [115] and Hitachi [116] (UK)'s experience that the customisation of an expert system requires a significant amount of effort to capture process knowledge from company employees and check its consistency prior to release of the tool. For specific jobs artificial intelligence systems will become increasing popular through an improved understanding of the principles involved in knowledge based systems by company software engineering staff, or through the purchase of third party software. A full discussion of the functional requirements of AI based tools is outside the scope of this report.

It is clear that computer support for decision making is necessary, not the least for coping with the large amounts of data created by today's computer simulation tools and from process measurements in the factory, for example.

The expertise possessed by company engineering staff should be enhanced by computer decision support tools rather than replaced by them; given the argument in the first paragraph of this section. For many applications such a support tool is probably no more complex than a comprehensive spread sheet package, using well proven software technology. It can provide a way of number crunching on a variety of data in the various areas of a company, from manufacturing process statistics to design evaluation of performance.

Such a package does require some additional features to simplify its use in the electronics product design process, these are:
**Monte Carlo simulation:**
By the addition of stochastic noise to the data to simulate process variations.

**Data location templates:**
To allow specific data from specific locations in company databases (product books) to be read by the selection of a pre-defined template.

Thus, production engineering or design management can view quality assurance statistical data according to their own desired interpretations. This implements a sort of “viewpoint” mechanism, whereby data is viewed and analysed by differing company personnel according to their own needs.

**Calculation templates:**
To allow specific calculations for any given analysis to be saved as templates in the engineering database system and restored by menu selection.

**Results templates:**
To unify the presentation of information to company documentation standards.

**Access and release control:**
To ensure that the results from a spread-sheet analysis are version controlled to prevent unauthorised creation of engineering database information or templates.
An electronics product, for example, could comprise a set of functions designed by electronics engineers together with a set of enclosures and mechanisms designed by mechanical engineers. All will be designed so as to be capable of fabrication to the desired volume on a production line. Many constraints will be imposed on the electronics product during its design, constraints from both the customer and the company, for example: constraining the colour of the packaging or constraining the final production cost of manufacture.

Although many constraints may be difficult to define or may vary rapidly during product design or manufacture it should be possible to collect many of them within a computer system, such that they may be checked against the evolving design to ensure their requirements are met.

*These constraints are normally statements of requirement. They will include, for example:*
2. The solder direction across the board will be north to south, or

3. Buried vias will not be allowed, or

4. The circuit will only use approved components, or

5. The circuit board must fit inside the enclosure, or

6. Circuit must be air cooled, or

7. The circuit components must be proof against 90% humidity, or

8. Circuit board tracks N$100 and N$201 must handle 100v at 10,000 feet altitude.

The traditional way of handling these constraints is by implicit means, so for example
constraint example (4.) above will be ensured by only providing the designer with approved
parts lists, or example (1.) will be defined by assumption that all circuits are flow soldered.

Unfortunately implicit constraints are not easy to check for consistency across a design, nor
are they easy to evolve. So, if production engineering change the soldering from flow to
reflow soldering then they must issue change notices to all appropriate personnel, or hold
meetings, informing them of the changes. Yet, if each computer tool knew of the change
then the way in which the changed constraint affected each part of a design could be
highlighted by the computer. A pre-requisite for this is that some one has to work out
beforehand how each production constraint affects the evolving circuits and mechanisms.
This, however, is quite feasible since much time is already spent by production engineers in
performing the very checks a computer should do.

Although this thesis cannot provide a comprehensive list of design constraints, the
following sub-sections will show in a variety of areas within a company how constraints
are applied to a design and how a computer can cross-check them. The functions are then
defined in general. However, rather than embed each constraint explicitly in the computer
support tools, a more general approach is recommended.

9.2.8.1. Database of constraints and cross-checks

Documents will already exist within a company that detail many of the constraints
designers should abide by. It will be appropriate to use these in the construction of an
engineering product book that defines design for manufacturing issues.
Information must be checked for syntax as it is entered into the constraints database, since free-format English text is not easily amenable to computer checking.

**9.2.8.2. Truth maintenance**

*Design* consistency may be maintained *using Truth maintenance systems (TMS)*, these commercially available artificial intelligence (AI) tools are based on pattern matching techniques and AI-based reasoning. They ascertain the correctness of predicate logic based English textual statements held in a database by using artificial intelligence reasoning algorithms (based upon predicate logics), the reader is referred to early work by Doyle [117] and De Kleer [118] on this matter.

**9.2.8.3. Step-wise refinement of constraints**

An evolving design is very unlikely to satisfy all its attendant constraints until it has been signed off for production. This means that the constraints described below will have to be derived in either a step-wise refinement manner or at prescribed stages in the design process as a result of *design decisions*. Two further segregations of constraints are important here, those obtained from a top-down (ie. customer or function driven) and those derived in a bottom up manner from production engineering requirements (ie. company driven). The latter tend to be stable over a number of projects, so for example solder flow equipment will be applied to all circuit manufacture. Whereas environmental constraints of the design function will depend heavily on the design itself. Specific examples for digital circuit engineering are given below.

*Constraints must be categorised in a manner that reflects their real cost of attainment and also their importance in relation to the company. A constraint comprises:*

1. *The constraining factor*
2. *A man days cost to complete that factor if the constraint is not met prior to production and*
3. *An associated real financial cost to accomplish (b).*
Functional Specification

If either (2.) or (3.) are unknown then a note should be made signalling that the constraint is risky. A summation of the risks of the constraints in the entire system is a measure that reflects the likelihood of completion of the project on deadline.

Some constraints are effectively fixed by company investments and aims, for example the methods of assembly available to a production engineer is likely to be a slow changing constraint; ie. a company may use currently manual assembly methods, but is investigating automatic assembly or outside contract assembly as options for the future.

Other constraints are fixed by the customer, for example the colour of the enclosure or the function of the circuits and some constraints are dynamic and are only defined after certain design decisions have been made, for example: the package size of the electronic product is dependent on many parameters, some can only be stated at the outset of a project, but assigned a value following design decisions such as how the component layout of a circuit board will affect the height of the design and thus the clearances with respect to its enclosure.

Step-wise refinement of constraints is a significant departure from current design techniques, where most manufacturing rule violations are checked as a post-processing activity following PCB layout. There is no reason why this should be so, since much of the information required is already known prior to layout. For example:–

**Schematic editor:**
The ability to explicitly constrain parts of the evolving design to particular layout or placement parameters. Thus a design may be given a solder flow orientation to specify the flow direction prior to board layout. This allows the layout algorithms to refine the resultant circuit board to minimise solder traps during production.

The ability to constrain the positioning of a circuit component to a particular circuit board position. Thus a designer may fix the position of a high frequency component to be close to an external connector.

The ability to constrain the positioning of components by grouping their final layout positions. Thus a designer can explicitly control the placement of circuit components to
clusters, allowing say, high frequency de-coupling capacitors to be positioned close to a specific integrated circuit.

*The ability to make a first placement of a component prior to circuit layout or routing being performed by the drafting engineer.*

*The ability to manually route selected nets or parts of nets prior to circuit layout or routing being performed by the drafting engineer.*

*The ability to apply the above features in a hierarchical fashion.*

**Substrate profile:**
*The ability to define the circuit board shape profile prior to layout and routing by a drafting engineer.* Thus allowing early information from other constraining parameters, perhaps from mechanical considerations of the product, to be defined and act as a constraint on the developing circuit.

The ability of an engineer to define mounting holes and other fixtures and fittings prior to layout and routing.

**Other constraints:**
*As defined above, each parameter may be set or modified using the schematic editor facilities.* Normal change control activities are expected to be operational in this respect, as defined in Design Control in Section 9.2.7. (page 194) above.

### 9.2.8.4. Constraints

The following constraints are defined as either *<fixed>*, where the constraint is constant from the start of a design, *<phase>* where a constraint is attained at a certain point (phase) in the design process or *<decision>* where a constraint is contingent on a design decision being made. For example: a circuit board may be flow soldered, the direction of the board being decided by a production engineer. The point in time of the *<decision>* is, however, crucial. If the choice of board orientation is made after the circuit has been laid out by a drafting engineer, rather than before, then the layout and routing algorithms in the CAD
tool cannot modify the tracking to minimise solder traps and other features that directly affect the manufacturing yield of the board. So, the correct decision point is just before circuit layout.

Many other manufacturing constraints can be assigned decision points in this manner, however the assignment of decisions to specific points in the design process are company specific and are thus not included below.

The ability to tag constraints with specific decision points <fixed>, <phase> or <decision>.

The ability to check that a constraint has been satisfied at the specified phase in the design.

The ability to group and display constraints by the above tags.

9.2.8.5. Examples of constraints data

For clarity the following examples are described in 9 point text.

Environmental:
Environmental constraints include:

- Temperature: operating and storage ranges <phase>
- Humidity: operating and storage ranges <phase>
- Dust: operating and storage ranges <phase>
- Vibration: operating and storage ranges <phase>
- EMC: operating and storage ranges <phase>

Other issues may include type of solder flux, recyclable materials, etc.

Purchasing:
The cost of each component on the stock list of a company is a constraint on the final cost of a design. These must be available in the engineering database of a company to allow the evolving financial cost of a design to be calculated.

- Component costs <fixed> (fixed outside of design engineering control)

Assembly:
Assembly constraints include:

- Soldering – hand, wave, reflow <phase>
- Pcb direction through solder <phase>
Functional Specification

- Component packing density on pcb <decision>
- Hand assemble components <decision>

Board manufacture:

Board manufacture constraints include:

- Artwork tolerancing <fixed>
- Aperture definitions <fixed>
- Minimum track width - signal - power - other <fixed>
- Minimum hole size - via, component <fixed>
- Minimum in pad to hole radial copper (annular ring) - via, component, other (sockets, auto-assembly) <fixed>
- Board finishes roller tin, reflow, hot air levelling <decision>
- Solder resist <decision>
- Screen printed ink, photo-imageable ink, photo-imageable dry film <decision>

Production test:

Production test constraints include:

- Bed of nails/ functional test <decision>
- Test probe points/connectors/busses <phase>
- Function <phase>

Design:

Design constraints include:

- Four design paths <phase>
  (places limits on amount of change from existing design)
- Power consumption <phase>
- Power dissipation <phase>
- Net current carrying capacity <decision>
- Net voltage breakdown <decision>
- Surface mount components side A, side B <decision>
- Number of sides to circuit board <decision>
- Flexi/rigid <decision>
- No. of layers <decision>
- Material -FR2,3,4 . . . <decision>
- Material thickness <decision>
- Weight of copper <decision>
- Thickness of copper <decision>
A set of "post-layout processing" functions are required to provide the necessary computer linkages to production planning and production equipment. These have traditionally been implemented as separate programmes that are run after layout has been completed. However, one must partition the checks into three sections:

- **Run prior to layout**
- **Run during layout**
- **Run following layout**

Each of these issues will be dealt with in the below.

Specific prohibitions of function may also be imposed on layout tools. Where, for example, the tool is being used to modify an existing drawing the changes may be constrained to be in particular areas of the board surface or layer. The most common usage of this facility would
be in introducing un-necessary change to production by an unwitting design or layout engineer.

For example:

- **Manual or automatic layout on Repeat Order designs cannot modify tooling and assembly fixtures unless prior authorisation is obtained for the tool to do so.**

- **Variant design tooling holes and fixtures may be changed, but possibly only in certain areas of the circuit boards.**

- **Innovative and Strategic designs have no such constraints imposed upon them, although warnings will be given if constraints or cross-checks are violated during a design project. It is then incumbent on the project team to make specific provision where violations have occurred.**

### 9.2.9.1. Run prior to layout:

A number of mainly static checks must be performed on the engineering database, checking that the circuit data to be used conforms to company requirements and are classed as quality assurance measurements.

For reduced parts count/cost – performed and component sensitivity checks using Monte Carlo analysis by simulation tools or by various statistical experiments on the “real thing”.

A parts and wire netlist count of a design may be compared to a historical database of circuit boards and classified into rough “yield” bands. An expert system approach can embed this knowledge in a software programme and provide guesses as to the locations of possible manufacturing problems in terms of the raw netlist.

Requirements for circuit board material, copper densities, minimum wire thicknesses and other parameters also provide useful information for early yield estimates. These should all be available from the DFM constraints database.

Again static checks for rule infringement of manual and automatic assembly regulations by expected density of components.
Functional Specification

*And static checks for rule infringement of known field service limitations*, ie. part too heavy for one person to handle — against rule that field service is normally one man on site.

9.2.9.2. Run during layout:

*Of necessity a series of dynamic checks must be carried by layout tools as part of the optimisation process of the circuit board.*

*The ability to represent the physical accuracy of the printed circuit fabrication processes in the computer layout support tool to assess production yields.* The layout tool must be able to utilise production engineering constraints on circuit board tolerance to dynamically adjust track widths, separations and overlaps to improve production yield of the manufactured board.

At this stage in the design a circuit board topology is evolving a more refined yield estimate. The number of board layers and vias in a design may be compared to a historical database of circuit boards and classified into rough "yield" bands. An expert system approach can embed this knowledge in a software programme and provide guesses as to the locations of possible manufacturing problems in terms of the raw netlist.

9.2.9.3. Run after layout:

Tool and assembly sequencing are both complex sorting and optimisation problems. Often only a satisfactory solution is found rather than an optimal solution. Artificial intelligence techniques may well provide improvements on what currently is often a manual operation.

*Of necessity a series of dynamic checks must be carried by layout tools as part of the optimisation process of the circuit board after layout tool has completed.*
Tool sequencing: Set jaw size & minimum component spacing.

Translate sequences to machine tool control language.

Assembly sequencing: Using physical layout netlists parts may be sequenced for assembly. Algorithms are normally based on component size and assembly type (manual, pick 'n place, bandolier).

Translate sequences to appropriate machine or operator language.

Panelisation: The automatic jointing of small pcbs to construct one large one, saving on photoplotting and other costs.
9.3.1. Introduction

The “optional” Digital Circuit Engineering tools within the computer support tool framework are discussed below in relation to the core modules of the framework. Certain functional extensions to the core modules are also described.

Although most features discussed in this section are incremental enhancements of existing features present in digital engineering CAD tools. The major departure developed in the previous section and placed in context here is the concept of design product books. The argument is that insufficient design information is recorded in company archival data, so that when problems arise, either in production and field support or because an engineer leaves the company, the information needed to correct it is not to hand. Although various company procedures and practices have evolved in attempts to remedy the situation, non are linked in with computer design support tools.
The product book philosophy can play a useful role in capturing design knowledge so often missing from design reports of products.

Too much emphasis is currently placed on the circuit schematic diagram and its subsequent translation to circuit layout. This is partly due to the manner in which computer aided design (CAD) tools evolved, as graphics based systems, and partly due to the way in which engineers develop electronic circuits, as “one man team’s” where communication of design intent is restricted to the satisfaction of input/output signal constraints. The result is often a hand annotated circuit schematic diagram and much verbal communication between designer and other members of a development team.

A new way:
The product book approach requires that a circuit is now represented as a description supported by a circuit diagram. The description includes function, test, layout issues and other constraints of operation.

The problem is to force engineers to adopt the extra burden of writing their developing knowledge and design information down as they carry out their designing. Currently, schematic capture CAD tools offer immediate satisfaction to the drawing skills of the engineer, but textual material is often an add-on to a diagram in the form of “comment”.

Free-format comments (placed anywhere) are not particularly easy to version control or even track in the same way a diagram is, yet these comments are often of significant value to production, test or other group within a company. So, rather than making the schematic capture drawing package more sophisticated, the author recommends making the document preparation system capable of handling schematic diagrams. In this way, the system for handling company documents is tied tightly in with one of the major limitations of design knowledge capture, the paucity of information currently recorded in schematic diagrams in structured ways.

Design traceability:
Operational visibility is necessary for quality control by all engineers engaged in the design process. So that rules employed by CAD tools and the decisions made by them are always visible and thus traceable.
9.3.2. Design schematic capture and early layout

**Database structure:**
Section 9.2.2. (page 161) above recommends the use of a document preparation system to produce product books that describe, amongst other things, the design and production engineering of a product. This allows the design database to be template based, following the product book templates discussed in Section 9.2.6.2. (page 190) and design constraints templates and data discussed in Section 9.2.8. (page 201).

The routine use of template based writing, i.e. encouraging engineers to diligently fill in the gaps under a variety of template headings, can be problematic if the information required for the manufacture of a design changes from that described in the templates, although in practice only innovative and strategic designs are likely to suffer this problem; variant and repeat order designs being the more common and the least affected by change of this nature.

However, schematic and layout diagrams are still required, but their role is reduced to that of providing graphical illustrations, net lists of connectivity or topology to the circuit board, assembly and test stations (and to simulation facilities). The data needed to check that an evolving design is actually manufacturable or testable is held in other sections of the appropriate product book. So, now, the design database structure is that of the product books, with some machine readable sections – the net lists describing electronics circuits and their topologies.

9.3.2.1. Version control

*Version control of stored data follows company regulations: for example, development versions are purely numerical, once approved versions follow Alpha-numeric coding.*

*These must conform to recommendations described in Design Control in Section 9.2.7. above. Also, schematic editors must provide tracking of authors and date of change for the following types of circuit editing.*

*Author name, date of creation to be inserted in appropriate box on circuit drawing.*
Author name, date of edit to be inserted in correct revision box on circuit drawing.

Author name, date of commentary to be inserted in appropriate box on circuit drawing. No change to the circuit is involved. Only the addition of a commentary.

The ability to guarantee that a circuit net-list is not changed by just adding a comment. This allows circuit release level information to remain unchanged, but the edit version to be updated and effectively differentiating between production information and engineering information.

**Hypertext:**

Arbitrary text (selection of fonts, sizes, and orientations) and graphics insertable in drawings without upsetting the electrical consistency of the circuits.

An on-line equivalent of the engineers’ notebook is necessary to capture the notes and comments relating to specific drawings under development. Hypertext techniques can be used to display the commentaries.

#### 9.3.2.2. Check for electrical consistency

Check for unconnected wires.

Check for illegal connections. For example, two outputs shorted together that are not wired-OR or wired-AND circuits. Some things are technology dependent, for example bidirectional gates (transmission gates) are only available in MOS technology, not bipolar.

Check fan-out of device is not exceeded.

Check fan-in of device is not exceeded.

Check connector pin wiring consistency (plug to socket naming and wiring) error on wrong power connections, warning on other inconsistent wire naming.

#### 9.3.2.3. Other facilities

**Embedded simulation:**

Digital logic designers are sometimes unable to think coherently about Boolean logic operations.
The ability to simulate a small part of a net to confirm the correctness of a circuit connectivity. This can save design time by not requiring edit-compile-simulate loops, which is the normal mode of circuit simulation. Some circuit schematic editors provide this as standard.

Early placement and other routing constraints:
The underlying constraint consistency mechanisms discussed above in Section 9.2.8.1. (page 202) may be driven directly from engineer interactions with the digital engineering tools. Thus allowing an engineer to modify or add a constraint to the constraints database for a design whilst using the schematic editor. These have already been discussed in the above section.

The ability for a design engineer to specify a constraining physical location for a component or wire route on a circuit board prior to submission to layout drafting.

Viewing constraints:
As proposed earlier in Section 9.2.8. (page 201) engineering constraints come in many different shapes and sizes; so the manner in which they may best be viewed will depend on the type of constraint, whether they be displayable graphically or numerically, list or table is not easy to define at this stage.

However it is likely that the choice of display technique may well be company specific and so should be user definable.

Extraction of parameters during edit sessions:
The ability to construct a costing, in financial or other terms, of the current circuit under development. For example: the total financial cost of the circuit or sub-circuit; the total physical area of all the components; or some arithmetic combination of such parameters to allow estimates of production costs.

9.3.3. Device models

Device models currently embody arbitrary naming properties, device pinouts and device graphical symbol attributes. The device pinouts and symbols are used to convey the schematic diagram wiring structure to the engineer and to the net listing software. The
named properties usage is not often prescribed by CAD tool vendors, leaving the engineering company to decide the best function of this facility.

The most common use of named properties is to convey component layout constraints to the layout and placement algorithms in the pcb and other layout packages. Much needs to be done in terms of standardisation of naming conventions for this use, since they are normally tied to specific layout tool packages.

*It is also logical for the librarian programme (that maintains the company library of components) to be tightly integrated with inventory control and component approvals procedures, so that all necessary parts cross-references are available from purchasing, from design and from quality assurance.*

### 9.3.3.1. Properties required to be embedded in library components

**Symbol graphics:**
These are the graphical attributes of the device model, including body, pins, instance name and company part reference number.

**Function:**
A mathematical model of the function of the device, representable hierarchically and mixed at any level; for example part described in VHDL, part in circuit schematic diagram.

**Electrical attributes:**
These are the tolerances of the device functions and also known side-effects of device operation, for example radio frequency interference.

**Mechanical attributes:**
These are the physical dimensions of the component, including mechanical tolerances (discussed below).

**Manufacturing attributes:**
These include whether the component may be vapour phase soldered or immersed in water for cleaning. Also the cost of assembly and related constraints and polygonal no-go areas for place and routing for electrical and manufacturing reasons.
**Parts attributes:**
To specify a mechanical tolerance for each physical entity on the circuit schematic diagram and thence on the layout diagram.

Each physical attribute of the final physical circuit has a manufacturing tolerance. Most of these tolerances will be vanishingly small when compared to the assembly process and the tolerances of the circuit board manufacture and component population thereof. However, under certain conditions these tolerances accumulate and become significant factors for production yields. It is therefore necessary to maintain tolerance values for all aspects of components, to reflect the real-world physical process variations.

The decision to not use device tolerances is then available to design and production engineers, rather than the present situation, that they are often un-obtainable and therefore unwittingly ignored.

**9.3.4. Design for manufacture**

Design for manufacture is extremely important. Designs that are likely to not be manufacturable or have low production yields must be detected early on in the product development process and assessed for viability. As part of this activity it is clear that design engineers must have "ownership" of the problem, since they are probably the only company personnel capable of recognising deficiencies in an evolving design.

* A number of features are necessary, they are described below:

**9.3.4.1. Process characterisation**

*Automatic dissemination of process data and results.*

Although the collection of this data is routine for production and quality engineers, the dissemination is not always automatic, so the information must be fed into the company DFM database, proving design engineers with the means to understand the relationship between the schematic view they have of production to that of the real-world, via improved
models in their simulation and decision support tools. This is especially important in analogue, high speed digital and microwave designs.

9.3.4.2. Parameter extraction

*Routine parameter extraction as measured by in-coming parts inspection.*

Manual and automatic parameter extraction of circuit and manufacturing parameters on incoming components and sub-assemblies provide a means of assessing the impact of each component on the design and manufacturing processes. This is an on-going activity and feeds the DFM database that is used by engineering teams to evaluate design and manufacture issues.

The combination of both circuit and manufacturing parameters in the DFM database is important, since this clusters information that is of immediate value to the design engineer (the circuit parameters) with the (what is often perceived as) less useful information and data on manufacturing. In terms of CAD tool interactions, this means that the manufacturing data essential for DFM is displayed in the menu structure of the on-line (or on paper) reference book and is therefore more likely to be attended to by a design engineer.

9.3.4.3. Design costs

*Component costs must be available as part of the DFM database, the costs should be related to particular manufacturer sources and thus to component parameters and their tolerances.*

This is since different manufacturers may use the same part number for what are two subtly different devices, for example: different contact wire pitches or different functional, voltage or timing specifications (see Section 9.2.8.5., page 206 above).

Ultimately a decision to rename a part based upon an accumulation of these differences may have to be made (design and production engineering must be made aware of these changes and their reasons through the DFM database).
9.3.4.4. Assembly estimates

*All costs of assembly must be included in a DFM database.* This is done to pass the ownership of manufacturing costs to design engineers. This can best be achieved by adding these costs on a piece by piece basis to component libraries for CAD tools.

9.3.5. Testability assessment

*Test connector types, test probe access to components and test points and also product modularity and common test assemblies recommended or preferred by test engineering.*

9.3.6. Layout constraints

*Restrictions imposed on a design by tooling holes and fittings must be made available to both designer and drafting engineer.*

Manual or automatic layout on Repeat Order designs cannot modify tooling and assembly fixtures unless prior authorisation is obtained for the tool to do so.

Variant design tooling holes and fixtures may be changed, but possibly only in certain areas of the circuit boards.

Innovative and Strategic designs have no such constraints imposed upon them. Rather they exist as reminders and only warnings are issued if they are broken.

9.3.7. Design functional description

*Provide simulation of arbitrary electronic circuits, at varying levels of detail as part of the process of proving product function and manufacturability.*

*Estimate engineering costs and check adherence to company standards and function across the operating range of parameters.*

The list given below is intended to show areas of current support for simulation in commercial products, it is expected that tool control, systems integration and exchange of
data between these separate tools will be possible under the various standards initiatives through CFI, JESSI and STEP.

9.3.7.1. Mathematical modelling

The following are optional technology support tools:

• Arithmetic manipulation tools

• Symbolic algebra manipulation tools

9.3.7.2. Behavioural modelling

The following are optional technology support tools:

• High level modelling of behaviour – for example Saber, Ella, VHDL.

  High level circuit modelling is now becoming a standard feature of digital logic CAD simulators, where mixed circuit level and VHDL models can be simulated together.

9.3.7.3. Circuit level modelling

The following are optional technology support tools:

• Digital logic circuit simulation

• Mixed analogue circuit and digital logic circuit simulation

• Analogue circuit simulation

• Digital timing assessment

• Microwave circuit simulation

• Electro-magnetic simulation (2 and 3 dimensions), transformer and motor design for example
• Circuit interaction modelling – EMC, RFI, signal noise
  All should provide circuit signal timing over the full range of operating parameters.

9.3.8. Design physical layout

Physical placement and routing of schematic diagrams onto integrated circuits, hybrid ceramic substrates and onto printed circuit boards (flexible or rigid) are essentially solving the same problem, that of maze routing.

However, the only distinction between these disparate types of layout is that different constraints of the manufacturing processes are used in the fabrication of the parts. Integrated circuits are possibly the most constrained of layouts and are relatively easy to define limits for and thus to programme software tools for conformance to. Hybrids and printed circuit boards are less well constrained and thus more difficult to define limiting design factors for and therefore to control automatically.

The minimum functions required are:

• Manual and autoplacement of components
• Manual and autorouting of circuit wires
• Photoplotter aperture definitions – numbers 200-300 defined as portable standards

Functions required in addition to the minimum required for the automatic generation of artwork suitable for photoplotters are:

• Template definition of manufacturing artifacts (locating holes for example)
• Pre-defined circuit board shapes
• Arbitrary router and placement no-go areas attachable to any circuit board component as part of symbol, as defined above in Section 9.3.3.1.

• Ability to route and place according to text-based rules defining design and manufacturing constraints as discussed in Section 9.3.4. above.
9.3.9. Design testability

A variety of functions are required for testability analysis. In respect of analogue circuits:

- Test point generation
- Calculate voltage and current tables for test points
- Calculate waveforms at test points and generate test documentation

and for digital circuits:

- Test point generation
- Simulation of Functional test patterns and results
- Fault coverage
- Automatic test vector generation
- Automatic test circuit insertion
- Calculate waveforms at test points and generate test documentation

Automatic test of analogue circuits is not as well advanced as for digital logic circuits and will continue to be so, and therefore one additional reason why so many companies are employing digital techniques in their new designs.

9.4. DESIGN INFRASTRUCTURE

The fact that Japanese electronics firms face intense domestic and international competitive pressure requires them to maintain a high rate of new product introduction. It was not surprising to discover that all three Japanese companies visited undertake considerably more product design than any of the UK, European or US firms who participated in the research.

The research showed, crucially, that the product design and manufacture success of companies like Toshiba, Sony and Fujitsu regarded design as being of strategic importance to their business and they have each evolved a product design and product engineering support system or infrastructure which transcends individual projects. Such infrastructures, by facilitating the organisational learning process, enabled them to continuously improve both the design of their products and the processes by which those products are manufactured.
The more they design, the better they become at rapidly getting high quality products to the marketplace. This has been discussed in detail in Chapter 4 and the reader is referred to the relevant pages for further reference and in [119,120,121].

9.4.1. Design policy and strategy

An essential first step in establishing a successful design function is to recognise the fundamental importance of design and product development to the business. To do this the senior management team should demonstrate their commitment to design by implementing an appropriate design policy and strategy.

To be effective both the policy and the strategy should be documented and circulated throughout the company. Appropriate resourcing, at least with respect to prioritising any available spend, would further demonstrate this support. In terms of EDA tools a budget needs to be established for the improvement of existing facilities and to fund the development and training of design engineers.

However, adopting a strategic view of design requires more than financial resources it requires that good design practices be documented and implemented. Management must ensure that agreed procedures are followed. In this respect the EDA tool should monitor...
and control the progress of the evolving design through defined release gates and maintain appropriate version control. Electronic sign off should be used to ensure that design changes are communicated and approved by identified personnel.

9.4.2. Design Infrastructure

Having established an appropriate design policy and strategy an on going design infrastructure needs to be created. In the context of an electronics manufacturing company, the design infrastructure consists of the totality of supporting functions which allow the design activity to take place. As such, the design infrastructure includes provision of technology support in the form of appropriate engineering design hardware and software platforms. It also embodies a variety of organisational and cultural elements, the most significant of which include.

• The management policies, procedures and practices which ensure the effective management and control of design.

• The methodologies or guidelines adopted to ensure the various design tools are used correctly and support good design practice.

• The management methods used to ensure designs conform to requirements.

• The procedures necessary for identifying, capturing and re-using company knowledge.

• Policies providing for long term investment in people in order to enhance skill levels, improve job satisfaction and reduce staff turnover.

• The creation of an environment which promotes active, cross functional communication and which encourages the frequent, personal sharing of information and knowledge. This is outside the scope of this guide and the reader is referred to Harvard Business School report N9-491-066 [122].

9.4.3. Organisation for effective design

9.4.3.1. Design Information and knowledge management

Electronics product development involves the generation and use of considerable amounts of information. In most companies, much of the knowledge of how to use this information
is lost and needs to be recreated as design teams move from one project to the next. It is also
typical for companies to lose experienced staff, many of whom take with them a
considerable amount of vital knowledge and "wisdom."

Hence, it is vital that documentation of all information and knowledge generated during
product development be carried out according to an agreed set of rigorous corporate
standards. As part of this process, it is recommended that at least one member of the team or
committee involved in evaluating the product design be assigned the role of "scribe." After
each creative/analytic/audit process is undertaken, the scribe must ensure that the output of
that activity does not remain simply a "red penned" document. He or she must be tasked
with revising, updating and circulating the document in question and with ensuring that all
change control and/or configuration management procedures are complied with.

Elements of corporate knowledge which can and should be captured e.g:

- Library of approved components should be held in corporate knowledge base.
- Cost data, with respect to components and processes.
- Bid stage. Standard set of key cost issues. Analyse the key differences and
  apply them to standard calculations. This assumes companies have data
  indicating that the jobs they had successfully bid for had actually turned a
  profit for the company.

9.4.3.2. Systematic approach to learning from experience

In infrastructural terms it would appear to be a particularly sensible proposition that, just as
in Japan [123], organisational learning should play a vital role in the product development
strategies of U.K. and European electronics companies. However, the research has clearly
demonstrated that in this, as in a number of other competitive dimensions, these firms fared
poorly.

No U.K. and European companies in the survey had any formal, enforced procedures for
identifying, capturing and reusing company design or manufacture knowledge. Indeed,
most firms had clearly not even considered creating such organisational structures as a
means of improving their design to manufacture performance -- despite the fact that considerable unease was expressed over the amount of vital engineering knowledge which existed only in the heads of key employees.

9.4.3.3. Retaining hard won knowledge and skills

Low staff turnover can increase company effectiveness in a number of other ways, not least because it is possible for those firms to retain hard won engineering experience, which is not usually recorded either in a computer database or on paper, within the company. In particular, it should be noted that:

- Staff turnover loses company knowledge
- Staff turnover loses company secrets
- Staff turnover loses unwritten documentation
- New staff take time to integrate and make errors during the learning process
- New staff can bring with them a "Not Invented Here" approach and prefer to avoid re-use of company designs

However, it must also be acknowledged that:

- New staff bring new ideas

9.4.3.4. Multi-disciplinary teams

Companies should make maximum use of design teams in order to ensure that the appropriate expertise is applied to the project at the required times. Interdisciplinary teams consisting of personnel from electronics engineering, mechanical engineering (mechanisms and materials), software engineering, production engineering and technical authoring should be created for each project. While it will also be necessary to include representatives from marketing and purchasing from time to time, other useful input to the
product development process can be obtained from industrial designers and social scientists, the latter advising the team on changing social and behavioural attitudes among the products potential purchasers.

Figure 29 below highlights one possible multi-disciplinary product development team configuration. It also shows that the various product development activities occur in parallel with each other.

**Figure 29: Product development team configuration**

<table>
<thead>
<tr>
<th>Product development project</th>
<th>Engineering <em>(Product design)</em></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Technology <em>(Architecture, Logic, LSI . . .)</em></td>
</tr>
<tr>
<td></td>
<td>Manufacturing technology</td>
</tr>
<tr>
<td></td>
<td>Equipment <em>(Manufacturing, Test)</em></td>
</tr>
<tr>
<td></td>
<td>Design tools <em>(CAD/CAE)</em></td>
</tr>
<tr>
<td></td>
<td>Test, maintenance, diagnosis <em>(QC/QA)</em></td>
</tr>
<tr>
<td></td>
<td>Information systems <em>(Technology/market trends)</em></td>
</tr>
<tr>
<td></td>
<td>Marketing</td>
</tr>
<tr>
<td></td>
<td>Industrial design</td>
</tr>
</tbody>
</table>

**9.4.3.5. matrix organisation**

Matrix structures should be employed as a means of effectively managing project personnel. The matrices are organised as sets of technically specialised "columns", each headed by a technical manager. As Figure 30 below illustrates, a new project is allocated a "row" across the matrix, and personnel with the necessary skills are selected from the technical columns. A project manager, typically drawn from the company's engineering function, is tasked with managing each row. Projects may require marketing knowledge, purchasing knowledge or even accounting knowledge at different phases in the design process, hence these skills could form additional column specialties in the product development matrices.

While not all skills will be required for every activity, the correct expertise set must be applied at the appropriate times. This is particularly important where group decision-making or creative meetings are scheduled. In such circumstances, it is vital to
bring differing viewpoints to bear on problems in as “ego-less” and un-biased an environment as possible.

9.4.4. Human resources

While acknowledging the difficulties involved in attempting to transplant Japanese organisational practices into Western manufacturing environments, it is nevertheless instructive to note that the lifetime employment system practiced by the larger Japanese corporations enables those firms to trust their employees with even the most confidential information, secure in the knowledge that it is unlikely to be “leaked” to competitors. Low staff turnover (around 2% per annum in the firms visited) can increase company effectiveness in a number of other ways, not least because it is possible for those firms to retain hard won engineering experience within the company.

9.4.4.1. training

Employee training in many U.K. electronics companies is inadequate and has typically been used to support mature processes, often resulting in highly motivated graduates being placed in stultifying environments where they feel their talents are being wasted. In addition, it has traditionally been constrained by limited budgets and by management fear.
that expensively trained staff will defect to competitors offering promotion, higher salary and more challenging jobs.

Such concerns are understandable. There is no doubt that loss of experienced and highly qualified engineering staff can represent a serious competitive problem to any electronics business, particularly since, in most cases, they will take with them irreplaceable knowledge and wisdom which is unlikely either to have been written down or captured electronically. Nevertheless, companies are more likely to retain engineering staff who have been effectively trained in a manner which reflects best practice.

Training programmes should be carried out in a variety of ways. Classroom based, on-the-job training (OJT), continuous updating of skills and so on. It should be noted that OJT is widely used in the leading Japanese electronics companies and is certainly a technique that used to be common in the UK.

In addition to the normal concept of training, new engineering staff should be trained in the Four Path model of engineering design, to develop their understanding of minimisation of risk in company design. Repeat Order and Variant design should be taught first, followed by Innovative and Strategic design, to ensure that the skills of production engineering and engineering change are understood before progressing to more “blue-sky” and un-constrained design work.

9.5. SUMMARY

A functional specification for a next generation CAD toolkit has been shown. It has been partitioned according to Best Practice recommendations and aspects of the Four Path model of engineering design.

The specification deals with three aspects of design and thus makes recommendations for (i) company infrastructure, (ii) common base design functionality and (iii) digital design support functionality (an optional tool within the framework).

Company infrastructure is concerned with information management, the operation of multidisciplinary teams, matrix management organisation and training of personnel. The
Functional Specification

common base functionality specifies a human computer interface, a document preparation system, project management functions and an electronic mail system for the proposed CAD toolkit. It also defines a design database structure, which is centred around the product book concept, design control functions and a new system of constraints and consistency checking of designs. Finally functional links to production engineering are presented.

9.6. REFERENCES FOR CHAPTER 9.


10.1. CONCLUSIONS

In conclusion, this thesis derives a functional specification for a CAD tool framework for
the support of electronics product design. The specification has been developed from an
understanding of the problems encountered by electronics designers in industry, from best
practises in industry and from a new model of the electronics product design process
developed from a review of the literature and from a series of case studies of electronics
design in industry.

The author asserts that this thesis develops three contributions to knowledge in the domain
of electronic product design (a) a case study review of problems encountered during the
design of an electronic product in the industry, (b) a new model of the design process and
(c) a functional specification for a next generation CAD tool framework. Conclusions for
each are presented separately below.

10.1.1. Case study

In depth interviews with senior designers and their management in a wide variety of
electronics companies have been completed. Analysis of those interviews has allowed the
author to describe the problems and achievements of electronics designers in what is a
diverse and highly competitive industry. It is clear that the most pressing problems in
electronics design are those of management and communication rather than short comings
of existing computer aided design tools. Although is also clear that current CAD tools exist
in relative isolation from the business of design as point solutions to technological design
problems (logic synthesis and automatic schematic layout for example).

The conclusion drawn from this is that computer aided design tools must provide support
for design management and communications in order that their advantages of consistency
and speed can be fully integrated into the complex business of electronics product design.
Conclusions

The development of CAD frameworks to satisfy the need for uniform HCI and database exchange across CAD disparate (and vendor independent) tools is insufficient and a functional specification that attends to the combined needs of both people and business practices during the design process is required. One such functional specification has been presented and debated in this thesis.

10.1.2. New model of the design process

A four path model of electronics engineering design has been presented. It allows engineering management to develop a portfolio of design types based upon their effect on existing design and production facilities. Strategic designs allow growth into new technological areas over the medium and long term. Innovative designs explicitly involve creative thinking and Variant designs are mainly market driven in terms of the additional design work involved. Repeat order designs are constrained to prevent engineers from unwittingly altering production or assembly features of a design, so minimising the impact on production of small changes to existing designs.

The four path model relies on two fundamental assertions (a) that limited design knowledge (either personal internalised knowledge or external access to knowledge) will constrain the design capabilities of designers and (b) a design's innovation may need to be controlled to limit the amount of change imposed on production by a design. The first is a natural result of using people to design entities (recognising that designers behave as “administrative men”, cf: New knowledge, page 88) and the latter only holds if changes to production will have a financial impact on a company. This will be true whilst the underlying trends in technology are towards tighter and tighter manufacturing tolerances and towards finer and finer circuit dimensions. Reductions in both tolerances and dimensions have real cost implications to electronics product production and cannot be ameliorated by investment in flexible manufacturing systems and thus are parameters that require careful management by engineers engaged in design and production engineering.

The selection of design path is aided by the author's development of two mathematical expressions Design Complexity and Design Yield. Design Complexity provides a formal
Conclusions

way of ascribing a risk factor to a design, it allows the estimation of the amount of new knowledge required by company personnel to complete a design. The greater the amount of new knowledge required, the greater the project risk. Design Yield provides an estimate of manpower required to complete a project, based on a design’s Complexity measure.

Together the Four Path Model and the Design Complexity and Yield metrics provide a formal way of describing a company’s design portfolio, one that is specifically based upon the knowledge base which exists within a company’s personnel.

10.1.3. Functional specification

The functional specification developed is new and attends to the real industrial requirements of CAD tools and their support frameworks, not just the technological needs of design. This has been shown to include design policy, human to human communications, design configuration and change control, design product books and the application of constraints on the evolving design.

Functional specifications for CAD tools have tended to rely on user feedback to guide their specification in what can only be described as ad hoc market driven changes. As a result they have grown in a way that does not necessarily optimise the overall design process, but rather in ways that improve the short term needs of designers by, say, adding new features to aid very specific design functions at the expense of tying the control of CAD tools together in ways that have direct bearing on engineering design procedures and practices; by for example adherence to BS5750: part 1, or by designing for manufacture, instead of faster layout algorithms or circuit synthesis tools (driven by the integrated circuit design community and not necessarily from the other areas in electronics design).

Design policy and Best practice:

The 4 path design process model is used to control the implementation of design policy and the application of Best Practice to company design practice. Aspects of design management are implemented directly in CAD tools when appropriate. So, for example, the assertion of “repeat order design” status on a product book forces much of the data, information and
design knowledge held within it to be read-only. Such locking, for example, prevents critical manufacturing specifications from being altered.

**Communications:**
Electronic mail is used as the vehicle for controlled information exchanges and change control requests. Mail is integrated within the Product book system and allows direct access to electronic mail during a design editing session.

**Design product books:**
It is erroneous to assume that schematic capture tools provide a rich and definitive description of a design.

An integrated method of design capture has been presented that de-emphasises the schematic diagram as the repository of design knowledge. This is replaced by an active document system called product books.

Product books are hierarchically organised to allow both simple and complex projects to be handled.

Software daemons maintain design consistency and provide viewpoints of the design documentation suitable for design, production and purchasing.

Designs exist within the product book structure as text and schematic diagrams within a skeleton framework of sections, each providing information for different aspects of the design and manufacturing process.

Theoretical and practical domain knowledge may also be integrated into the product book scheme simply by including electronic versions of textbooks and other reference material into the product book system.

**Constraints:**
Product books contain definitions of manufacturing and other constraints. Each constraint is maintained within a constraints propagation system that automatically highlights violations. The severity of the warning is related to the type of design path being followed in the current design product book.
Design configuration:
Design configurations and engineering change controls are applied to product book sections, diagrams and constraints.

The author has validated his theories and derivations by seeking the advice of practitioners at all stages in the research. Thus the 4 path model and the functional specification have been refined by the comments received from design managers and professional designers in electronics companies.

10.2. FURTHER WORK

The researches carried out for this thesis have generated a substantial amount of potential further work, described below, most of which is empirically based upon cognitive psychology and ethnography.

10.2.1. Review a company operating the 4 path model

The 4 path model has been reviewed by a number of industrial design managers. Their comments have all been very favourable, but the acid test of the model would be to evaluate its usefulness to a company engaged in electronics product design and manufacture. To this end the author has entered into dialogue with design management in several companies as part of the final qualification of the 4 path model. It is hoped that refinements to the model gained from this detailed analysis by third parties will be available within a few years.

10.2.2. Study design group interactions

Improvement to the design process can only be possible if the interactions between people working in product design are well understood. A number of studies of individual design engineers have been discussed earlier in this thesis, but group interactions in technical and social levels are necessary before a fuller understanding of design is possible. The work of Noud Hendriks and colleagues at Philips consumer products research group in Eindhoven is relevant here (discussed in models of the design process), but in addition the author of this thesis has recently initiated research into the social interactions in the work place. This
includes designer to designer and designer to design management interactions. It is hoped that this work will enable extensions to the studies and conclusions of this thesis.

10.2.3. Evaluate designer schema access and value to creativity.

A key feature of the 4 path model is the segmentation of design into categories. It is intuitively obvious that each of the four paths requires the engineer to exhibit different types of design skill. But it is not clear whether one should expect experts or novice engineers to be better at particular types of design. The traditional view is that more experience of design both in depth and in breadth is what makes an expert. Although this is borne out by psychological studies of the differences between expert and novice, it does not demonstrate any predeterminate ability at different types of design. Experts exhibit top-down design, breadth first goal seeking behaviour predominantly and novices show a predominance of top-down depth first searching behaviour. This is intuitively obvious, since experts already have assimilated the necessary design technology and physics at the bottom level in design terms, whereas novices will be lacking this knowledge and will be forced to seek it whilst they are actively designing.

The problem is that depth first goal seeking behaviour is arguably not good for defining the linkages between blocks in a design, and in fact novices have been shown to make more mistakes than experts at these interfaces. So it could be theorised that experts could be good at repeat order design and also at variant design. But, as they are so well practised at running down their internalised design schemas of previous designs they may well not be as good at innovative design as novices. Strategic designs explicitly require new knowledge and are therefore perhaps more dependent on the learning abilities of individuals rather than their abilities to traverse their own knowledge bases in novel ways.

Additionally novices are unlikely to have knowledge of past failures in their design experiences, making innovation easier, since they will not reject a potential solution at a top level in a design hierarchy, but will progress a solution down to its technological basis. Whereas an expert may well mis-classify the potential solution as being similar to a previous failed design solution and thus may well label the design solution as a blind alley
Conclusions

and follow other, more orthodox, routes to a solution; and thus missing the innovative solution completely.

So the author proposes to investigate the relationship between innovation and design experience in a structured way using techniques developed in the PEDA and Desmate work.

10.2.4. Product book evaluation

The concept that information (and knowledge) is central to design has been introduced in the development of the 4 path model of design. This assertion has led to the idea of company archival standards for design information being based around the Product Book concept. Although a prototype product book editor has been developed (an example is shown in appendix 4.) a more detailed examination of its feasibility in an industrial environment is necessary. Therefore the author suggests that an entire production constraints database for a small design be collected and embodied within the tool to test out the ease of use together with a review of the effectiveness of the concept. To this end the author has contacted a number of companies with a view to seeking this information.

10.3. FINAL CONCLUSIONS

Taken as a whole, this thesis provides a firm footing for future research in design science and in computer support systems for the electronics industry.

The author has reviewed the use of computers in the electronics product design process. Best practices and problems encountered in design have also been observed in a case study encompassing a wide range of electronics companies, from small enterprises to large multinationals.

A new model of the design process has been developed that addresses the needs identified from the case study and also extends current models of the engineering design process to cover aspects of human cognitive limitations and company knowledge, as well as showing how designs may be evaluated according to their impact on production. The model and the
best practices have given rise to a new concept for company engineering documentation, the Product Book. These also provide a logical framework for constraining CAD tools and their users (designers) as means of controlling costs in the design process.

Finally a new functional specification for next generation CAD tools to support the electronics product design process has been synthesized from a review of the existing design techniques and CAD support, from the Four Path model and from Best Practices. This specification differs from current perceptions of computer functionality in the CAD tool industry by addressing human needs together with company needs of computer supported design, rather than just providing more technological support for the designer in isolation.
APPENDIX 1. CASE STUDY

QUESTION TEMPLATES
1. COMPANY PROFILE

1.1. Type of business:

1.2. Major product types:

1.3. Personnel:
   1.3.1. Administration:
   1.3.2. Design:
   1.3.3. Production:
   1.3.4. Test:

1.4. Turnover:

1.5. Competitive dimensions: (Cost, quality, reliability)

1.6. Level of competition:

1.7. Main competitors:

1.8. Types of computer support tools: (Design & manufacture)
   1.8.1. Electronics design:
   1.8.2. Mechanical design:
   1.8.3. Manufacture:

1.9. New designs/period:

1.10. Production volumes/year:

2. STRATEGY

2.1. Overall company strategy:

2.2. Position of design within strategy:

2.3. Successes and failures in product introduction:

2.4. Product market share:

3. MANAGEMENT PROCEDURES

3.1. Design review procedure: (Concept to prod.)
   3.1.1. Description of signoff stages: (Incl. adherence)
   3.1.2. Problem areas/iterations:
   3.1.3. Standards adhered to:

3.2. Simultaneous engineering: (Yes/no & degree of success)

3.3. Engineering Change Control:

4. NEW TECHNOLOGIES/MATERIALS

5. DESIGN METHODOLOGY (Engineering practice between sign-off)
Appendix 1

5.  IDEFO validation: (Comments/diagram)
   5.1. Diagram identifiers:
   5.1.2. Comments:

6.  MANUFACTURING METHODOLOGY
   6.1. IDEFO validation: (Comments/diagram)
       6.1.1. Diagram identifiers:
       6.1.2. Comments:

7.  INFORMATION
   7.1. Product:
       7.1.1. Storage: (Incl. staff turnover & problems)
       7.1.2. Presentation:
       7.1.3. Policy:

8.  CUSTOMER RELATIONSHIPS
   8.1. Specification engineering: (Well constrained/wandering goal-posts)

   8.2. Level of contact:
       8.2.1. Joint development/design:

page 242
9. **SUPPLIER RELATIONSHIPS**

9.1. Level of contact:

9.2. Quality issues:

10. **CONFIGURATION MANAGEMENT**

10.1. Techniques:

10.2. Problems:

11. **TOOLS:** (Usage/problems/support)

11.1. In-house:

11.2. Bought in:
APPENDIX 2. CASE STUDY COMPANY PROFILES
2.1. Outline descriptions of UK/European case study companies

Please note that for reasons of confidentiality each UK/European company is only referred to by its organisation number.

<table>
<thead>
<tr>
<th>Org</th>
<th>Sector Type</th>
<th>Turnover £M</th>
<th>New designs per period</th>
<th>Production volumes per period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PCB manufacture</td>
<td>600</td>
<td>1000 ECNs/month</td>
<td>8000 boards per week; 1000 different boards per week</td>
</tr>
<tr>
<td>2</td>
<td>PCB contract work</td>
<td>3</td>
<td>4 per day</td>
<td>300,000 sq ft of board per year</td>
</tr>
<tr>
<td>3</td>
<td>Automotive electronics</td>
<td>1,307</td>
<td>6 new; 6 revisions/year</td>
<td>50K – 100K per product</td>
</tr>
<tr>
<td>4</td>
<td>Aerospace</td>
<td>601</td>
<td>2 per year</td>
<td>1500 per year: 750 systems, 750 boards</td>
</tr>
<tr>
<td>5</td>
<td>Telecoms, analog products, support tools, research</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>Programmable controllers</td>
<td>44</td>
<td>1/year new, 2/year upgrade, 3/year fault correction</td>
<td>750 units/week</td>
</tr>
<tr>
<td>7</td>
<td>Sailboat and power boat instruments</td>
<td>5</td>
<td>4/5 improvements to existing products/year</td>
<td>200–3000 per year</td>
</tr>
<tr>
<td>8</td>
<td>Defence C3I systems</td>
<td>20</td>
<td>20 new boards per year; 3 – 5 reworks/board</td>
<td>100 off for boards; 5–10 whole systems</td>
</tr>
<tr>
<td>9</td>
<td>Electronic/electromechanical devices</td>
<td>5</td>
<td>10–12 per year</td>
<td>100–200K</td>
</tr>
<tr>
<td>10</td>
<td>Consumer electronics products</td>
<td>100</td>
<td>1/year new; 25–30 derived models</td>
<td>35 PCBs per month across 40 TV models; 11 main board chassis each; 350,000 TV sets</td>
</tr>
<tr>
<td>11</td>
<td>IC product design and fabrication</td>
<td>42</td>
<td>5/year new</td>
<td>500 total wafer starts per week. 10 million devices per year</td>
</tr>
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</table>
### TABLE 1 (Contd)

<table>
<thead>
<tr>
<th>Org</th>
<th>Sector Type</th>
<th>Turnover £M</th>
<th>New designs per period</th>
<th>Production volumes per period</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>High volume capacitor design and fabrication</td>
<td>15</td>
<td>2/year new</td>
<td>80K per week</td>
</tr>
<tr>
<td>13</td>
<td>Transactional electronics</td>
<td>200</td>
<td>2/3 per year product support; 2/3 strategic development; 30/40 major changes</td>
<td>10K–100K per year</td>
</tr>
<tr>
<td>14</td>
<td>Consumer electronics</td>
<td>6,400</td>
<td>3/4 year new; 3/4 year adaptations; 50 redesigns</td>
<td>Company unwilling to reveal this information</td>
</tr>
<tr>
<td>15</td>
<td>Automotive electronics</td>
<td>178</td>
<td>15–20/year new; 2/year redesigns; 10–15 per year changes due to design faults</td>
<td>Low volumes on each of a wide range of products</td>
</tr>
<tr>
<td>16</td>
<td>Radar systems</td>
<td>---</td>
<td>80 new PCB designs/year</td>
<td>1–10/year</td>
</tr>
<tr>
<td>17</td>
<td>Defence electronics</td>
<td>9,805</td>
<td>30–40/year new; no information on reworks</td>
<td>1/year– 240/month</td>
</tr>
<tr>
<td>18</td>
<td>Hybrid circuits</td>
<td>1.5</td>
<td>3/month new; 3/month redesigns</td>
<td>100 – 1000</td>
</tr>
</tbody>
</table>

### 2.2. Outline descriptions of U.S. case study companies

#### 2.2.1 Data General — Boston

Data General (DG) in Boston is primarily concerned with electronics design. In fact, design is regarded as so central to corporate survival that it is resourced at over 10% gross annual turnover. In addition, the R&D function is given preferential treatment with staff there given better salaries and working conditions. Fabrication of the company’s products is carried out away from Boston at sites both within the United States and in Japan. The Boston site employs some 9,300 staff, of whom 300 are engineering staff.

DG competes on two main dimensions: time-to-market and on hardware processing speed. The company currently has two strategic product lines, the Eclipse (proprietary architecture) and the AViiON (Open Systems) product ranges. They currently have about a one year cycle time on Eclipse developments and nine months on their AViiON open systems.
2.2.2 MIT Computer Architectures Group — Boston

The MIT Computer Architectures Group is involved in a number of research projects, some of which are funded through the U.S. Department of Defence. The projects include:

- The "J-machine" project investigating fine grain parallelism using around 1000 nodes in a three-dimensional mesh ($1 million U.S. DOD contract)

- A shared memory 64–256 node machine

- A high speed routing chip using 50–100Mhz channels

- A custom DSP support base

- A directory-based caching system for multiprocessing

It was discovered, however, that the MIT group was not using any advanced tools or techniques for either hardware or software design.

2.2.3 Hewlett Packard Printed Circuit Division — Palo Alto

With an annual turnover of $140 million, the Hewlett Packard (HP) Printed Circuit Division is the third largest fabricator of Printed Circuit Boards (PCBs) in United States. The division has four plants world wide, two of which (in Japan and Mexico) are joint-venture companies.

The Printed Circuit Division has a world wide system called Order Express that can post a PCB schematic from CAD to a manufacturing plant in 22 minutes. If it fails a design rule check (DRC), corrective action can be initiated by the remote CAM engineer who can circle the fault on the diagram. The layout engineer will see this mirrored on his display in real-time. HP currently takes 33 hours to post PCB schematics and initiate production, but they aim to cut this to 45 minutes. It takes their best competitors 5 days to accomplish the same operation.

2.2.4 USAF — Sacramento

The USAF at Sacramento designs radars, air traffic control and weather forecasting equipment, UHF radios and electronic warfare systems. They also maintain existing equipment and reverse engineer obsolete equipment.
2.3 Outline descriptions of Japanese case study companies

2.3.1 Toshiba — Fuchu Works

Toshiba’s Fuchu Works employs a total of 7,500 staff, of which 4,200 are full-time employees. Of the full-time employees, 20% are used to develop software for mid-range and process control computers, 15% develop microcomputer software, 20% are systems engineers (software and hardware) and 20% are hardware engineers. The remainder perform Quality Assurance functions. The plant makes a 15% contribution to Toshiba Group sales, and has had a recent growth rate of between 13% – 15% per annum.

The main products produced by Toshiba’s Fuchu Works can be grouped into three areas:

- **Information Processing and Control Systems**
  - *Super minicomputers and super engineering workstations (Sparc laptops)*
  - *Next generation integrated control systems*
  - *CIM and plant automation systems etc*

- **Energy Systems**
  - *Monitoring and control systems for power plants*
  - *Control equipment for power plants*
  - *New energy and energy saving systems etc*

- **Industrial Equipment**
  - *Transportation systems (Maglev)*
  - *Elevators and escalators*
  - *Mechatronics equipment etc*

- **Printed Wiring Boards and Hybrid Functional Circuits**

2.3.2 Toshiba — Ome Works

Toshiba’s Ome Works employs a total of 3,700 staff, of which 1,400 are engineers. 700 of these work in manufacturing control, 400 are part time employees and the remainder are contracted into the plant from subsidiary companies and from software engineering companies. The Ome plant has two of its own subsidiaries, Toshiba Computer Engineering Corporation (300 engineers) and Toshiba Software Engineering Corporation (300 engineers).

The main products produced by Toshiba’s Ome Works can be grouped into two areas:

- **Information Processing and Control Systems Group**
Appendix 2

Distributed Data Processing Computers
Minicomputers
LAN equipment, packet switching units and data conversion units
Small business computers, personal computers and Japanese word processors etc

• Software
  Package software
  Distribution and banking systems
  Government systems
  Industrial systems

2.3.3 Sony Semiconductor Division — Atsugi Technology Centre

The Atsugi Technology Centre of Sony’s Semiconductor Division employs 1,700 staff, not including those in sales and marketing, out of a total 7,000 employees in the company’s entire semiconductor group. The Division’s annual turnover is currently around £700 million, from sales of such products as:

• ASICs for audio and visual products, as well as for computer peripherals

• CCD image sensors

• SRAMs

• Single chip MPUs and Gallium Arsenide (GA) lasers

The Atsugi facility carries out R&D into, and design of, leading-edge LSI devices. They design and fabricate more than 100 new semiconductor each year, of which 20% are totally new.

2.3.4 Fujitsu Mainframe Division — Kawasaki

The Fujitsu Mainframe Division is part of the company’s Information processing Group. The Division is engaged in the design and manufacture of Supercomputers (VP2000 Series), Mainframe Computers (M Series) and the new Fault Tolerant Communications Control Processor (SURE2000). The latter is a completely non-stop system, even when changes are required to hardware or software.

In fiscal 1990, Fujitsu’s Information Processing Group spent (excluding software) some 7% of net sales on R&D. Much of this expenditure went on the development 0.5 micron integrated circuit technology.

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2.4. Outline descriptions of Korean case study companies

2.4.1 Samsung corporate profile

The Samsung Corporation is estimated by Fortune Magazine to be the 15th largest company in the world outside the United States. The company is heavily involved in the development of semiconductors, communications equipment, computers (joint ventures with HP), as well as aerospace and defence products. It is also a major provider of insurance and leisure facilities within Korea and elsewhere in the world.

The company supports four electronics institutes, together with a supporting CAE Centre. Nevertheless, while Samsung invests some 8% of turnover in electronics research, it is interesting to note that it derives only 40% of its revenue from manufacturing, of which only 25% comes from its electronics interests.

2.4.2 Samsung Colour TV Division -- Suwon City

Samsung's Colour TV Division employs some 2,500 employees and has a revenue of $1 billion. Much of their work involves copying Japanese TV designs, although they have recently begun to conduct research into HDTV. 80% of their products are exported to the United States.

2.4.3 Samsung VTR Division -- Suwon City

Samsung's VTR Division is similarly involved in copying Japanese VTR products. The Division manufactures 350,000 VTRs per annum.

2.4.4 Samsung ASIC Research Centre -- Seoul

The ASIC Research Centre was established circa 1989 to conduct research into Application Specific Integrated Circuits (ASICs). The Centre uses commercial design software from the U.S., and is having mixed results in encouraging the use of simulation in the wider Samsung organisation.

The Centre is currently training young ASIC engineers, and is currently employing 90 engineers -- up from 30 two years ago. Staff are primarily U.S. educated.
APPENDIX 3. A GENERIC MODEL OF THE ELECTRONICS PRODUCT DESIGN PROCESS
3.1 Top Level View Of The Design Process

Figure 31 below illustrates the overall structure of the generic electronics product design process.

The design process is structured into a hierarchy of five phases, each of which comprises a series of activities. Activities, which stipulate what must be done in order to design electronic products effectively, will each produce one or more deliverables and will each be supported by a number of techniques. How activities are undertaken and how the deliverables are produced depends upon the nature of the activities (creative, analytical task) and upon the set of techniques used.

The methodology's phases are as follows:

- Phase 1: Generate Product Concepts
- Phase 2: Generate Product Solutions
- Phase 3(a): Develop Product
- Phase 3(b): Develop Process
- Phase 4(a): Validate Product
- Phase 4(b): Validate Process
- Phase 5: Manufacture Product

3.1.1 Management of the design process

It is vital that senior executives of the company drive the product development process, including its design aspects, and that they ensure the process is effectively managed.

This can only occur, however, if the Board takes an interest in the work and if there is a clear assignment of responsibility, to a product development committee or task force, for the collection, collation and screening of new product ideas [1]. Criteria must be set for new
Appendix 3.

product selection and budgets established for market research and design/development. A formal procedure for handling the new product development process must be set down.

In addition, management must have a clear appreciation of the fact that it is impossible to successfully manage a portfolio of electronics product development projects using a "single track" approach. For example, a product which is simply a variation of an existing, well-understood product is likely to require far less design and production effort than
would be necessary in the case of a product incorporating several entirely new and unfamiliar technologies. To date, however, projects involving both the “tried and tested” product and the “risky” product have typically been managed in a manner which fails to take into account the different levels of engineering risk involved in their respective development.

In contrast, the design process explicitly acknowledges that different categories of product entail different levels of engineering risk. It has adopted a four path development approach which categorises designs according to the amount of change required in the production processes and according to the percentage of new technical knowledge design engineers must assimilate. Figure 32 below demonstrates how this approach views designs as Repeat Order designs, Variant designs, Innovative designs and Strategic designs.

The design process also provides a mechanism for auditing the design via a series of five Release Gates, each of which is conducted by a project-independent PRODUCT RELEASE COMMITTEE. These gates are referred to as:

4. Initial Screen
5. Preliminary Assessment
6. Product Definition and Pre-development Business Analysis
7. Pre-test Review
8. Pre-production Review
The gates each provide the company with an opportunity to formally evaluate the evolving product design in a systematic and thoroughly documented manner. Their purpose is not to monitor the progress of the project. Thus, before development is allowed to proceed further, the design must satisfy a set of audit criteria laid down for each RELEASE GATE.

3.1.2 Corporate knowledge base

The electronics product creation and manufacture processes are both knowledge intensive activities in as much as a considerable number of sources of knowledge must be drawn upon in order to develop a product which meets the requirements [2]. Inevitably, some of the knowledge generated is lost between the various development stages [3] and that which survives tends to be distributed throughout the organisation. Loss and distribution, in turn, lead to the need to recreate that knowledge, a process which can lead to inconsistencies and an inability to transfer knowledge in ways other than those allowed by the sequential organisation of the different stages.
It is precisely because most companies make no systematic effort to capture and exploit design and manufacturing process knowledge that a key element of this approach is the Corporate Knowledge Base -- a knowledge reservoir which acts as an institutional memory. Such a knowledge base would prevent "reinvention of the wheel" occurring during each project by allowing lessons from past experience to be fed back into current practice. It would also significantly enhance the company's competitive bid generation capability.

The precise nature of the knowledge base, together with how it is created and used, will not be discussed in great detail in this document. However, it is not difficult to imagine the benefits which would accrue to an electronics manufacturing company from the creation of a centralised repository of design and manufacturing knowledge and expertise.

3.1.3 Supporting techniques

These include QFD, Design for Manufacture and Assembly (DFMA), Product and process FMEA, Taguchi methods, Poka Yoke, Simulation and SPC.

3.1.4 Design process modelling notation

It was initially proposed to model the electronics design process using the IDEF0 Structured Modelling Methodology developed by the U.S. Airforce ICAM programme [4]. However, a number of significant problems associated with using IDEF0 to model what is essentially an extremely creative and complex activity were uncovered. In particular, it was found that IDEF0's tendency to hide important events deep within a hierarchy makes the modelling methodology easy to use when attempting to capture details of a process. However, once that process has defined in an IDEF0 diagram tree, the information is neither easy to extract nor is it a simple matter to apply it to the reality of design process improvement.

Nor was IDEF0 helpful in developing tools to support the design process since the methodology partitions activities in a manner which is constrained, not by the natural boundaries of the activities and responsibilities of the personnel involved in the design process, but by the arbitrary maximum of six boxes available for use at each IDEF0 level.
Most importantly, however, the way in which IDEF0's uniform structure tends to hide differences in the various design process activities made it hard to represent activities involving "analysis" and those requiring "creative thought" in the variety of ways we felt were required of our design process model.

Figure 33: Process modelling notation

Comment symbol. May be attached to flow lines and to any other symbol. Information may be either text or reference to text elsewhere.

- Task symbol
- Retrieve old information
- Analytic/critique activity symbol
- Understand/critique TPSD
- Creative activity symbol
- Formulate concepts
- Concepts

Includes:
- New circuit behaviour
- New circuit test
- Production

Offline storage symbol for information to be used during later task/analysis

Printed document symbol

Company-level decision gate symbol

No Go

RELEASE GATE 4: Pre-test Review

Hold

Go

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Hence, the process model was developed using a modelling approach which overcomes many of IDEF0’s shortcomings. The approach adopted is based upon a number of widely used systems modelling methodologies, including the European Computer Manufacturers Association flow charting standard [5].

Figure 33 above illustrates the notation used in the model of the electronics product development process.

The existence of an activity box in the design process model is no indication of the effort necessary to complete that activity. This is because effort is project related and for simple designs, perhaps involving a high degree of repeat design, much existing documentation and decision making will have been carried out on a closely-related product and will not have to be re-visited.

NOTE: Horizontally adjacent boxes indicate concurrent engineering-type parallel activities, as well as the existence of interaction between those activities.

NOTE: Section 3.3 describes graphically the generic design process model activity tree presented in section 3.2. below.
3.2. The design process

PHASE 1: Generate Product Concepts

The outcomes of new product processes are largely decided in those early stages of the new product process which precede the actual development of the product [6]. In Western companies most corporate product development resources are still largely devoted to the middle and back-end stages while the pre-development activities which determine product success and failure are poorly resourced and carried out. In Japan, we have discovered the reverse to be the case.

It is important that managers resist the temptation to by-pass these crucial stages in order to move an ill-defined and poorly investigated project into development. The establishment of a series of strong release gates are an effective way of preventing short-cuts. Such gates impose a quality control mechanism on the process which ensures that the essential tasks have all been completed, that their execution is sound and that the project is still a viable investment. The release gates also chart the path forward for the next product development phase.

Each release gate has its own set of measures and criteria for passing the gate and which deal with various facets of the project. Such questions and hurdles include:

- Does the project continue to make economic and business sense?

- Have the essential steps been completed -- those steps or activities necessary to pass through the gate? Is the quality of execution of these activities adequate?

- Is the project on time and in budget? Have the milestones been hit?

- What steps or tasks need to be undertaken in the next phase or stage of the project. What milestones, dates and budgets need to be attached to these tasks?

All the activities occurring within PHASE 1 will be undertaken by members of the STRATEGIC DESIGN TEAM.
ACTIVITY 1: Customer

Activity type: External source of Customer Product Requirements (CPR)

Commentary:

Most electronic equipment is made, and usually designed, by a supplier for a customer who is, or represents the user. The specification comes from the user when he/she wants equipment designed in a bespoke manner, as opposed to buying it off-the-shelf. The fact that both the supplier and the customer may be large or small organisations, or even groups of similar firms, clearly indicates that different types of specifications will be required, each of which will involve different amounts of user design effort.

The various permutations of customer/supplier relationship can be described as follows [7]:

**Monopoly:**

Only one supplier. Stringent quality standards required by customer leading to removal of need for incoming goods inspection of components at customer site. Common in Japan. Less common in the West where many customers insist on at least two sources.

**One large customer, several suppliers:**

For example, in military and some civil fields such as telecommunications. Basic specification tends to be an agreement by the customer to specify certain suppliers as permissible and hence to prevent other firms from entering the market. The selected firms are required to fulfil a specification written by the customer which may be extremely specialised and which, when used by others, may achieve poor results. For example, much military equipment is specified for a short, but hard life whereas civil equipment is expected to work reliably for long periods under gentle conditions.

**Many customers and suppliers:**

Where there are many customers and many suppliers, it is not clear whether a single specification can be made and used. If the customers form a group, such as a trade association, they can transform themselves into a single customer while remaining financially independent.
Consultants acting for many customers:
Where there are many customers, and the subject is not in their own field, they may be unable to write and supervise a detailed specification. This is common in utilities, such as those distributing electricity, gas and water, which use electronic communication and control schemes but only start a new type of scheme at intervals of two years or more. To set up an internal group that would understand the subject would be slow and, at the completion of the work, the group would have nothing further to occupy itself with. Consultant engineers exist to fill this gap.

In certain circumstances, customer requirements may be modified by a good salesman, often acting as an interpreter in an interactive process, in ways which suit the company. This is especially true where the customer has only an incomplete idea of the end product's functionality and features.

ACTIVITY 2: Get Customer Product Requirements (CPR)

Activity type: Task

Rationale:
The first written requirements documentation obtained from the customer.

Inputs:
Customer dialog

Deliverables:
Customer requirements

Commentary:
It is crucial at this point to develop an unambiguous requirements definition because, among other things, the specification language used can present major difficulties. Hence, the accuracy of decomposition of the specification into marketing, purchasing, engineering and production aspects needs to be checked and requirements prioritised according to customer importance. Customer acceptance and test requirements must also be defined at this stage.

It is important that the customer takes considerable care in developing its product requirements by thinking in terms of deliverables. This can be accomplished by ensuring
that specification document statements are prefixed with MAY/MAY NOT and MUST/MUST NOT. In order to ensure that a good agreement exists between the company and its customer, it is prudent to eliminate any degree of flexibility from the requirements generation process.

Although the design process model does not mandate the use of any particular techniques, it is recommended that Quality Functional Deployment (QFD) be used to formalise all customer requirements. Adherence to QFD then subsequently allows formal evaluation of the evolving product against the original customer CPR. Discrepancies can then be highlighted at the specific stage in the long translation process from CPR to delivered product.

**ACTIVITY 3: Understand CPR**

**Activity type: Task**

**Rationale:**
To develop an understanding of customer requirements and to remove ambiguity from the CPR document.

**Inputs:**
Customer product requirements.

**Deliverables:**
CPR document.

**Commentary:**
The company's first task should be to check whether the CPR is legally binding. A CPR may be couched in legal terms and will have to be carefully examined to determine the document's business, engineering and manufacturing implications. Since any misunderstandings of the CPR will undoubtedly cause significant problems later, company lawyers must be given the opportunity to annotate the CPR, highlighting significant legal phraseology.
Having been passed by the legal department, the CPR should be analysed by the STRATEGIC DESIGN TEAM comprising senior personnel from marketing, design, production, test and purchasing. The team should also be able to call upon industrial design expertise, where this is appropriate. The primary purpose of understanding the CPR is to identify those requirements which might:

• Prevent implementation

• Require a longer development period than is available

• Cause design/production difficulties

• Limit production volumes

ACTIVITY 3 is therefore the first phase of an ongoing translation process which culminates in the generation of the Commercial Product Specification (CRS) in ACTIVITY 10 below. Each part of this process refines the generated documentation and leads to the production of the Commercial Product Specification (CRS). The CRS represents the company’s understanding of the product requirements and is phrased in company, rather than customer terminology.

ACTIVITY 4: First Cut solutions

Activity type: Creative

Inputs:
Customer product requirements.

Deliverables:
CPR document/A

Commentary:
Try and carry out an early creative session to reduce potential search space of solutions later in process. This activity is undertaken by the Strategic Design team.
ACTIVITY 5: RELEASE GATE 1 -- Initial screen

Activity type: Company-level decision point

Rationale:
Allows an independent, company-level audit of the early STRATEGIC DESIGN TEAM work assessing the viability of the project. Failure to carry out such an audit could result in a project bid which will not be profitable for the company.

ACTIVITY 8 is the point at which decisions are first made to commit resources to a project.

Inputs:
CPR/A document.

Deliverables:
Released CPR/A document.

Commentary:
The data on which the viability of project is assessed should be continuously reviewed. The decision to proceed on a project should be based on the assessment of such information as:

• The recognition of a market requirement.

• The proposal of a specification for a product.

• The evaluation of the proportion of the available market lost to the competition.

• The evaluation of how many of the specified product would be sold and over what period of time.

• The evaluation of the design and production introduction costs.

• The availability of resources.

• The evaluation of the timescale leading to the first and subsequent production models.
• The accuracy of the above data i.e. the risk factor. If any of the above data were to change, the conclusion as to the viability of the product might be different. It is therefore necessary to continuously or frequently review the basic data and, in the event of change, to reassess the viability of the project.

Nevertheless, this audit activity was rated in [8] as one of the most weakly executed in the product development process. Typically, this research showed that the GO/KILL/HOLD decision nodes are poorly executed in most firms and omitted altogether in other areas.

The audit should be carried out by the PRODUCT RELEASE COMMITTEE, comprising senior company management personnel up to Board level, and should be based on a standardised list of screening criteria. These should be largely non-financial and based upon a number of “must meet” and “should meet” criteria. Examples of such criteria include: 50% lighter, 30% cheaper and 25% improvement in development time.

ACTIVITY 6: Hold until assessment complete

Activity type: Task

Rationale:
To prevent projects from proceeding until the company-level audit has been completed satisfactorily.

Inputs:
CPR/A

Deliverables:
Authorisation to proceed

Commentary:
It is always tempting to cut corners on the company-level audit, or even to avoid carrying it out entirely, particularly where the project team is working to tight deadlines. However, the cost implications of NOT completing the CPR analysis to company satisfaction will only be understood much later in the design process and at stages where significant real costs are already likely to have been incurred.
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The most common problem encountered here will be that of “wandering goal posts” caused by changing customer requirements as the incomplete specification evolves. It is vital to avoid proceeding without fully agreeing the customer’s needs.

ACTIVITY 7: Customer liaison & feedback

Activity type: Task

Rationale:
To resolve any outstanding issues and/or ambiguities in respect of the CPR and the first cut solutions.

Inputs:
CPR document.

Deliverables:
Updated CPR

Commentary:
Relationships to customers vary. In some cases, a customer’s needs may be modified by a good salesman, often acting as an interpreter in an interactive process, to suit the needs of the company.

Salesmen are often technical engineers and thus can converse in engineering terms with the prospective client. In such circumstances, the sales engineer must be involved in the process of understanding the CPR (ACTIVITY 3) in order to allow him/her to gain a deeper insight into the customer’s product requirements. A written note from the design team to the salesman is NOT sufficient. Personal involvement is important to establish “ownership” of the requirements.

Where ACTIVITY 3 has indicated that tradeoffs need to be made, the customer should be notified and asked to provide written clarification.
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Additionally, the cost of implementation may be important for project timescales and, where customer changes to the original requirements have cost implications, these must be communicated to the customer in writing.

ACTIVITY 8: Preliminary technical analysis

Activity type: Analysis

Rationale:
To convert the customer requirements set into your company requirements set. NOT DOING this activity begs the customer to require things your company cannot deliver.

Inputs:
CPR document.

Deliverables:
CPR/A document.

Commentary:
ACTIVITY 6 (Preliminary technical analysis) and ACTIVITY 7 (Preliminary market analysis) take place in parallel with each other. While interaction may take place between those personnel carrying out the preliminary technical and market analyses, 90% of communication is likely to be informal and meetings should be scheduled to facilitate knowledge sharing.

ACTIVITY 6 is primarily concerned with examining the CPR in respect of design and manufacture feasibility, hence an assessment of company "capability" should be made at this stage in order to determine whether the proposed project fits with internal company strengths. Naturally, this first pass cannot be expected to provide a detailed risk analysis, but its output should define the riskier portions of the project and suggest possible solutions. Some detailed work may have to carried out here.

Any product partitioning undertaken here will not be binding upon the project, but recommendations would be appropriate. A more detailed analysis, which occurs after the
Appendix 3.

CRS/A document has been released (ACTIVITY 18), is used to provide a more definitive partitioning of the product into its hardware, software and mechanical elements and to provide a detailed risk analysis of the project. The important thing to appreciate is that in many companies the personnel involved in ACTIVITY 6 will be more senior than those involved after ACTIVITY 18 and their wisdom (or misconceptions) will be recorded in the CPR/A and will be communicated to others via this mechanism.

If there is no customer (internal or external) ACTIVITY 8 and ACTIVITY 9 may provide the first opportunity to critique an informal product proposal generated from within the business.

On a bespoke product, the technical people must liaise with their counterparts in the customer company in order to discuss the finer points of the technical specification proposals.

**ACTIVITY 9: Preliminary market analysis**

**Activity type:** Analysis

**Rationale:**

Ensures that the commercial reasons for undertaking the product are not lost sight of.

**Inputs:**

CPR document.

**Deliverables:**

CPR/A document.

**Commentary:**

Marketing inputs should play a key role right from the outset of the project. Preliminary market analysis constitutes an early and inexpensive step designed to test the market attractiveness and market acceptance of the new product.
Activities include:

- Focus groups
- Discussions with key customers
- Small sample phone surveys or similar

The fact that a product without a market is unlikely to be profitable for the company makes it essential that the technical design reflects the appropriate aspects of the company marketing philosophy. Hence, early unification of the aims in these two, often conflicting areas, is vital.

**ACTIVITY 10: Create Product Commercial Requirement Specification (CRS)**

**Activity type: Creative**

**Rationale:**
To translate the customer’s product requirements, as defined and agreed in the CPR, into an internally understood specification which the company can use as the basis for proceeding with actual product development.

**Inputs:**
CPR/A document.

**Deliverables:**
CRS document.
Commentary:
As with all creative activities certain rules can be followed when attempting to generate new ideas. Brainstorming is a surprisingly well-defined technique for generating new and innovative concepts. Creative activities should be given equal prominence to analytical ones within the product development process. However, care should be taken to ensure that the two kinds of activity are separated in time since humans are extremely poor at being simultaneously creative and analytic [9].

It should be noted that the creation of the CRS does not involve the same kind of primary creative processes as those required in formulating initial product concepts (ACTIVITY 19). This is because the development of the commercial product specification will always be constrained by the various issues raised during the preceding activities defining and agreeing the customer product requirements. Hence, marketing constraints, technical timescales and manufacturing volumes will already have been discussed and documented. It is at this point, however, that they are formally tabled in a cross-functional design team meeting.

It is at this stage that efforts will be made to document such factors as specific engineering cost requirements (definitions of sizes, power consumptions, speed of operation and so on), levels of funding, estimates of manpower requirements, project timescales and company objectives. This will allow the enterprise view of the product development project to be easily understood by readers of the CRS document.

ACTIVITY 11: Critique CRS

Activity type: Analysis

Rationale:
To ensure the CRS is correct and that the development of the specified product will not make unreasonable financial, technical and human resource demands upon the company.

Inputs:
CRS document.
Deliverables:
Critiqued CRS document.

Commentary:
There are likely to be a series of corporate and product strategies in existence which constrain the analytical deliberations regarding the CRS. Hence, the commercial product specifications must be tested against company knowledge derived from past projects (assuming such knowledge has been captured and can be made available in meaningful format) as well as in relation to the personal “know-how” of those who will be called upon to implement the terms of the CRS once it has been approved.

The documented output from this analytical activity will consist of an internal interpretation of the CPR and, hence, part of this activity will involve comparing the agreed CPR requirements with those set out in the CRS. Every effort must be made, at this point, to ensure that all CPR requirements are faithfully mapped across to the CRS.

ACTIVITY 12: OK?

Activity type: Design team internal decision point

Rationale:
To prevent incomplete, ambiguous or contradictory requirements from being enshrined in an official company document (the CRS).

Inputs:
Critiqued CRS document.

Deliverables:
Critiqued CRS document.

Commentary:
The fact that, in many companies, decision makers do not always possess the appropriate knowledge upon which to base their decisions means that the critiqued CRS must be
evaluated by members of the STRATEGIC DESIGN TEAM at this stage. The purpose of the evaluation is to ensure that a good mix of technical and company business knowledge is brought to bear to ensure the CRS meets both customer and company requirements.

If the contents of the CRS are approved, the document should be sent to the PRODUCT RELEASE COMMITTEE. The committee will be tasked with carrying out the Preliminary Assessment at RELEASE GATE 2 (ACTIVITY 16). If the CRS is rejected, the design team must seek to understand the cause of the failure.

**ACTIVITY 13: Analyse cause of rejection**

Activity type: Analysis

Rationale:
To expedite revision of the CRS.

Inputs:
Critiqued CRS document.

Deliverables:

Commentary:
The STRATEGIC DESIGN TEAM must analyse why the CRS has been rejected. Appropriate action follows in ACTIVITY 14 and ACTIVITY 15 or at ACTIVITY 27.

**ACTIVITY 14: CRS failed?**

Activity type: Design team internal decision point

Inputs:
CRS

Deliverables:
Decision to fail CRS

Commentary:
The STRATEGIC DESIGN TEAM must decide whether failure has resulted from shortcomings in the way the CRS has been generated. If this is the case, the team should convene as per ACTIVITY 10, Create Commercial Product Specification.
ACTIVITY 15: CPR failed?

Activity type: Design team internal decision point

Inputs:
CPR

Deliverables:
Decision to fail CPR

Commentary:
The STRATEGIC DESIGN TEAM must decide whether failure has resulted from shortcomings in the way the customer has specified his requirements in the CPR. If this is the case, the team must consult with the customer in order to resolve the outstanding problems.

ACTIVITY 16: RELEASE GATE 2 -- Preliminary Assessment

Activity type: Company-level decision point

Rationale:
To avoid committing cash and manpower to a non-viable project.

A good specification is essential to project success. In order to recognise correctly the state of progress of a project, it is necessary to:

- Verify the specification is explicit and complete.
- Verify that the equipment, subassemblies and components conform to their specifications.
- Verify that the product which meets the specification also meets the requirement.

Inputs:
Critiqued CRS document.

Deliverables:
Preliminary assessment report.
Commentary:
Repeats RELEASE GATE 1 (ACTIVITY 5) but, in this case, evaluators have better market and technical information. Development and manufacturing financial criteria can be introduced at this gate as well.

This activity is an audit on activity completion prior to this point and a resume of the potential project risks.

ACTIVITY 17: Hold until assessment complete

Activity type: Task

Rationale:
To prevent 'jumping the gun'.

Inputs:
CRS

Deliverables:
Authorisation to proceed

Commentary:
This is easy to avoid doing in a project with tight deadlines. However, the cost implications of NOT completing the CRS to company satisfaction will only be understood much further down the line in the design process, at points where real costs will have been incurred.

The most common problem is 'wandering goal posts', as the incomplete specification evolves during the project development phases. Incomplete evidence (in the form of a poor CRS) can cause an incorrect decision to be made at release gate 2 (ACTIVITY 16).
ACTIVITY 18: Release CRS/A

Activity type: Task

Inputs:
CRS/A

Deliverables:
Release controlled CRS/A as final part of Product Book 1.

Commentary:
Is the internal mailing list correct? Ensure all personnel on development project receive up to date copy of CRS & changes (appendices): dated and revision controlled (in case changes do occur).
PHASE 2: Generate Product Conceptual Solutions

This phase generates data, information, knowledge and constraints for product book 2, the conceptual development database.

ACTIVITY 19: Formulate initial product concepts

Activity type: Creative

Rationale:

To generate new ways of solving new and possibly old problems.

Inputs:
Strategic design team

Deliverables:
Product concepts (technical and commercial)

Commentary:

A structured look at the product beyond those attributes specified in the CPR and CRS. This may be the first time specific function details are laid down. The reason for this is that commercial and customer requirements may not go into detail over how to achieve specific product facilities. So, for example, the CPR and CRS may just say 'must have magnetic data reader', but not suggest any conceptual, behavioural or circuit solutions.

The various tried and tested “ideation” techniques described in Appendix A of this document must be applied here, and the results analysed in Analyse concepts (ACTIVITY 22) below. Ensuring that true lateral thinking be applied here.

Concept formation should not just be limited to the function of the product, but to the way in which could be manufactured and tested. A new book should be created at this point, detailing the Product Concepts, Behaviours and Solutions (in Product book 2). This will be added to by subsequent stages up to and including Do selected PDP (ACTIVITY 41), generating a succinct set of critically assessed options for development. Additional chapters in book 2 will be derived from Test concept in market (ACTIVITY 20) and Competitive analysis (ACTIVITY 21).
Depending on the make-up of the design team during this activity and Develop behavioural solutions (ACTIVITY 24), the resulting concept of this activity may contain aspects of behavioural solutions. The object of separating these two concerns is not to prevent this type of "mixed mode" thinking, but to prevent a diversion of energy from ideation to behavioural modelling. The detail of the latter activity belongs below in Develop behavioural solutions (ACTIVITY 24). Although pointers to this detail are quite acceptable here.

ACTIVITY 20: Test concept in market

Activity type: Task

Inputs:
CRS/A

Deliverables:
Customer responses appended to CRS/A

Commentary:
A test of the proposed product with customers (either in focus groups of larger sample surveys) to determine likely market acceptance. Despite the fact that the product is not yet developed, a model or representation of the product can be displayed to prospective users to gauge reaction and purchase intent.

ACTIVITY 21: Competitive analysis

Activity type: Task

Inputs:
CRS/A and technical evaluation of competitors products

Deliverables:
Report on results

Commentary:
Competitive analysis should be an on-going and vital part of a company’s strategic planning process. Although its occurs as an activity in the design process model, it is not to
say that the product development team should suddenly be expected to make a "cold start" at assessing competitor products, prices, costs, technologies, production capabilities and capacities and marketing strategies. It should rather be the case that such corporate information is fed into the design process at this stage with appropriate team members being tasked with fine tuning the analysis with respect to the product under consideration.

On a gross, corporate level, such a competitive assessment should provide insight into such competitive weaknesses as product deficiencies, service problems and shortages of R&D staff in critical areas which will indicate where competitive advantage might be gained. However, a firm should not simply monitor its existing competitors [10]. It should also scan the environment for potential competitors since the price of ignoring these rivals and of neglecting to take pro-active steps to avoid or blunt their impact can be extremely high. Reverse engineering of competing products is an important routine activity here, as is intelligence gathering on trends in the market.

The technological environment also requires close attention not only because of its evolutionary impact on existing products but also because many innovations are introduced from outside a traditional industry [11]. This study also suggests that replacement technologies may emerge and develop while companies using the old technology are lulled into complacency by near term prosperity.

Thorough analysis of a firm's customers and non-customers is a vital, but often undervalued strategic activity. However, it should go beyond attempting to devise ways of getting the customer to repeat or expand an order and should reveal emerging technologies, competitive advantages and disadvantages and new product ideas.

Other areas which need to be monitored, but which do not directly concern us here are the economic, political/regulatory and social environments.
ACTIVITY 22: Analyse concepts

Activity type: Analysis

Inputs:
Product concepts (technical and commercial)

Deliverables:
Critique of Product Concepts

Commentary:
This activity is the companion of Formulate initial product concepts (ACTIVITY 19). It is shown as separate, since the two tasks are mutually exclusive because people cannot be truly creative and analytic at the same time, or even in the same meeting!

This activity should be carried out by the same design team that created the initial concepts. The resulting ideas should then be ‘fleshed out’ in terms of behaviour or even circuit description if required in Develop behavioural solutions (ACTIVITY 24). QFD may be used here, as a check on the compatibility of the customer requirements to the product concepts formulated above.

Although it is tempting to develop the behavioural solutions under this activity, ‘Analyse concepts’ is only necessary as a stepping stone to Develop behavioural solutions (ACTIVITY 24). Identifying the important things to check, test and evaluate; allowing a rapid loop transit if there are any problems in Formulate initial product concepts (ACTIVITY 19), or modifications required due to Test concept in market (ACTIVITY 20), Competitive analysis (ACTIVITY 21) actions.

Product Book 2 will carry the results of this analysis as an appendix to the product concepts chapter.
ACTIVITY 23: OK?

Activity type: Design team internal decision point

Inputs:
ACTIVITY 22

Deliverables:
Internal approval

Commentary:
The only criteria used here are those of 'structural integrity', such that each set of conceptual ideas proposed as possible ways of achieving the CRS should be logically sensible. Any options that have not been defined sufficiently to allow this level of scrutiny should either be rejected or a decision made to explore the concepts in more detail.

ACTIVITY 24: Develop behavioural solutions

Activity type: Creative

Inputs:
Product Concepts chapter in book 2

Deliverables:
Behavioural solutions to concepts in book 2.

Commentary:
The creative team, which now may be a different group of people from that involved in Formulate initial product concepts (ACTIVITY 19), now has to develop an understanding of the possible behaviours of the concepts created above. Currently modelling by simulation or prototyping are the most cost-effective methods available, although formal verification may prove a use adjunct to these methods in the future [ref].

The initial solutions should be created by ideation techniques, then substance given to them by proof by simulation, verification or experiment. Product Book 2 is extended in the light of the new information gained during this activity, adding potential Functional solutions.
Tools like ELLA, HELIX, VHDL, SABER and VERILOG are available to ease the modelling procedure, although simulation using FORTRAN, PASCAL or 'C' procedures are always an option.

Behavioural models of manufacturing processes can be executed in factory simulation tools like SIMAN [12].

**ACTIVITY 25: Analyse Solutions**

**Activity type:** Analysis

The winnowing stage, removes non-runners

**Inputs:**

ACTIVITY 24

**Deliverables:**

Reduced set of behavioural solutions

**Commentary:**

At this point in the product development process, there is a need to take an objective look at the wider issues involved. Unless this occurs, the company may limit its perspective to the technology it knows (for example, microprocessors) and may, by reconciling the customer CPR with an existing product, decide to skip most of the previous stages. This state of affairs would inhibit the evolution of company products, a process which should take place as new technologies become available.

The DETAIL DESIGN TEAM must look at the wider implications of solutions, including technical implications. Solutions should be analysed against some criteria which may include assessing the risk involved in "sticking to the technology you know" in order to get to the market faster. However, it is rare for design personnel to know or understand the implications of their decisions on production engineering and if, for example, design staff have worked on the assumption that a process has a poor yield, production must be informed of that fact.
It is important to accept that this is the winnowing stage and solutions not acceptable to the company should be rejected at this point. The seemingly pointless task of creating ideas, exploring solutions (ACTIVITIES 19 through 24) and then rejecting them is important, however. It prevents the company becoming narrowly focussed in technology and strategy terms because the design team has been forced to take a formal, short term “look over the horizons” at competitors and the market place.

An appendix to Product Concepts, Behaviours and Solutions is generated as a result of this activity, the PCBS/A.

ACTIVITY 26: Mismatch?

Activity type: Design team internal decision point

Inputs:
Book 2 product concepts, book 1 CRS & CPR

Deliverables:
Acceptance of book 2 solutions

Commentary:
Solutions dissected by peers with respect to CRS and CPR. If there are any discrepancies then an iteration around the early conceptual design loop is needed. Perhaps even contact with the customer is called for!

ACTIVITY 27: Continue?

Activity type: Design team internal decision point

Inputs:
ACTIVITY 26

Deliverables:
Approval

Commentary:
This is a generic loop continue point, causing a decision to be made by senior technical management to either iterate (by seeking clarification or further information) or call a halt to the project.
ACTIVITY 28: Re-assess requirements in light of constraints

Activity type: Analysis

Inputs:
ACTIVITY 27

Deliverables:

Commentary:
If the project is continuing a dispassionate assessment of the current state of the project and its documentation may be needed. This is necessarily a group activity involving all members of the senior design team (team A).

ACTIVITY 29: Liaise with customer

Activity type: Task

Inputs:
ACTIVITY 28

Deliverables:
Customer aware of situation. Action plan initiated/completed

Commentary:
A company standard for customer liaison should be enacted at this point to discuss the issues raised that are causing delay in the project. Care should be taken in handling ones customers, but the truth must always be given.

ACTIVITY 30: Compare and analyse vs existing products

Activity type: Analysis

Rationale:
To identify common ground between existing products and the proposals, to reduce design time and manufacturing costs.
Appendix 3.

Inputs:
Existing product range's book 2/3's

Deliverables:
Update of book 2 to reflect potential product overlaps

Commentary:
After a series of outward looking activities have established the best sets of solutions for the proposed product (ACTIVITY 8 to ACTIVITY 25). One can now perform a detailed comparison of these with existing products. A natural bias toward existing designs will exist in all the design personnel, but prior to this activity this bias should be kept in check to ensure a careful survey of specification, behaviours and implementation strategies can take place.

The analyses are technical and financial in nature and should focus on attempting to define the cost of making the proposed product a variant design of an existing product. It may be that one of the options explored at the earlier stages in the design process was exactly this, but the relative costs of each proposed solution set must be calculated and compared. The resultant analysis document is an additional appendix to Product Book 2. Thus a report on why the product is evolving as defined is being recorded by the company during the early development phase, a time when normally documentation is fragmented and held in marketing, design, accounting, purchasing and management files.

This work would be carried out by STRATEGIC DESIGN TEAM, with the addition of an invited guest, the technical author scheduled to document the product. The technical author will have already attended an earlier meeting (with design team A) when the CRS was evaluated (Critique CRS, ACTIVITY 11). This allows an early insight of the product by the technical author, which will help him or her to review other appropriate product lines for relevant manuals, preventing a 'cold start' on creating maintainence and user guides for the new product.

To overcome the considerable compression in the amount of time available for solving design and production problems, manufacturers must be able to use lessons from previous product development activities to aid the current one. Such a corporate learning process
recognises that there exist generic or repeating elements in the product, the processes or in the design steps themselves [13]. It also requires that such learning be systematised and include such elements as expert knowledge, best practice, current vs previous case histories and support for bid estimation procedures.

**ACTIVITY 31: Choose concept solution set to implement**

**Activity type:** Decision

**Rationale:**
To narrow product implementation options to one

**Inputs:**
Book 2

**Deliverables:**
Recommendation for selection of alternate product solutions

**Commentary:**
Now a complete review of possible behavioural solutions is available, a choice must be made to follow only one solution set to product. A technical specification of this will be written in the next activity.

The activity should carried out by STRATEGIC DESIGN TEAM.

At this point the degree of 'sameness' or compatibility with existing products is known, this allows production engineering to give the first estimate of the production scheduling needed when entering the manufacturing phase of the development. The Master Production Schedule (MPS) for the factory may be adjusted or consolidated as necessary, giving a rough cut capacity plan if the project is leading toward a variant, innovative or strategic product development path. It is important to note here that the design process model is only concerned with information and activities related to the task of product design. Strategic decisions that significantly alter the product lead times are outside the scope of this model, therefore any impact on manufacturing due to choice of design route and the consequent product lead times are assumed to be normal and achievable.
ACTIVITY 32: Develop technical specification document (TPSD)

Activity type: Task

Inputs:
ACTIVITY 31

Deliverables:
TPS part of book 2

Commentary:
This activity translates book 2 data into a precise form into a form that can be understood by design team B (to become active in the project at Establish enlarged project team (ACTIVITY 39). Product book 2 is, at this point, a discussion document, but the last part to be written, the TPS, is a specification document for book 3. Therefore, the chosen block structure, partitioning, timing and other engineering costs have to be extracted from the Book 2 and rewritten in tabular and diagrammatic form. This allows a formal consistency cross check of customer requirements and company solutions.

ACTIVITY 33: Select product development path

Activity type: Task

Rationale:
A development organisation must have an adequate mix of projects over a spectrum of priorities. Variant, innovative and strategic.

Inputs:
Book 2

Deliverables:
PDP

Commentary:
As a direct result of Choose concept solution set to implement (ACTIVITY 31) it is now possible to allocate a design path to the project and subsequently perform a critical path analysis of the manpower and development budget requirements, creating the Critical Path Document CPD and selecting the Product Development Path. There are four paths: Repeat order, Variant design, Innovative design and Strategic design.
This task may be performed by a design manager, but the CPD must be part of the body of knowledge reviewed at RELEASE GATE 3 (ACTIVITY 35), to ensure senior management understand the implications of the design route chosen.

**ACTIVITY 34: Hold until assessment complete**

*Activity type: Task*

**Inputs:**

ACTIVITY 33

**Deliverables:**

Progression to next activity

**Commentary:**

Again, a tight timescale may encourage a partial sign-off of the TPSD and subsequent approval to commit more company cash to the project before all the risks have been highlighted and approved. Although the CPD may be considered by financial management to be the single important review document, the TPSD is crucial too, for it is not unknown for mistakes and previously unknown constraints to be uncovered during the translation process from PCBFC.

**ACTIVITY 35: RELEASE GATE 3 -- Project definition and pre-development business analysis**

*Activity type: Company-level decision point*

**Inputs:**

Book 2

**Deliverables:**

Approval to continue on to gate 4

**Commentary:**

Critical final gate prior to product development. Financial analysis is one element. Another element involves reaching agreement on project definition. This entails consideration of target market, product concept, benefits to be delivered, positioning strategy, product features and attributes and product specifications.
Handled by personnel from finance, production, marketing, design (product & industrial), purchasing and customer (where appropriate).

Involves making commitments to product development materials, resources and manpower. It is therefore a significant stage in the product development project.

**ACTIVITY 36: Analyse problems**

**Activity type:** Analysis

**Inputs:**
Book 2

**Deliverables:**
Identified failures

**Commentary:**
Design team A must attempt to understand the issues resulting in the failure of the project. Can it be recovered? What caused the failure?

Can a modification to the specification save the project. A minimal intervention strategy should be applied.

**ACTIVITY 37: Solutions wrong?**

**Activity type:** Design team internal decision point

**Inputs:**
Book 2

**Deliverables:**

**Commentary:**
A more significant failing of the project is possible here, for it will cost more in delay and manpower to fix a problem located earlier in the design process.
ACTIVITY 38: PDP/TPS wrong?

Activity type: Design team internal decision point

Inputs:
Book 2

Deliverables:

Commentary:
The technical specification could be illogical or incomplete. A previously unknown risk may have been uncovered, forcing a re-evaluation of the technology and timescales. Perhaps the project is really an innovative design rather than a variant design.

ACTIVITY 39: Establish enlarged project team

Activity type: Task

Inputs:
Book 2

Deliverables:

Commentary:

- For PDP "A": Production led, design liaison.

- For PDP "B": Production/Design led.

- For PDP "C": Design led, assign production liaison.

- For PDP "D": Research and design led, assign production to R & D team.

The new expanded design team may only have as a common thread one person who has been involved earlier in the project. Therefore the new design team is now ‘design team B’

The project manager must have technical credibility in practice. But there is a danger in taking the top designer and making him/her project leader without training him/her in wider aspects of the company.
A matrix structure where the pool of designers have 'technical management' appropriate to their specialisations, but project teams have managers that cross the skills capabilities. This can be regarded as inefficient, but appears to pay dividends in flexibility and communication.

**ACTIVITY 40: Develop tentative marketing plan**

**Activity type:** Task

**Inputs:**
Book 2, Book 1

**Deliverables:**
TMP

**Commentary:**
Now a critical path exists, product launch plans can be discussed.

**PHASE 3: Develop Product Technical Solutions**

This phase generates data, information, knowledge and constraints for product book 3, the technical development database.

**Commentary:**
It is important to understand that there are four ways of designing an electronic product [14]. Each impacts differently on the company in terms of resources required and the product lead times. Therefore, it is imperative that any new project be categorised in these terms to make explicit the issues of resourcing and product lead time at an early stage as possible in the project itself.

It is unlikely that any real evaluation of the problems of the new development project in these terms is possible until a careful analysis of the proposals and existing product lines already in manufacture, done in Compare and analyse vs existing products (ACTIVITY 30). Although it may be company policy to only do repeat orders and variant
design (ACTIVITY 42 and ACTIVITY 43 respectively), a long term company view will indeed require innovative and strategic development projects (ACTIVITY 44 and ACTIVITY 45 respectively).

It is imperative that senior management recognise the need of all four types of design within the company and adjust company policy, objectives and strategy in line with the four possible design tracks. Additionally, the ability to categorise programmes of work on product development accurately as being repeat order, variant design, innovative design or strategic design is important and it must be recognised by the most senior management in the company as being so.

Failure to allocate proper resources (as strategic decisions) has led to a number of company projects in the UK being allocated to a development approach when, in fact, reviews of sensible criteria would have led to a series of strategic or innovative research programmes. Different in timescale, engineering approach and manpower.

ACTIVITY 41: Do selected PDP

Activity type: Task

Inputs:
Book 2

Deliverables:
Product

Commentary:
Start the detailed product design. This point may be reached within a few weeks for a small scale development project, or may require upwards of a year for large scale engineering systems.

ACTIVITY 42: Do Product Design Path "A"

Activity type:

Commentary:
DO A REPEAT ORDER DESIGN
ACTIVITY 43: Do Product Design Path "B"

Activity type: Task

Commentary:
DO A VARIANT DESIGN OF AN EXISTING PRODUCT

ACTIVITY 44: Do Product Design Path "C"

Activity type: Task

Commentary:
DO AN INNOVATIVE DESIGN. This involves new combinations of proven ideas and new technology. For example: a company makes cellnet telephones and has experience of designing computer control systems in the cellnet telephones. An innovative product might be found by combining the cellnet communications facilities with computing machines, giving true mobile computing ability. The technical risk associated with such an innovative design would be in choosing a computer operating system, and hardware configuration to satisfy the new customer base. For example: the current de facto standard for personal computers is MSDOS, with UNIX for workstations, which is the correct choice? Can the product be made light enough for portable use? Do we have the production equipment necessary to fabricate the new product?

The design process model makes no suppositions that the project has real or potential customers for the facilities being designed, only that by due consideration of the percentage new knowledge to design or production engineering, an innovative product development path is indicated. This signals to senior company management that appropriate project support is required and careful assessment of risk is necessary. For safety, a company may only wish to carry one innovative project, whilst running a number of variant design projects.
ACTIVITY 45: Do Product Design Path "D"

Activity type: Task

Commentary:

DO A STRATEGIC DESIGN. This involves new principles of engineering for the company personnel. The risks on this type of project are many-fold.

The management of strategic projects is different from the other design paths above since routes A, B and C all have relatively near-term goals. Keeping project focus is therefore easier. Also, as the problems will be largely new for the engineering staff, the potential solutions will not be obvious nor easy to elicit by brainstorming or other group methods. Training or external consultation may be needed in addition to the existing support tools, since information, knowledge and wisdom has to acquired from somewhere.

The design process model makes no suppositions that the project has real or potential customers for the facilities being designed, only that by due consideration of the percentage new knowledge to design or production engineering, an strategic product development path is indicated. This signals to senior company management that appropriate project support is required and carful assessment of risk is necessary. For safety, a company may only wish to carry one strategic project, whilst running a number of variant design projects.

Strategic projects are defined as those essential to the long term future of the company. In other words, a strategic project will be breaking new ground, be risky as a result and may not have a very well defined projected customer base, but in the eyes of the CRS be necessary to undertake.
PRODUCT DESIGN PATH A: Repeat Order

Commentary:

A repeat order design is defined as a near zero percent change to the design or production an existing product, see figure 1 at the end of the process model diagram. In practice this may extend to a few percentage points of effort to update the design and production information. The key issue is that there is no new knowledge required to implement the design changes, as newness represents uncertainty and risk that is more associated with a variant design.

It may seem counter intuitive to have to run through all the above stages just to recognise that the customer can be satisfied with a repeat order of an existing product. However, the reason for this potential route is two-fold; to allow for systems design techniques and for software configuration techniques.

Systems design may require parts of existing products to be re-used in new designs and therefore only require making again. It may well be the configuration of such building blocks that is new and therefore will require all the preceding stages of this design process to check and evaluate the problems of the new concept.

Also, with software technology tending to replace hardware and mechanical modules in products, giving a new flexibility to a design; it is now possible to have a completely new product function, but employing existing mechanics and electronics; requiring only software changes to implement the new function. Again, it may become apparent only at Chose concept solution set to implement (ACTIVITY 31) that software modification of an existing product is a viable option.

It is a moot point whether a software change is regarded as requiring new design knowledge or not. It is more likely that the design process model would split up at Establish enlarged project team (ACTIVITY 39), requiring hardware to be a Do Product Design Path "A" (ACTIVITY 42) and software to be a Do Product Design Path "B" (ACTIVITY 43).
ACTIVITY 46: Retrieve old data

Activity type: Task

Inputs:
Book 3 of existing selected product

Deliverables:
Book 3 of current product

Commentary:
Look at outstanding modifications and problems outstanding from the last product run.


ACTIVITY 47: No paperwork?

Activity type: Design team internal decision point

Inputs:
ACTIVITY 46

Deliverables:
Action to remedy

Commentary:
Seek high and low for the existing information on how and what to manufacture.

ACTIVITY 48: PANIC

Activity type: Task

Inputs:
ACTIVITY 47

Deliverables:
Run about like headless chickens

Commentary:
PANIC!
ACTIVITY 49: Any past problems?

Activity type: Design team internal decision point

Rationale:
To ensure that the production information is up to date and stable prior to making the product.

Inputs:
Book 3

Deliverables:
List of outstanding problems

Commentary:
After having recovered the design and manufacturing information for the product it is appropriate to review the status of the last production run and check that there are no 'outstanding' Engineering Change Notes (ECN). Since it is important to have a stable set of information with which to schedule and control production.

ACTIVITY 50: Analyse design problems

Activity type: Analysis

Inputs:
ACTIVITY 49

Deliverables:
Risk analysis

Commentary:
Any outstanding ECNs must be attended to and problems corrected prior to manufacture. Design related problems include revision of circuit board to account for wiring changes, component changes and functional faults reported from test and field service.

A review of customer feedback reports, field service reports and manufacturing reports for information that may lead to improved efficiency or lower production costs should be carried out.
Problems, their fixes and costs are reported in the Problem Analysis Report (PAR).

ACTIVITY 51: Analyse production problems

Activity type: Analysis

Inputs:
ACTIVITY 49

Deliverables:
Risk analysis

Commentary:
Any outstanding ECNs must be attended to and problems corrected prior to manufacture. Manufacturing-related problems include revision of assembly instructions to account for new equipment, component changes, cost reductions and yield problems from manufacturing test.

A review of customer feedback reports, field service reports and manufacturing reports for information that may lead to improved efficiency or lower production costs should be carried out.

Problems, their fixes and costs are reported in the Problem Analysis Report (PAR).

ACTIVITY 52: Quantify cost of fix/change

Activity type: Analysis

Inputs:
PAR

Deliverables:
Cost of changes

Commentary:
Once identified, any change recommended in the PAR must be assessed for cost and impact on deadlines before approval to carry out the changes can be given.
ACTIVITY 53: Acceptable cost?

Activity type: Design team internal decision point

Inputs:
ACTIVITY 52

Deliverables:
Update Book 3 cost estimates

Commentary:
This approval is normally given by the design team leader.

ACTIVITY 54: Continue?

Activity type: Design team internal decision point

Inputs:
ACTIVITY 53

Deliverables:
Authorisation to continue

Commentary:
If the cost of change is too high then it must be referred to a higher authority for approval or dismissal. Since the additional cost may have to be borne by the customer, rather than the company.

ACTIVITY 55: Raise ECNs

Activity type: Task

Inputs:
ACTIVITY 53

Deliverables:
ECN's

Commentary:
If a problem has been identified, costed and accepted, then raise the change notice paperwork to appropriate personnel.
ACTIVITY 56: Approved?

Activity type: Central ECN committee decision point

Inputs:
ACTIVITY 55

Deliverables:
Authorisation of ECN release

Commentary:
Approval by central ECN committee

ACTIVITY 57: Modify change proposal

Activity type: Task

Inputs:
ACTIVITY 56

Deliverables:
Modified change

Commentary:
If approval is not gained, iterate around the change proposal loop. The reasons for failure here are likely to be business oriented, rather than technology oriented.

ACTIVITY 58: Implement changes

Activity type: Task

Inputs:
ACTIVITY 56

Deliverables:
Altered documentation (book 3)

Commentary:
No design work involved. Only process modifications.
ACTIVITY 59: Issue schedule

Activity type: Task

Inputs:
ACTIVITY 58

Deliverables:
MPS

Commentary:
Manufacturing control schedule, parts issue and so on (Master Production Schedule)

ACTIVITY 60: Make trial batch

Activity type: Task

Inputs:
ACTIVITY 59

Deliverables:
First samples of new product

Commentary:
Make to production standard to check both design and manufacturing processes.
ACTIVITY 61: Problems?
Activity type: Design team internal decision point

Inputs:
ACTIVITY 60

Deliverables:
ECN's if problems

Commentary:
Check product function and assembly

ACTIVITY 62: Production test
Activity type: Task

Inputs:
ACTIVITY 60

Deliverables:
List of faults

Commentary:
Check batch out. Look for faults that affect design function and design yield.

ACTIVITY 63: Problems?
Activity type: Design team internal decision point

Inputs:
ACTIVITY 62

Deliverables:
List of faults

Commentary:
None

ACTIVITY 64: Ramp up to full production
Activity type: Task

Commentary:
None
ACTIVITY 65: Raise ECNs

Activity type: Task

Inputs:
Problems at various stages of design

Deliverables:
Raised Engineering Change Notes

Commentary:
ECN's are raised following a problem identification.

ACTIVITY 66: Approved?

Activity type: Design team internal decision point

Inputs:
ACTIVITY 65

Deliverables:
Released ECN

Commentary:
Look for side-effects of ECN, estimate cost of change and approve action

ACTIVITY 67: Modify change proposal

Activity type: Task

Inputs:
ACTIVITY 66

Deliverables:
ECN

Commentary:
Change ECN to fit purpose
ACTIVITY 68: Implement changes

Activity type: Task

Inputs:
ACTIVITY 66

Deliverables:

Commentary:
PRODUCT DESIGN PATH B: Variant Design

Commentary:

Variant design is defined as up to twenty percent new knowledge in electronics design or production of the new product.

There is a need for speed and flexibility in this area. These requirements can be illustrated by considering the fact that when an aerospace company in the South East developed a new flight simulator they took longer and spent more than they had done for their first generation product. This happened even though the product was almost an exact copy of the first. Company historical data was almost non-existent and key personnel were different in each development project.

Within a product development project there is likely to be varying amounts of work required across the engineering sectors of the company. Therefore, it is likely that the design process model would split up at Establish enlarged project team (ACTIVITY 39), perhaps requiring hardware to be a Do Product Design Path "A" (ACTIVITY 42), software and mechanics to be a Do Product Design Path "B" (ACTIVITY 43). If the product needs industrial design (human interface, packaging technology, aesthetics), it may even involve some innovative design, requiring a separate path specifically for this, Do Product Design Path "C" (ACTIVITY 44).

ACTIVITY 69: Retrieve old data

Activity type: Task

Inputs:
Existing product's book 3.

Deliverables:
Book 3 of new product

Commentary:
Use existing book 3 of existing product to form basis of new product variant.
ACTIVITY 70: Understand/critique/update Product Book 3

Activity type: Analysis

Inputs:
Book 3

Deliverables:
Book 3 with irrelevant bits removed

Commentary:
Since the project team has increased in size to accommodate the work load, the new members of the team will need to repeat the exercise of understanding the TPSD and perhaps questioning some of the specifications defined within it.

This activity will raise some problems in respect of the functionality of the design proposed in book 3. All possible problems should be aired at this juncture and documented in book 3, as well as hiding (using the editor) irrelevant bits of book 3 (that were of the part of the existing production that is to be changed. This enables the next creative phase to operate to a set of requirements; for example: 'how are we going to get the required behaviour in the space and power consumption we know is available?'.

Other aspects of the TPSD may define particular circuit function or even circuit schematic in detail. The task of design team B in these cases is to check whether this detail actually ties up with the technical specification. In doing so, they also comprehend the operation of the defined circuits and functions that are relevant to their own specialisations.

ACTIVITY 71: Formulate solutions

Activity type: Creative

Inputs:
Book 2 & book 3

Deliverables:
Extensions to book 3

Commentary:
The solutions formed at this stage may be formulated rapidly, awaiting laborious checking in Analyse for failure (null hypothesis) (ACTIVITY 72), below.
The circuits will be more specific in detail than the concepts derived above (in Formulate concepts – Behaviour -> Function, NO TAG). So, a microprocessor concept will be developed further, specifying the data path width, the input/output relationships and the operating speed. This is commonly regarded as the ‘detailed block diagram’ phase. First estimates of software code modules will also be specified at this point. Complete and detailed circuit descriptions are developed later in Define new circuits (ACTIVITY 82).

**ACTIVITY 72: Analyse for failure (null hypothesis)**

**Activity type:** Analysis

**Inputs:**

Book 3

**Deliverables:**

Design faults highlighted

**Commentary:**

Group discussion should encourage the best options to be selected. Leaving an individual to complete this task may result in a biased reasoning and analysis, especially if the person does not possess a wealth of experience.

Estimates of circuit speed, size, cost and power consumption may be made at this point, together with a ‘devils advocate’ game of attempting to prove the design will fail. Succeeding in this game will show up the short comings of the design. It is called the Null Hypothesis, since it is the standard scientific method of proving a theorem – failing to prove it is wrong, by implication proves it is right (until proven wrong at a later date!). Mathematical methods of achieving the same goal (formal methods) may replace this technique for the certain types of digital design in the future. ELLA currently has a set of mathematically proven library components with which to construct a design, the assumption being that the whole design is the sum of the proven parts and thus proven itself.
ACTIVITY 73: Failure?

Activity type: Design team internal decision point

Inputs:
ACTIVITY 72

Deliverables:

Commentary:
Are there any options to assess?

Do any of the solutions fail to satisfy all the technical criteria?

ACTIVITY 74: Assess risk of each solution

Activity type: Analysis

Inputs:
ACTIVITY 72

Deliverables:
Risk report

Commentary:
Assess risk to company, including risk of not proceeding. Attempt to quantify:

- Reliability of components
- Newness of technology
- Costs to produce
- Timescales
- Costs to test
- Engineering costs
  Many of these factors will be interrelated.
The TPSD/A must now be extended to include a risk analysis of each solution set.

**ACTIVITY 75: Select best solution set**

**Activity type:** Task

**Inputs:**

**ACTIVITY 74**

**Deliverables:**

Changes to book 3

**Commentary:**

The best solution set is the one with minimal risk to the company, not the nicest or most elegant solution set. Thus, this activity must be carried out by the entire DETAIL DESIGN TEAM to avoid a biased choice. The chosen solution set should now consistute book 3 chapter 1, and others where appropriate.

**ACTIVITY 76: Define links**

**Activity type:** Task

**Inputs:**

Book 3

**Deliverables:**

Updated book 3

**Commentary:**

The functional block diagram is concerned with the detailed functional aspects of the circuits, the linking signals are defined here, from knowledge of the functional requirements. Digital designs require bus bit widths, control signal names and data structure definition; analogue designs need voltage and current characteristics of linking signals defined.
ACTIVITY 77: Refine timing and function specification

Activity type: Task

Inputs:
ACTIVITY 75

Deliverables:
Updated book 3

Commentary:
A more detailed timing estimate can now be added to the design project knowledge pool.

ACTIVITY 78: Develop production test capability

Activity type: Task

Inputs:
book 3

Deliverables:
Updated book 3

Commentary:
As circuits are being defined, it is appropriate to embark on the important task of developing the production test capability.

The existence of a complete suite of functional block diagrams for the product allows production test engineering to confirm the original test philosophy has been adhered to. If new production test equipment is being developed, this is the point at which the first detailed analysis of testability may be carried out. However, until the circuit wiring boards have been placed and routed a bed-of-nails cannot be defined, nor can the correctness of any functional testing be assured.
ACTIVITY 79: Refine engineering costs and constraints

Activity type: Task

Inputs:
book 3

Deliverables:
Updated book 3

Commentary:
An engineering cost is an aspect of the specification of the circuit that is separate from the functionality required. Engineering costs are extremely important, being metrics of project success that often relate directly back to the original customer CPR. For example, the device must be battery powered and must last at least four hours before recharging, could be a customer CPR, the engineering costs of power consumption for each circuit in the device must be estimated at early stages in the project to constrain the type of implementation chosen. These estimates must then be refined during the project, to ensure they are not exceeded; for a reduced battery life may cause the project to fail even though the device functions perfectly.

This activity is progressed though the project to completion. Estimates of engineering costs are continuously being refined by all aspects of the work. Cost, speed, power consumption, electromagnetic susceptibility, size of final circuits are but a few of the engineering costs under constant consideration and refinement. Manufacturing constraints are also updated during the project.
ACTIVITY 80: Refine Critical Path Document (CPD)

Activity type: Task

Inputs:
Book 3 – CPD

Deliverables:
Updated book 3 – CPD

Commentary:
A variant project will have an amount of unknown or new knowledge that will have to be explored and understood by the design team. Each could have a direct effect on the time scale of the project, and thus affect the critical path of the project. Therefore, the CPD must be revised regularly and all delays analysed for impact on the project timescale and profit.

ACTIVITY 81: Refine marketing plan

Activity type: Task

Inputs:
TMP (held in book 1)

Deliverables:
Updated TMP (held in book 1)

Commentary:

ACTIVITY 82: Define new circuits

Activity type: Creative

Inputs:
Book 3 – Chapter 1

Deliverables:
Updated book 3 – Chapter 1

Commentary:
Convert functional block diagrams into circuit schematic diagrams. This is a direct application of the basic electronics knowledge schooled into the engineer at college and subsequently enriched by professional experience and training.
Revision control is an internal matter for the design team, but should be recorded as a matter of course.

**ACTIVITY 83: Modify old circuits**

**Activity type:** Creative

**Inputs:**

Book 3 – Chapter 1

**Deliverables:**

Updated book 3 – Chapter 1

**Commentary:**

Edit old circuits appropriately to conform to new requirements (a complete understanding of the circuit behaviour is needed to accomplish this).

Revision control is an internal matter for the design team, but should be recorded as a matter of course.

**ACTIVITY 84: Refine engineering costs**

**Activity type:** Task

**Inputs:**

Book 3

**Deliverables:**

Updated book 3

**Commentary:**

This is the same type of activity as ACTIVITY 80, however, as the circuit schematic diagrams develop a more detailed picture can be formed of the component count, the board area estimates and power consumptions.
ACTIVITY 85: Document design

Activity type: Task

Inputs:
Book 3

Deliverables:
User guides, field service guides and others

Commentary:
Design engineers engaged on the project must keep up to date descriptions of their circuits and the modifications, tests and other salient information.

ACTIVITY 86: Do testability analysis

Activity type: Task

Inputs:
Book 3

Deliverables:
Updated book 3

Commentary:
Ensure the evolving design is testable and is within the testability philosophy written down in the CRS and TPSD.

The activities defined here are expected to take place throughout the circuit definition phase of the design.

ACTIVITY 87: Simulate/analyse/breadboard circuits

Activity type: Task

Inputs:
Book 3

Deliverables:
Updated book 3

Commentary:
Simulate/analyse/breadboard circuits to evaluate function and engineering costs. It is normal to define the input stimuli and to evaluate the internal function by recording the
resulting outputs. It is important to trace one's activity during this phase of debugging, to avoid cyclic behaviour and repeated test/ modification sequences through **OK?** (ACTIVITY 88).

Depending on the status of the project, this phase of the design may not be version or issue controlled (if early prototyping). Later, if problems are discovered during **Prototype build to production standard or during manufacture** then redesign and re-work will be controlled by the in-house quality assurance system.

**ACTIVITY 88: OK?**

Activity type: Design team internal decision point

Inputs:
ACTIVITY 87

Deliverables:
Approval to continue

Commentary:
Check circuit function, compatibility with other relevant aspects of product and ensure engineering cost estimates are within specified constraints.

Errors to be written down to ensure the “why it went faulty” or “why we chose this design route rather than the other route” are recorded for posterity. Company culture impact and managerial assessment of engineers should both encourage anonymous reporting of mistakes in a manner similar to the Civil Aviation Association pilot error reporting programme.

**ACTIVITY 89: Prototype build to production standard**

Activity type: Task

Rationale:
Making sure the device can be made to production tolerances. **NOT DOING** begs the design and layout engineers to ignore manufacturing costs.
Inputs:

Deliverables:

Commentary:
Making to production standard does not mean that it has been made on the production line. Although the production line may have a special build facility, entailing running the job through production as a 'special'. It is more likely that a prototyping line or wireman will assemble the product at this point, but taking care to work within production tolerances.

Things to look out for are:

1. Printed wiring board not conforming to production standard in physical design rules: track to track distances, solder trapping junctions, drill hole diameters and other physical parameters.

2. Components not on company 'approved list'. They may be unsuitable for manufacturing processes running in the factory, not auto-insertable or affected by the vapour phase soldering technique employed or not now available in production (being superceded perhaps), for example.

ACTIVITY 90: Develop production test

Activity type: Task

Inputs:
Book 3

Deliverables:
Updated book 3

Commentary:
The existence of a complete suite of functional block diagrams and circuit diagrams for the product allows production test engineering to initiate the production test programme.

Production test is required to ensure that the build process results in a completely functional and fault free product. High reliability automatic fabrication may allow reduced testing, but a final assembly test will still be required, often after a 'on-soak' period.
ACTIVITY 91: Assess impact on production

Activity type: Task

Inputs:
Book 3

Deliverables:
Updated book 3 + management report

Commentary:
Assess the effect of the product on manufacturing schedules and manpower

ACTIVITY 92: Test tooling

Activity type: Task

Inputs:
Book 3

Deliverables:
Report setting out requirements for tooling

Commentary:
Check at circuit design stage that the design can use existing test tooling structures, for example:

- Bed of nails format
- Functional test harness

ACTIVITY 93: Analyse function of production prototype

Activity type: Task

Inputs:
Prototype
Appendix 3.

Deliverables:
List of problems

Commentary:
This may be the first real prototype (especially if simulation techniques have been used through out the design process). Checking the functionality and the conformance to requirements is an essential task. If the work involves printed wiring boards, then the design revision level should be up to date i.e. make sure the correct version of the electronics is being debugged.

ACTIVITY 94: Goto review?

Activity type: Design team internal decision

Inputs:
ACTIVITY 93

Deliverables:
Internal approval to progress

Commentary:
Goto ‘0’ if failed. Proceeding to RELEASE GATE 4 (ACTIVITY 99), without correcting the fault may pass manufacturing the problem, which will lead to an increase in costs associated with the corrective actions required to fix the faults.

ACTIVITY 95: Do testability analysis (production test)

Activity type: Task

Inputs:
ACTIVITY 94

Deliverables:
Report on analysis

Commentary:
Done by test engineer, using standard test evaluation algorithms, which are probably best company and customer defined.
ACTIVITY 96: 95% testability?

Activity type: Design team internal decision point

Inputs:
ACTIVITY 95

Deliverables:
Assess prototype for acceptance

Commentary:
The acceptable level of test is dependant on the type of design and desired production throughput. Integrated circuits are normally 95 to 100% testable at present. Bed of nails testers can achieve 100% testability, although 100% functional test may be interpreted differently by customer and company respectively. It is important to refer back to customer acceptance requirements in the CPR to define the assessment needs of this decision activity.

ACTIVITY 97: Test wrong?

Activity type: Design team internal decision point

Inputs:
ACTIVITY 96

Deliverables:
Identification of failing

Commentary:
Who, or what, is at fault here? The circuit, the tester, the test engineer or the designer may be the cause of the problem.

ACTIVITY 98: Circuits wrong

Activity type: Design team internal decision point

Inputs:
ACTIVITY 97

Deliverables:
Raise ECN

Commentary:
If circuits wrong, redesign to correct problem. This step may cause an ECN to be raised.
ACTIVITY 99: RELEASE GATE 4 -- Pre-test review

Activity type: Company-level decision point

Inputs:
ACTIVITY 96

Deliverables:
Approval to progress to batch production

Commentary:
RELEASE GATE 4 begins post development stages of product development cycle. The gate revisits the question of whether the project continues to be a viable business venture in light of the new information gained during product development and the development of the marketing plan.

Serves as a quality control check on the development phase.

A number of performance monitors are checked and recorded at this point too, allowing design management to assess the project progress in terms of design iterations, problem lists, new knowledge sought, failed deadlines, failed critical paths and plan corrective action.

ACTIVITY 100: Hold until assessment complete

Activity type: Task

Inputs:
ACTIVITY 99

Deliverables:
Hold on progress

Commentary:
RELEASE GATE 4: Pre-test review (ACTIVITY 99), is the most important staging point prior to Production handover, (ACTIVITY 112). It is extremely important that the product design is complete in all aspects.
This may be the first time mechanics and electronics (and software) have been operating together. A grave error may be made at this point, for a failure to Hold until assessment complete may lead to premature production release of the electronics, with subsequent testing of the mechanical/electronic interface revealing design failings in the electronics.

**ACTIVITY 101: Make trial batch**

*Activity type: Task*

**Inputs:**
ACTIVITY 99

**Deliverables:**
First samples of new product

**Commentary:**
Make to production standard to check both design and manufacturing processes.

**ACTIVITY 102: Production test**

*Activity type: Task*

**Inputs:**
ACTIVITY 101

**Deliverables:**
Note test performance/failings

**Commentary:**
Are all the tests in-place in manufacturing to ensure fabrication of product is correct?

**ACTIVITY 103: Fail?**

*Activity type: Design team internal decision point*

**Inputs:**
ACTIVITY 102

**Deliverables:**
Problem notification report

**Commentary:**
Failure could be due to incorrect information from design team B, or a problem in production itself.
ACTIVITY 104: Analyse cause of failure

Activity type: Analysis

Inputs:
ACTIVITY 103

Deliverables:
Raise ECN

Commentary:
Where do the problems reside? Careful and un-biased reasoning should prevail to ensure a rapid resolution of the faults.

ACTIVITY 105: Circuit failure?

Activity type: Design team internal decision point

Inputs:
ACTIVITY 104

Deliverables:
Raise ECN

Commentary:
If the circuit fails, then perhaps the tolerances the design team worked to are different to those applied in volume production? Record reason for failure in the appropriate chapter of the CPBFC.

ACTIVITY 106: TPSD failure?

Activity type: Design team internal decision point

Inputs:
ACTIVITY 104

Deliverables:
Raise ECN

Commentary:
Where the original technical specification was wrong. The further up the line the error occurs, the costlier in time and money it will be to put right.
ACTIVITY 107: Release prototype to customer

Activity type: Task

Inputs:
ACTIVITY 102

Deliverables:
Prototype

Commentary:
Often, the customer will require an early version of the product to work with. Modifications requested by the customer to correct problems at this stage must be analysed as either: (a) companies fault, or (b) customers fault. This allows costs to be negotiated accordingly. It is important that any contractual matters in this respect must be defined at or before RELEASE GATE 3 (ACTIVITY 35).

ACTIVITY 108: Complete design documentation

Activity type: Task

Inputs:
Book 3

Deliverables:
All technical authored guides

Commentary:
Technical authors complete user guides, maintainence guides and assembly instructions, in cooperation with Design team B.

ACTIVITY 109: Get response

Activity type: Task

Inputs:
ACTIVITY 107

Deliverables:
Report from customer on prototype performance and acceptability

Commentary:
The customers obviously are important, their comments are also important; but their impact on the project MUST be assessed carefully by Design Team B, then by Design team A if needed.
ACTIVITY 110: Changes?
Activity type: Design team internal decision point

Inputs:
ACTIVITY 109

Deliverables:
ECN raised

Commentary:
If changes are required, ECNs will have to be raised at this point.

ACTIVITY 111: RELEASE GATE 5 -- Pre-production review
Activity type: Company-level decision point

Inputs:

ACTIVITY 110

Deliverables:
Approval to continue to full production

Commentary:
Considers test results. If tests are considered valid, the project is ready for handover to production. Additionally, most control documentation, CPR, CRS, TPSD and the PCBFC will be complete and ready for issue ‘freezing’.

Review the CPD and record delays and the mistakes and problems that caused them in an appendix to the CPD (for future reference). Also, feedback problems to all concerned for project debriefing.

ACTIVITY 112: Production handover
Activity type: Task

Inputs:
Book 3

Deliverables:
Book 3

Commentary:
Personnel from Design team B will be involved (share responsibility) in any problems found during the first production batch and until full production is achieved. Effectively
being 'on-call' for the duration, perhaps even being resident in the factory during the trial batch production run.

**ACTIVITY 113: Hold until assessment complete**

Activity type:

**Inputs:**
ACTIVITY 111

**Deliverables:**
Hold project progress

**Commentary:**
None

**ACTIVITY 114: Raise ECNs**

Activity type: Task

**Inputs:**
Problem Notification

**Deliverables:**
ECN raised

**Commentary:**
None

**ACTIVITY 115: Approved?**

Activity type: Design team internal decision point

**Inputs:**
ECN

**Deliverables:**
Approved ECN

**Commentary:**
None
ACTIVITY 116: Implement changes

Activity type: Task

Inputs:
ECN

Deliverables:
Modified ECN

Commentary:
None

ACTIVITY 117: Re-Issue schedule

Activity type: Task

Inputs:
MPS

Deliverables:
Wait for ECN to be completed then re-issue manufacturing build request

Commentary:
None

PRODUCT DESIGN PATH  C: Innovative Design

Innovative design follows the same path as for Variant Design, but the gates are more rigorous as the risks are higher.

PRODUCT DESIGN PATH  D: Strategic Design

Strategic design is a review of basic principles and the development of a demonstrator. Acceptance of the demonstrator by the company then allows the new product to follow the Innovative Design path.
REFERENCES


page 326
3.3. The Design Process – activity flow charts

The following pages describe graphically the generic design process model activity tree presented in section 3.2., found from page 259 above.

Glossary for Design Process Flow Chart

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCT</td>
<td>Circuit</td>
</tr>
<tr>
<td>CPD</td>
<td>Critical Path Document</td>
</tr>
<tr>
<td>CPR</td>
<td>Customer Product Requirements</td>
</tr>
<tr>
<td>CPS</td>
<td>Commercial Product Specification</td>
</tr>
<tr>
<td>DFM</td>
<td>Design for Manufacture</td>
</tr>
<tr>
<td>ECN</td>
<td>Engineering Change Note</td>
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<tr>
<td>MPS</td>
<td>Master Production Schedule</td>
</tr>
<tr>
<td>PDP</td>
<td>Product Development Path</td>
</tr>
<tr>
<td>QFD</td>
<td>Quality Functional Deployment</td>
</tr>
<tr>
<td>SPC</td>
<td>Statistical Process Control</td>
</tr>
<tr>
<td>TPS</td>
<td>Technical Product Specification</td>
</tr>
</tbody>
</table>
Top level view of the EDT Electronic Product Design Process Model

Customer needs

Generate Product Concepts
Activity 1-25

Generate Product Solutions
Activity 24-38

Develop Product
Activity 39-44
Path A: As 46-58
Path B: 69-119
Path C: as B
Path D: *

Validate Product
Activity 58-112

Path design

Validated Process

Valid product

Product

QFD
DFM
Creativity techniques

QFD
Process FMEA
Simulation
Product FMEA
Poka Yoke

Product FMEA
Taguchi

Validation testing

SPC
Creativity techniques

Not addressed in detail in the EDT Process Model

Series of constraint sets in re-strategy feeding into the design process

Design path D develops a strategic product and involves a fundamental review of principles which lead to a demonstration. Product development then proceeds as for Path C.
Appendix 3

Legend for Design Process Flow Chart

Legend for Design Process Flow Chart

- **Task symbol**: Find old paperwork
- **Analytic/critical activity symbol**: Understand/critical 1PSD
- **Creative activity symbol**: Formulate concepts (Behaviour function)
- **Internal decision box symbol**: Problems
- **Company-level decision gate symbol**: RELEASE GATE 4: Pre-test Review

Includes:
- New circuit behaviour
- New circuit test
- Production

Comment symbol: May be attached to flow lines and to any other symbol. Information may be either text or reference to text elsewhere.

Illustration:

- **Offline storage symbol**: for information to be used during later task/analysis

- **Printed document symbol**:

**NOTE**: Horizontally adjacent boxes indicate Concurrent Engineering-type parallel activities as well as the existence of interaction between those activities.
Appendix 3

Generate Product Concepts

1. Customer
   - Modify CPR

2. First cut solutions
   - Understated CPR
   - Does company wish to bid for project?

3. First cut solutions
   - Held until statement complete
   - Held until release gate 1: Initial Screen

4. CPR
   - Preliminary technical analysis
   - Preliminary market analysis
   - CPR

5. CPR
   - CPR

6. CPR
   - CPR

7. Modify concepts
   - Create product concept
   - CPR
   - Define new product requirement specification (CRS)
   - CPS
   - Define new product requirement specification (CRS)
   - CPS
   - Define new product requirement specification (CRS)
   - CPS
   - Define new product requirement specification (CRS)
   - CPS
   - Define new product requirement specification (CRS)
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Generate Product Solutions

1. Preliminary Assessment Report
2. CPS
3. Release CPS
4. Product Concepts
5. Analyse product concepts
6. Analyse product concepts (Product Book 2)
7. OK?
8. Develop behavioural solutions
9. Behavioural solutions (Product Book 2)
10. Analyse solutions

Decision Points:
- No: Go to Release Gate 3: Preliminary Assessment
- Yes: Continue

Final Steps:
- Reasons requirements in light of criteria
- Liaise with customer

Product Book 1

Product Book 2

Headed by senior personnel from:
- Marketing
- Production
- Design
- Purchasing

Involves:
- Preliminary market assessment
- Preliminary technical assessment
- Uses some financial criteria

Page 331
Repeat Order

1. Retrieve old information

2. Investigate

3. Investigate paperwork

4. Analyze design problems

5. Analyze production problems

6. Machine changes
   - Process problems
   - Machine tolerance problems
   - Test
   - Quality/yield/repair
   - Component availability
   - Tooling costs
   - Costs associated with process/machine changes

7. Who decides and according to what criteria?

8. Acceptable cost?

9. Raise ECNs

10. Approved

11. Implement changes

12. Issue schedule

Appendix 3

Including:
- MPS
- BOM
- Cabinet drawings

Machine changes
- Process problems
- Machine tolerance problems
- Test
- Quality/yield/repair
- Component availability
- Tooling costs
- Costs associated with process/machine changes

Appendix 3

[Refer to senior management?]
Appendix 3

Variant Design

TPS

Retrieve old information

In the light of old paperwork

Includes:
- Partitioning into new & existing act functions
- Elimination of confirmation bias

Verification activity using low level circuit function symbols seek to eliminate confirmation bias

Solutions

Analyze for failure (null hypothesis)

Failure?

Risk to company, including risk of not proceeding

Quantify:
- Reliability of component
- Newness of technology
- Costs to produce
- Timescale
- Costs to fix
- Engineering costs

Assess risk of each solution
Review mistakes and delays

(101) Make trial batch

(102) Production test

Test results

(103) Fail?

No

(104) Analyse causes of failure

Yes

(105) CCT failure

(106) TPS failure

(107) Release prototype to customer

(108) Complete design documentation

(109) Get response

(110) Changes?

Yes

(111) Hold until assessment exception

(112) Production handover

(113) Design team special turn in production

(114) Raise ECN's

(115) Appraise?

No

(116) Implement changes

(117) Issue schedule

Appendix 3

---

Yes

B

RELEASE GATE 5: Pre-production Review

Go

No Go

Design team special turn in production

page 337
G) Innovative design

As for F except gates are more rigorous with regard to risk and failure.

Prototype may not be to production standard.

H) Strategic design

A fundamental review of basic principles, leading to a demonstrator which will only provide illumination on principles and their constraints.

Product design then takes place by innovative design procedures, in G.
APPENDIX 4. (A) INCREMENTAL REFINEMENT OF CIRCUIT WIRING BOARD SIZE
(B) ENGINEERING EXAMPLES OF THE DESIGN SYSTEM
(C) AN EXAMPLE DATABASE
(D) A LISP EXEMPLAR IMPLEMENTATION OF THE PRODUCT BOOK MODEL
Appendix 4.: Engineering Examples

(a) Incremental Refinement of Circuit Wiring Board Size

An example will now be discussed in some detail to highlight the way in which specifications associated with engineering costs (and not circuit function) are refined during the design process. The steps taken during the refinement are then discussed in terms of requirements for the EDT functional specification, with reference to the Four path model of design.

At Product specification/Conceptual Product Specification stage: the requirement could well be defined as "the circuit must fit into an IEC 297-3 half height rack card with environmental protection conforming to DIN40050 (BS5490, IEC529) IP30." An additional constraint may be that this is not negotiable and must not be exceeded (perhaps for other cost or packing density reasons, such as the ability to retrograde fit the new circuit as an up-grade to an existing product).

At Conceptual Product Specification/Concept stage: the electronics engineering team responsible for the development of the Conceptual Product Specification to PCBS would then identify and evaluate potential options would be constrained by this requirement. However, no exact dimensions for size will be available unless all the components for the design are already known and the circuit board laid out. If it is clear at this stage that the design is certain to be a repeat order or variant design then information will exist defining the circuit physical dimensions of the already designed circuit, However uncertainty still exists, for until the cost reductions exercises or new extensions to the design are completed the exact size of the circuit board is still subject to variation.

At Conceptual Design to Product Development Proposal stage: the exact meaning of the DIN standard should be expanded to concisely represent the size constraint on the
Appendix 4: Engineering Examples

circuit to be designed. So, the size constraint will become "the circuit must fit into a 220mm long by ??? mm wide circuit board to conform to IEC297-3 with environmental protection for protection against small foreign bodies (diameter over 2.5mm) and no protection against water ingress, conforming to DIN40050 (BS5490, IEC529) IP30."

Assuming that the design is a variant of an existing design, then, at this point it will be confirmed that the circuit board is likely to be near that of the existing product. The actual sizes of the existing product would then be extracted from the company archive, showing that, for example, the existing product fitted onto a 220 high by ???mm wide by 2mm depth circuit board, with 75% packing density of components with a two layer printed wiring construction. The proposed modifications to this existing circuit can then be assessed with respect to this detailed size information to ascertain the risk of failure to conform to this specification.

At Product Development Proposal to circuit design stage: The electronics engineers responsible for the design of the circuit are unlikely to check the size constraints of the evolving design until the desired functionality of the design is assured. However, tools such as RAPIDS and BCA can offer continuous checking of the design even during this cyclic phase of circuit creation, test and modification.

Circuit Layout: this phase fixes the size of the now completed circuit functionality that hopefully still conforms to the original specifications, and satisfies the size constraint defined in the CPS.
Analysis of exemplar engineering constraint problem

Now as shown above in the previous section the size constraint is propagated from the original specification down to the circuit layout stage in the design process. The engineering cost undergoes stepwise refinement and is finally defined as a height, width and depth constraint (of circuit board itself) on the circuit layout. Checks for conformance to this specification may be instigated by a company specialist in packaging (who, perhaps is developing the mechanics of the enclosure) by talking to the engineering staff developing the electronics. It may be more efficient, however, to ensure that the size criteria is available in the design database for the circuit and that it is updated automatically by the tools involved in the creation of the circuit and its packaging. Automatic constraint checking by computer can then take place during the product development. This type of checking is known as truth maintainence and systems for carrying this out have been developed by members of the artificial intelligence community for solving a number of constraint propagation problems in machine planning and reasoning.

What has not been discussed is the setting of design constraints by implication. In the above example, this may be shown as the additional constraint that circuit components may not be greater than Nmm in height, where N is the size of the as yet undefined parameter of rack card spacing in the horizontal plane. Whilst it is clearly difficult to check a design against 100% of undefined parameters, assumptions can be made of the design requirements from prior experience and applied to the current design. So the missing card spacing parameter could be identified as salient to the current design by machine based deductive logical reasoning.
(b) Engineering Examples of the Design System

(i) A Repeat Order design

A complex electronics product has had a problem notification report (PNR) raised concerning the over-heating of a circuit board in its enclosure, the problem has been reported by field service.

1.  **PNR (raised by field service engineer) --> ECN system** collects it, author and date stamps it, appends it for reference to product book 3, in PNR chapter (acts as a history record for PNR & corresponding ECN)

2.  **ECN system --> looks up contact list against project number for engineer in charge**

3.  **ECN system --> raises mail message to project leader & copies PNR to him/her**

4.  **Project leader --> reads email ECN, raises PNR to Repeat Order design status, allocates resources.**

5.  **Project leader --> request meeting from meetings scheduler, topic is PNR, meetings list is default minimal engineering team.**

6.  **Project leader --> allocates PNR responsibility to one member of meeting team (PNR leader and notifies ECN system)**

7.  **ECN system --> sends PNR copies to all meetings team, with PNR leader.**

8.  **Meetings Scheduler (if problem is deemed major) --> consults individual diaries and books meeting, including room for first meeting.**

9.  ... (email dialogue may arise between problem team)

10. ... product acquired by PNR team

11. ... Book 3 circuit layouts and circuit component power dissipations consulted, problem assessed in laboratory.

12. ... decision to re-layout cct board --> noted in product book 3 as a change to a repeat order design (in chapter 5 PCB design)

13. **DPS layout modified, DPS prompts for reason why change (at start of layout session), checks authority to start edit of layout of new version.**
14. **Layout tool** all pre-existing constraints and cross-checks are applied to the new layout during (pre- and post-layout where appropriate as well) the layout session.

15. **Layout tool** all existing tooling holes and assembly fixtures are retained (and deletion prevented) as this is a Repeat Order design.

16. . . . (completion of placement and layout also assumes completion of assembly scheduling and build data for new board)

17. **Thermal simulation** of new layout completed (if possible) or seeks approval to build new pcb . . . . (assume successful or continue with second approach . . . to fit holes in chassis (may have been cheaper but not an electronic example!!)

18. **DPS changes** approved by project leader (via ECN mail sign-off request)


20. **DPS updates design** (as against build, ie. design group internal document tracking) release numbers of all changed documents or parts of documents.

21. **DPS adds** change note at front of book 1,2 and 3 pointing to change in this chapter.

22. **DPS updates build** (ie. company wide tracking) release numbers to match all changed documents or parts of documents to new approval level.

23. **Project leader** --> raises ECN to fix problem in production batches, using DPS generated references to latest versions from which to build from.

24. **ECN system** --> raises mail message to production engineer responsible

25. . . . and so on.
(ii) A Variant design

A palm sized hand-held calculator is to be developed by a company that already has a number of desktop calculators in its design portfolio.

Prior to a discussion of the how the EDT functional specification may be used during the design process, a reverse engineering exercise of a real palm-sized calculator has resulted in the following final specification:

Analysis of calculator:-

**Box:**

# sized for keypad, display & batteries
# moulded for assembly
# moulded for retrofit of batteries as well
# screen printed legend on front only
# back moulded with opening advice
# back cleaned by scouring and de-burring
# depth profile determined by display, pcb fixture and battery depth.
# holes determined by key pad layout and dimensions
# back fits front by sliding action on moulded rails

**Display:**

# 8 digit
# 34mm by 12mm by 3mm max
# step edge at edge connector 2mm overhang for connector
# light pressure fit into locating hole
# characters are numeric
# additional characters on right side -E are 2.5mm high by 2mm
# decimal point in between every character
# 27 pins on edge connector, encoded as [M,E,-,7 segments, gnd, 8 decimal points and 8 column strobes]

**Keyboard:**

# pressure pad, with resistive rubber membrane
# keys are on 10mm pitch
Appendix 4.: Engineering Examples

# keys are 5mm square or 12mm by 5mm (for +,0 and on/off)
# characters are 5mm high by 2mm wide, spacing is 1mm
# key set is 0-9, +,-,.*,%, + and mc, mr, m+, m-
# and OFF, CE, ON/C

PCB:

# gold flash
# substrate material
# no. layers - 2
# max conductor 0.5mm
# min conductor - determined by TAB pinout
# TAB 44 pin
# resistors - smd - 2off
# capacitors - smd OR normal - 1off
# size 74 by 31 mm
# fixtures cross thread screws 9off, 4 clustered along edge
# locating lugs - 2off 2.5mm dia each
  connector to ensure good mating surface.
# edge connector (pressure mating) to LCD display 27 way single sided,
  1mm wide, 1.5mm pitch
# 6mm slot into edge of pcb for non-smd capacitor (not used)
# battery connections 6mm by 2mm, labelled +,-
# pcb ID no. on both sides
# key pad side is mostly contact pads for resistive rubber switches

Battery:

# space for 1 or 2 6mm dia by 3mm cells wired in parallel (although only one is used - possibly as they were not sure whether the logic would work at 1.5v instead of 3v)
# tapered fit into socket
# metal conductors pressure fit to pcb
# screw positioned to give good mating surfaces
The design project will be split into sections, each corresponding to phases in the Four Path model of Design, see figure 34 below. So, driven by a customer specification, conceptual design is followed by embodiment and finally detail design. At each stage the appropriate product books describing the evolving product would be created/updated.

It is assumed that the necessary members of a multi-disciplinary team are available to work on the project.

**NOTE:** since this example covers more ground than the previous example, the level of detail will not be as great as used for the Repeat Order design problem.

![Figure 34 Overview of the Four Path Product Design Sequence](image)

**Product book 1: Customer Specification of Requirements:**

Design a calculator,

- costing less than 50p to me,
- 8 digits or so.
hand held,
long battery life,
basic functions and memory,
pleasant styling.
simple to use, but useful to punter
100,000 p.a volume

A set of product books will now be developed in outline to demonstrate the function and utility of the product book concept.
Appendix 4: Engineering Examples

Product Book 1 – Initial Company design:

A series of creative design sessions take place, which (amongst marketing and other issues) generate the following product concepts: Product function, Constraining factors, Decisions identified, Design issues to be resolved and Risk Assessment.

These form the core of product book 2 definition of the project. Specific chapters (1–17) will now have paragraphs for function, risk and design constraints, for example. Additional sections to book 2 will be pre-defined by a set of templates, detailing relevant manufacturing limitations. Although, being an Innovative Design a decision will already have been made concerning the need to adhere to current manufacturing constraints.

Product function:

- Functions: +, =, *, /, %, sqrt, constant, memory (mc, mr, m+, m-)
  - not scientific.
  - not programmable. (too complex it seems by assumption ie. too many keys, complex chipery and resultant design time is not variant but innovative as have not done this before)
- New algorithm exploration – simulate in software to show how (for example multiplication)?
- Accuracy – ?? sizes of LCDs
- Physical size – palm of hand 80mm by 50mm say
- Battery/Solar cell – voltage, power, size
- Key pad size, type – no. of keys, spacings, feel, reliability, cost
- Display type, size, character size
- Display control – multiplexed (requiring [M.E., 7 segments, gnd, 8 decimal points and 8 column strobes] or 9 col. strobes and more letters
- Test strategy
- Operating voltage – calculator chips dependent
- Power consumption – ditto
- Case material/size/assembly
- Reliability – power, vibration, temperature, keypad mechanical wear
  - torsion of case.
- ease of fabrication
- low cost requires very high level of integration

NOTES: may have to look up keypad design, bcd, binary or decimal arithmetic and display power considerations.
Constraining factors:

cost --> printed circuit simplicity, chip complexity
function --> chip complexity
function && chip complexity --> pinout
usefulness --> accuracy
accuracy of function --> chip complexity
accuracy of function --> display type, size
HCI --> display size
HCI --> keypad dimensions and feel
pcb size --> case size
no. of keypads --> functions
no. keypads --> HCI
kepad size --> case size
display size --> case size
chip power --> battery/solar cell
component count --> cost, size, reliability, assembly

Decisions identified:

# single chip
# low voltage (single battery/solar cell array)
# function set and keypad set
# HCI limits on keypad, case and display size
# case material
# estimated case/pcb size
# proposed construction
# chip self test includes exercise of display, else vendors test

Design issues to be resolved:

# exact size and shape?
# exact assembly?
# key pad test - possibly by assembly inspection?
# exact display?
# on/off button or timeout to save power?
Risk Assessment:

Time: Is the time available enough?
Design: Is it too complex for our engineers?
Fabrication: will it require some new assembly techniques?
Appendix 4: Engineering Examples

**Product Book 2 – Conceptual Specification:**

Following this initial product session, during which the data created on the new project would be written into product book 2, leaving the contents as below:

**Introduction:**

Introduction to project

**1. FUNCTIONALITY**

Hand held calculator, 8 digit display, battery operation, +,-,=,mem,k & % functions

**2. EXTERNAL INTERFACES**

None

**3. INTERNAL INTERFACES**

Keypad, LCD display, batteries

**4. FIELD MAINTAINENCE**

None – user replace batteries

**5. PHYSICAL INTERFACE**

Fit enclosure -> NN01 (points directly to enclosure specification in mechanical product book 2 sections)

**6. DESIGN VALIDATION CRITERIA**

Simulations of proposed ASIC, build mock-up of enclosure/keypad for HCI

**7. TEST STRATEGY**

Self-test built into ASIC

Manual inspection of LCD and keypad operation

**8. POWER SUPPLY**

3v or 1.5v
9. ENVIRONMENTAL

Temp: office 0–40°C

Humidity: normal (world) office conditions

Dust: (must work after being in user's pocket)

Vibration: (must work after being in user's pocket)

10. STANDARDS

none (but could have been a whole list of stds).

11. HEALTH & SAFETY

none (key word)

12. COST

Total: less than 50p (key words: all)

13. TIMESCALES

less than 12 months (key words: all)

14. QUALITY ISSUES

expected life, early life failure rate, MTBF, battery life, production yield

15. MECHANICAL ENGINEERING

Design keypad and enclosure

16. MANUFACTURING

enclosure to pcb fitting, materials for pcb, keypad, enclosure

17. RISKS

arithmetic algorithms, low voltage operation, size, time scale
18. TECHNICAL DOCUMENTATION (USER MANUAL, FIELD MAINTENANCE, ETC)

User manual to be printed on package

No other customer documentation

<table>
<thead>
<tr>
<th>Checklists</th>
</tr>
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</table>
| **GATE 1 Initial screen** | Is is technically feasible?  
Is there expertise in house to design it  
List problems and possible solutions  
Comment on likely stability of specification |
| **GATE 2 - Prelim assessment of specification and requirements** | Is feasible  
assess if technical risk in CPS & tech. review are acceptable  
check estimates of materials costs & production volumes  
check CPS for tooling costs and identifiable engineering charges for in-house and potential sub-contractors (ASICS, PCBs and mouldings, for example)  
check CPS has made evaluation of enclosures &  
check CPS for coverage of variants of basic design (for future development)  
check for adherence to company and int'l stds  
check if design proposals signal manufacturing changes  
check statements on proposed test strategy  
check skills and equipment availability plan  
check technical spec developed  
check risk assessment is still valid |
| **path select** |  |
| **GATE 3 pre development risk assessment and detailed product technical specification** | check external interfaces are specified for timing, functionality, physical connections, standards, scope for variation (ie. define limits of operation)  
check internal functions and their limits of operation are discussed in TPSD  
check testability analysis |

Table 6: Company Gates during the early phases of design
GATE: pre-design review

As part of the pre-design review a series of checks would be carried out, of the type outlined in Table 6. Additionally, an assessment of the nature of the design task would be undertaken. This complexity metric not only provides an early indicator of the risk involved in the programme of work, it also provides a number of preventative measures that directly affect CAD tool usage for Repeat Order and Variant designs, by controlling the amount of change a circuit layout can undergo during a Repeat Order layout exercise for example (see previous example, item 15. page 344, in this appendix).

The design complexity figure of merit obtained from this provides an indicator of the type of design support required to carry out the design task.

\[
\frac{(A + B) \cdot (1 + F) \cdot (1 + G))}{(D + mE) \cdot H}
\]

design magnitude \hspace{1cm} design novelty

eqn. 1

Where

- A is the sum total number of functions of each device in the circuit,
- B is the number of functions of the desired circuit
- C – not used
- D is the number of similar designs done by the engineer tasked with the design (% prior knowledge. Additionally if no similar designs have been done, but an engineer attended a relevant course to acquire 1-50% know-how and thus a value for D of 0.01 to 0.50
- E is is the number of similar designs performed by company engineers
- F is the current rate of change of the design requirements (for example: revisions per calendar month, i.e. \(\partial A/\partial B\))
- G is the number of functions (in A and B) new to the designer(s)
- H is the experience of the proposed designer(s) (in years).

setting \(m=0.8\), since knowledge residing in other company individuals is not accessible in the same way as from the individual involved. Probably proportional to size of company too.
Complexity is therefore:

A = 16+1+1 (no. of components),
B = 25+8 (no. of functions),
D = 0.01 (designer similar designs – propose to use new own design IC, will require
new mouldings and keyboard),
E = 0 (company similar designs),
F = 0 (design revisions),
G = 6 (known functions),
H = 10 (experience of designer)

making: \[(18+33)/0.01+0 \times (1+0).(1+6)/10 \] = 5200 x 0.7 = 3640.

Although there is an existing calculator design, this is different as single integrated circuit is to be used, simplified mouldings and new keyboard design are required and therefore innovative with a complexity of 3640.
**Appendix 4: Engineering Examples**

**Path Select: R,V,I,S --> Innovative**

| Internal GATE: circuit review | check power supply requirements AC & DC  
|                              | check safety and standards needs are met  
|                              | estimate cost of cct  
|                              | assess MTBF, early life failures and expected life  
|                              | check all limited life components are listed  
|                              | check timescale  
|                              | check risk assessment is still valid  
|                              | check TPS/TPSD specifications are met  
|                              | check engineering constraints are met and are at appropriate level of refinement, eg. component height, wire loom paths EMC, thermal, humidity, dust for operating and storage ranges, voltage stresses, isolation voltages  
|                              | check components for supply voltage, voltage stress, i/o current, operating frequency, operating temp, storage temp, isolation voltage.  
|                              | ensure test equipment/software/mechanics other hardware will be available for prototype proving  
|                              | check components are approved & not obsolete  
|                              | strategy for fabrication and field calibration  

| Internal GATE: post-layout review | ensure all design variants are reviewed for pcb issues  
|                                 | check good engineering practice has been observed  

| Internal GATE: test and manufacturing review | in-circuit test – test access to all nodes, access to all device pins, that exceptions are noted with reasons, and appropriate supply made available for tester gnds.  
|                                              | functional test – test connectors are available, functional test is feasible, equipment availability, test time.  
|                                              | calibration of circuit (& of test & measurement equipment), together with margins  

| GATE 4 pre prod review |

**Table 7: Company Gates during the middle and late phases of design**
Appendix 4.: Engineering Examples


This product book now has real engineering constraints and cross-checks embodied in it. Most of these would be pre-existent in the form of templates. Since this design is an innovative design, conformance to these constraints and cross-checks will not be mandatory, but violations will be highlighted.

Product book 3 is refined over several phases of the product design process, from embodiment design to detail design. The resultant technical documentation will hold a concise definition of the product function, together with all the constraints and cross-checks necessary for its manufacture and test. Table 7 describes the assessment gates carried out during this part of the design process, it is envisaged that most of the checks would be carried out with computer assistance by, for example, opening up the appropriate sections of product books for human perusal and by running through checks and constraints looking for violations.

**Introduction:**

A summary of implementation options of functions and manufacturing issues:

- # serial/parallel arithmetic
- # algorithms for arithmetic
- # integral display control
- # keypad interfacing and decoding
- # test functionality during manufacture

**1. FUNCTIONALITY**

Hand held calculator, 8 digit display, battery operation, +,-,=,mem,k & % functions

1.1. functionality (1st refinement phase)

1.1.a. Functions - +,-,*,/,%sqrt,constant, memory (mc,mr,m+,m-)

    not scientific,

    not programmable. (too complex it seems by assumption ie. too many keys, complex chipery and resultant design time is not variant but innovative as have not done this before)

1.1.a.1. Functionality (2nd refinement phase)

1.1.b. Algorithm exploration - simulate in software to show how (for example multiplication)?
1.1.c. Accuracy - 77 sizes of LCDs

1.1.d. Physical size – palm of hand 80mm by 50mm say

1.1.e. Battery/Solar cell – voltage, power, size – choice of batteries

1.1.f. Keypad size, type – no. of keys, spacings, feel, reliability, cost

1.1.g. Display type, size, character size

1.1.h. Display control – multiplexed (requiring[ME-,7 segments, gnd, 8 decimal points and 8 column strobes] or 9 col.

1.1.i. Strobes and more letters

1.1.j. Test strategy

1.1.k. Operating voltage – calculator chip dependent

1.1.l. Power consumption – ditto

1.1.m. Case material/size/assembly

1.1.n. Reliability – power, vibration, temperature, keypad mechanical wear, torsion of case.

1.1.o. Ease of fabrication

1.1.p. Low cost requires very high level of integration

NOTES: may have to look up keypad design, bcd, binary or decimal arithmetic and display power considerations.

2. EXTERNAL INTERFACES

Human factors

2.1.

Constrained by: finger size on keypad design, character size on display, overall enclosure size fits hand

2.2. Cross-checks:

3. INTERNAL INTERFACES

Keypad, LCD display, batteries

3.1. Constrained by: chip power

3.2. Cross-checks: mechanical sizings & placements

4. FIELD MAINTAINENCE

None: user replace batteries
4.1. Constrained by: cost

4.2. Cross-checks: none

5. PCB DESIGN AND PHYSICAL INTERFACES

fit enclosure --> NNO1 (points directly to enclosure specification)

5.1. Constrained by:

26. Net current carrying capacity
27. Net voltage breakdown
28. Surface mount components side A, side B
29. Number of sides to cct board
30. Flexi/rigid
31. No. of layers
32. Material - FR2,3,4 . . .
33. Material thickness
34. Weight of copper
35. Thickness of copper
36. Power consumption
37. Power dissipation
38. Size
39. Weight

5.2. Cross-checks:

40. height cross checks
41. position sensitive components
42. min/max tracking and special requirements for non-std layout (a) high voltage isolation zones, (b) small signal zones, (c) rf zones, high EMF zones
43. support points for boards
44. allow via holes, buried vias - YES/NO
45. number of layers (min,max)
46. peelable solder masking - YES/NO
47. Build strategy – single/double sided population – YES/NO
48. Define procedure for non-std build
49. Which sides are test points
50. Define silk screen masks showing (a) version, (b) name, (c) components position and orientation, (d)
51. Rules of screen layers – if automatic assembly try and use copper layers instead for version and name
52. Identify & tag CAD parts that are not BOM parts
53. PCB panelisation details

6. DESIGN VALIDATION CRITERIA

Simulations of proposed ASIC, build mock-up of enclosure/keypad for HCI

6.1. Constrained by:

6.2. Cross-checks:

7. TEST STRATEGY

7.1. Constrained by: chip power

Self-test built into ASIC

Manual inspection of LCD and keypad operation

Chip self test includes exercise of display, else vendor's test (key word)

7.2. Cross-checks:

54. Check test probe points and testability to requirements

55. Check specification performance has been achieved

56. Gain Q.A approval for tests

57. Complete production test strategy and confirm (a) test access to all required nodes, (b) probe points for power and ground according to test equipment requirements

8. POWER SUPPLY

Voltage: 3v or 1.5v
8.1.
Constrained by: chip power

9. ENVIRONMENTAL

Temp: office 0–40°C

Humidity: normal (world) office environment

Dust: must work after being in users pocket

Vibration: must work after being in users pocket

EMC: low emissions

9.1. Cross-checks:

Temp: confirm operating and storage ranges

Humidity: confirm operating and storage ranges

Dust: confirm operating and storage ranges

Vibration: confirm operating and storage ranges

EMC: confirm operating and storage ranges

10. STANDARDS

10.1. Constrained by: none (but could have been to a whole list of stds).

10.2. Cross-checks: none

11. HEALTH & SAFETY

none

11.1. Cross-checks:

12. COST

Total (incl. manufacturing costs): less than 50p
12.1. Constrained by: customer

Breakdown: cost --> printed circuit simplicity, chip complexity

12.2. Cross-checks: confirm with production control

13. TIMESCALES

less than 12 months (key words: all)

13.1. Constrained by: design of case moulding tools

13.2. Cross-checks: internal deadlines met

14. QUALITY ISSUES

expected life, early life failure rate, MTBF, battery life, production yield

14.1. Constrained by:

14.2. Cross-checks:

58. highlight shortest life components

59. assess evolving ccts for production yield

60. assess evolving mechanics for production yield

61. ensure production calibration equipment accuracy exceeds production calibration requirements

15. MECHANICAL ENGINEERING (ONLY ELECTRICALLY SALIENT ASPECTS SHOWN)

Design keypad and enclosure

15.1. Constrained by: pcb size, lcd size

15.2. Cross-checks:

62. mechanical detail drawing no.

63. electric field shielding (a) gaskets, (b) conductivity of enclosure parts, (c) earthing points, (d) special coatings for electrical static or EMF prevention AND conformance to electronics requirements

64. isolation zones and distances for specified physical effect

65. wire loom paths --> safety considerations and static and EMF control

66. ensure all connectors, heatsinks, switches, wire links, pins, feedthroughs, standoffs, retaining clips, earthing clips, fixing clips, locating holes, visual, auditory or tactile indicators are specified mechanically for position, dimensions and part number.
67. check position sensitive components from mechanical viewpoint

16. MANUFACTURING (PCB, ASSEMBLY & WIRING)

16.1. Constrained by:

ASSEMBLY

68. Soldering - hand, wave, reflow
69. Pcb direction through solder
70. Component packing density on pcb
71. Hand assemble components

BOARD MANUFACTURE

72. Artwork tolerancing
73. Aperture definitions
74. Minimum track width - signal - power - other
75. Minimum hole size - via, component
76. Minimum pad to hole radial copper (annular ring) - via, component, other (sockets, auto-assembly)
77. Board finishes roller tin, reflow, hot air levelling
78. Solder resist
79. Screen printed ink, photo-imageable ink, photo-imageable dry film
80. Production test
81. Bed of nails/functional test
82. Test probe points/connectors/busses
83. Function

16.2. Cross-checks:

84. Obtain solder report
85. Generate panellisation of pcb - homogenous or heterogenous, crop marks, mechanical handling requirements for size of boards
86. Check concessions raised for deviations from current build standard
87. Check parts list of variants on numeric release
88. Check design variants have been prototyped, tested and are now numeric released
89. check all corrective actions completed from previous reviews
90. check no outstanding problem notification reports (PNR)
91. check sample approval of PCBs are at numeric release
92. check ECN has been raised to release modules to numeric release.
93. check PCB layout satisfies all in-house and adopted standards
94. check voltage isolation between PCB layers is as defined
95. confirm populated and wired PCB will not foul enclosure.
96. check logo, part number, revision control and screen layers are on PCB and do not interfere with electrical wiring
97. check clearances on edge of PCB and around holes is to standard
98. check copper coverage is to standard
99. check layout compiles with current design guidelines
100. check free-space on PCB is available
101. check BOM components fit pin to pin spacings on board
102. confirm in-house components are to numeric release that agrees with BOM and they are formed to fit designed space and contact pitch
103. confirm BOM purchased components are preformed to designed requirements, ie thru'hole spacings, wire diameters, lead corner bend angles, length of wire, cropping required, support structures for components (vibration control)
104. check test points, numbers, clearances conform to in-house stds
105. ensure PCBs fit into test structure mechanically
106. specify date when kit of parts will be available
107. confirm first prototype production run date
108. generate assembly sequence
109. generate control files for automatic assembly machines
110. check PCB cost & timescale is confirmed
111. define optimum tooling requirements for PCB
112. check resources for prototype build are available for schedule
113. check for hire of specialised equipment for assembly or test
114. confirm parts for prototype build, (a) stock items, (b) new parts (approved?), (c) custom parts and (d) long lead time parts
17. RISKS

no risks

18. TECHNICAL DOCUMENTATION

115. design book – describe (a) cct diagrams, (b) notes on operation, (c) design calculations, (d) analysis of operation, (e) min/max tolerance analysis, (f) timing diagrams, (g) interactions with software, (h) environmental tests, and sections on all above ie 1-17

116. manufacturing book

117. field maintenance book

118. user book

119. PNR setup

120. ECN setup
Appendix 4.: Engineering Examples

(c) An example database

Introduction

A key problem facing engineering companies is the capture, control and recall of product design information from design and manufacturing staff. A solution to the problem proposed in this report is the integration of design schematic diagrams with all other design documentation, unifying the many editors and computer tools used by engineering and ancillary staff to create and store design information. The product book concept, described earlier, shows how a developing product generates a set of design books which describe all aspects of a product's form, function and manufacture. Product books are a convenient repository for company knowledge for each design undertaken. Design knowledge may be retrieved when a repeat order is required, or copied and altered when a variant design is required.

Significantly such a database (ie. design knowledge, information and data stored as plain text, diagrams and tables, etc) can become an active database simply by linking it into a computer checking scheme.

Recall that each design product book, when initially empty, is a template of headings, sections and prompts (figure 35 shows a partially filled book 3 template). Such a template will be filled out as a design progresses. Parts of the template will be unstructured, descriptive prose and parts will be rigid lists of manufacturing rules, for example. Although unstructured English prose is difficult to handle by computer in any other manner than text-based pattern matching, an object oriented database containing text and other objects may be more appropriate for a computer to check design consistency, to automatically generate reports and to partially automate the design assessment gates that a design must go through at various stages in its development.
Design consistency, automatic checking and report generating are not new to database managers. The concept of a dual function system, where human readable text and data can also be manipulated by computer is relatively new and offers a number of benefits over the traditional view of a database. For example, assume a check must be made by a production engineer on a particular stage of design; if the database is only machine readable, then an SQL (structured query language) programme must be developed and run on the database to extract the necessary information, a time consuming and possibly error prone exercise. However, on a human readable database, that same engineer can either use the indexing system built in to the word processing software and just turn to the appropriate page to check the information directly, or if the enquiry is a frequent one a programme may be written to find the data. The additional flexibility offered by a human readable database relies upon a person’s reading and writing skills and not on new and possibly un-natural software programming techniques; and so does not require any special training or knowledge of computers (apart from the now common skill of knowing how to work a word-processor).

Demonstration

A demonstration database outlining some of the ideas defined in the functional specification earlier has been partially developed using the Interleaf desktop publishing software. Interleaf conveniently uses the “office” metaphor in its human computer interface, so that a user sees a set of filing cabinets, drawers and folders in which documents, slides, faxes and memos can be held.

Figure 35 shows part of an innovative design (developed earlier in this appendix). The design contains a number of computer ‘active’ features, (a) constraints, (b) checks and (c) facts.
Constraints are generally physical limitations on the design that are derived from considerations of the manufacturing processes used to fabricate the product, for example using machine assembly techniques will constrain the types of component parts used in a design.

Checks are activities carried out by machine or specific personnel to ensure the design conforms to criteria laid down in company practice notes. In figure 35 for example, a check that can be scheduled by computer is to obtain a solder report for the specified product. An e-mail message would be constructed (using a template defining the questions to be asked) and sent to the person responsible for solder checks. They would be expected to respond to
this message and file a reply that holds the necessary information. This would be stored in a specific location within the product book structure and if required, further checking on the responses to the template questions could be carried out by computer. A failure to reply within a pre-determined period could initiate further mail messages to other personnel.

Facts are statements of design requirement, rather than functional or manufacturing constraints, and as such would perhaps be derived from customer of company needs. For example, the design must be coloured red, or must cost less than 50 pence. Facts are just checked for consistency, so that if it is declared as ‘fact’ that the bill of materials will cost no more than 50 pence, then when design consistency is checked, say once a week, that the total cost of the bill of materials will be calculated and the fact checked for consistency. If it fails then the offending item(s) are recorded in a document or mail message.

Facts may possess an audit trail through a design, allowing quality functional deployment (QFD) to be applied and traced through a design.
Appendix 4.: Engineering Examples

Figure 36: Example contents of a company parts library

Although not implemented in this demonstration of the active product book structure, design schematic diagrams and layout diagrams could easily be developed using the basic graphics capabilities of Interleaf (as many other DTP packages). Bills of materials can be automatically extracted from such diagrams and written to appendices of a product book. Such lists, as shown in figure 35, would enable layout tools to form printed circuit board structures. But in addition, all the necessary manufacturing information concerning soldering and assembly (and so on) is also to hand for correct layout rules to be applied.

Descriptions of parts held in design libraries must define a component from both a functional, purchasing and a manufacturing viewpoint. An example structure, shown above in figure 36, would not only describe a component's function, but its size and manner of assembly. This additional information provides a means of performing consistency checks between the bills of materials and the manufacturing processes. This is described below in an example.
The human interface to the active documentation is mediated through the definitions of rules held in the company manufacturing rule book. A rule specifies a set of conditions to be searched for and a process to be carried out if the conditions are found. So the rule:–

**Rule:** (and Assemble: by-machine Soldering: reflow solder) (print-obj-to-file "appendix 2")

would scan the selected design books looking for any object (a BOM part or something else) that has Assemble and Soldering properties as shown, when found each object is copied to "appendix 2".

---

**Figure 37: Example contents of a company manufacturing rule set**

Consistency checks on the database can also be carried out, for example to check if all defined constraints are consistent with the bill of materials requires the following rule to be activated:–
Consistency: (constraints BOM) (consistent)

Cross-checks are database searches that look for specific documents or mail messages within the design product book structure. Similarly a report generator is a rule whose left hand side is a set of conditions and whose right hand side is a named, where object matching the LHS of the expression are placed in the report.

Rules, checks, consistencies and reports can be grouped together as gates, allowing the construction of sets of activities to be carried out at specified design assessment gates, as shown in figure 37.
(d) A LISP exemplar implementation of the product book model

The following Lisp code implements the product book demonstration described above from page 369 on. It is runnable as a demonstration from within the Interleaf technical publishing system.

Only a partial implementation has been developed, it highlights all the basic features of the model.

(lisp-set-implementation "Interleaf Lisp" "2.0")

;; Module name: constraints
;; Purpose: test product book idea & show document truth maintenance in action
;; Notes:
;; Interfaces: runs as part of Interleaf document system

;; Audit: PFC
;; 29/9/92 PFC

;;;(use-application "dtk")
;;;(defun ver (print (eval ileaf-version)))

(in-package "user") ;; must be in "user", to be same as when in Listener
;;;(list-all-packages)

;;*********************************************************************
;;'FUNCTION DECLARATIONS' 'FUNCTION DECLARATIONS' 'FUNCTION DECLARATIONS' 'FUNCTION DECLARATIONS' 'FUNCTION DECLARATIONS' 'FUNCTION DECLARATIONS' 'FUNCTION DECLARATIONS' 'FUNCTION DECLARATIONS' 'FUNCTION DECLARATIONS' 'FUNCTION DECLARATIONS' 'FUNCTION DECLARATIONS' 'FUNCTION DECLARATIONS' 'FUNCTION DECLARATIONS' 'FUNCTION DECLARATIONS' 'FUNCTION DECLARATIONS'

;;; this next defun was from Nick Silv, Interleaf 18/9/92

(defun create-phil-doc(fname)
  (let (fptr)
    (dt-set-container *dt-desktop*)
    (setq fptr (dt-copy (dt-child-match (dt-find-create) "document" dt-document-class)))
    (tell fptr mid:set-name fname)
    fptr
  )
)

(defun x-insert (x-text)
  "insert x-text directly into the current document"
  (let ((mO (doc-point-marker)))

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(m1 (doc-point-marker)))
(tell m1 mid:set-props :follow-insert t)
(tell m1 mid:insert x-text) ;; might be multi line insert
(doc-goto-marker m1) ;; to end
(doc-flush-queue) ;; redisplay before selecting
;;;(tell *text-editor* mid:select m0 m1)
(doc-modify :small)
)

(defun x-insert-select (x-text)
  "insert x-text directly into the current document"
  (let ((m0 (doc-point-marker))
        (m1 (doc-point-marker)))
    (tell m1 mid:set-props :follow-insert t)
    (tell m1 mid:insert x-text) ;; might be multi line insert
    (doc-goto-marker m1) ;; to end
    (doc-flush-queue) ;; redisplay before selecting
    (tell *text-editor* mid:select m0 m1)
    (doc-modify :small)
  )

;;; get first word of text str in component
(defun get-first-word (ptr)
  "get the first text string word from the component"
  (let (m0 m1 val)
    (tell (tell ptr mid:get-document) mid:open) ;; set to current document
    (setq m0 (tell ptr mid:get-marker nil));;; see p.7-55 & 7-73
    ;; then copy it
    (setq m1 (tell m0 mid:copy))
    ;; then move it on to end of component
    (tell m1 mid:move-by 1 :by :word-endings)
    ;; now move text caret to it
    (doc-goto-marker m0)
    ;; then select contents
    (tell *text-editor* mid:select m0 m1)
    ;; and copy them
    (setq val (tell m0 mid:get-substring m1 t t))
    val)
  )

;;; example (get-first-word my-constr)

;;; get all text str in component
(defun get-text (ptr)
  "Get all the text available from the current cmpn"
  ;;
;;;; make where it is the current document
(let (m0 m1 val)
  (preserving-context
   (tell (tell ptr mid:get-document) mid:open)
   (setq m0 (tell ptr mid:get-marker nil)) ;; see p.7-73
   (setq m1 (tell ptr mid:get-marker t)) ;; see page 7-55
   (doc-goto-marker m0)
   ;; then select contents
   (tell *text-editor* mid:select m0 m1)
   (setq val (tell m0 mid:get-substring m1 t t)) val))
;;;(get-text c1) ;; middle bit is getting document ptr
;;;(get-text item)

;;;; get lhs of rule
(defun get-lhs (ptr)
  "A rule has structure <lhs> <rhs>"
  "this returns the text of the lhs"
  (let (m0 m1 val) (setq m0 (tell ptr mid:get-marker nil)) ;; see p.7-73
    ;; then copy it
    (setq m1 (tell m0 mid:copy))
    ;; then move it on to end of component
    (tell m1 mid:move-by 1 :by :cmpn-endings)
    ;; now move text caret to it
    ;;(doc-goto-marker m0)
    ;; then select contents
    ;;(tell *text-editor* mid:select m0 m1)
    ;; and copy them
    (setq val (tell m0 mid:get-substring m1 t t)) val)
  
) ;;; get rhs of rule
(defun get-rhs (ptr)
  "A rule has structure <lhs> <rhs>"
  "this returns the text of the rhs"
  (let (m0 m1 val) (setq m0 (tell ptr mid:get-marker nil)) ;; see p.7-73
    ;; then copy it
    (setq m1 (tell m0 mid:copy))
    ;; then move it on to end of component
    (tell m1 mid:move-by 1 :by :word-endings)
    ;; now move text caret to it
    ;;(doc-goto-marker m0)
    ;; then select contents

;;;(tell *text-editor* mid:select m0 m1)
;;; and copy them
(setq val (tell m0 mid:get-substring m1 t t))
(val)

;;; get named child object
(defun get-named-child (ptr name)
  "returns the child 'named' object"
(let (obj my-cmpn-name)
  (preserving-context
    ;;(print name)
    (setq obj nil)
    ;; run along structure (p.7–53) component by component
    (while (setq ptr (tell ptr mid:get-next :along :structure))
      (setq my-cmpn-name (tell ptr mid:get-name))
      ;;(print my-cmpn-name)
      (if (string-equal name my-cmpn-name)
        (setq obj ptr));;; return obj found
    )
    obj;;; return obj found, nil if not
  ))
)

;;;(setq chd (tell (car (cdr BOM-list)) mid:get-child))
;;;(stringp (tell chd mid:get-name))
;;;(tell (get-named-child chd "Part-ref") mid:get-name)

;;; example (get-lhs my-constraint
(defun print-txt-to-file (obj ftle)
  "opens default TPSB, then opens "file" and writes obj into it"
  "(print-to-file (obj file))"
(let (TPSB-book)
  (preserving-context
    (setq TPSB-book (dt-object file)) ;; store by default in to TPSB
    (tell TPSB-book mid:open)
    (tell *cmpn-editor* mid:deselect :all)
    (tell *cmpn-editor* mid:create "para")
    (x-insert obj)
  ))
)

;;;(print-txt-to-file "Failed consistency:-" "TPSB-design_A.boo/appendix2.doc")

(defun print-obj-to-file (obj fLle)
  "copy object to another file"
(let ( obj-top m0 m1 )
(preserving-context

(tell (tell obj mid:get-document) mid:open)
(tell *cmpn-editor* mid:deselect)
;;; copy to clipboard and then paste it
(setq obj-top (tell obj mid:get-top-cmpn))
(tell obj-top mid:select)
;;;(setq m0 (tell obj-top mid:get-marker nil))
;;;(setq m1 (tell obj-top mid:get-marker t))
(tell *cmpn-editor* mid:select)
(tell *cmpn-editor* mid:copy)
(setq TPSB-book (dt-object file)) ;;; store by default in to TPSB
(tell TPSB-book mid:open)
(tell *cmpn-editor* mid:deselect :all)
(tell *cmpn-editor* mid:paste)
))
)
;;;(print-obj-to-file (nth 0 r-list) "TPSB-design_A.boo/appendix2.doc")

(defun constraint-mishap (objpair BOM-item file)
"A note of the object its constraint violation printed to file as an error message"

(let (m0 m1 null obj-top TPSB-book obj-text obj constraint c-text b-text)
(preserving-context
 (setq obj (car objpair))
 (setq constraint (cdr objpair))
;;; get constraint text
;;;(tell (tell constraint mid:get-document) mid:open)
 (setq c-text (get-text (tell constraint mid:get-top-cmpn)))
(setq obj-text (get-text obj));;; get property that it failed consistency on
(setq b-text (get-text BOM-item))
;;; get part constraint property
(setq null (tell (tell obj mid:get-document) mid:open))
(setq null (tell *cmpn-editor* mid:deselect :all))
;;; copy to clipboard and then paste it
(setq obj-top (tell obj mid:get-top-cmpn))
(setq null (tell obj-top mid:select))
(setq m0 (tell obj-top mid:get-marker nil))
(setq m1 (tell obj-top mid:get-marker t))
(tell *cmpn-editor* mid:select)
(tell *cmpn-editor* mid:copy)
(setq TPSB-book (dt-object file)) ;;; store by default in to TPSB
(tell TPSB-book mid:open)
(setq null (tell *cmpn-editor* mid:deselect :all))
(setq null (tell *cmpn-editor* mid:goto :last))
(setq null (tell *cmpn-editor* mid:create "para"))
(setq s1 (concat "COMPONENT " b-text))
(setq s2 (concat "

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FAILED on Part property constraint " obj-text "
which is not compatible with "")
(setq s3 (concat "design constraint number: " c-text))

(x-insert (concat s1 s2 s3))

; (setq TPSB-book (dt-object file)); store into named file (appendix 2 perhaps)
;(tell TPSB-book mid:open)
;(tell *cmpn-editor* mid:deselect :all)
;(tell *cmpn-editor* mid:goto :last)
;(tell *cmpn-editor* mid:paste)
))

;;; (constraint-mishap (nth 0 r-list) "TPSB-design_A.boo/appendix2.doc")
;;; (setq objpair (nth 0 r-list)) (setq file "TPSB-design_A.boo/appendix2.doc")

(defun doe-read-only (doe)
"make an entire document read-only"
;;; now find the first component in document
(let (my-cmpn)
(setq doe (dt-object doe))
(tell doe mid:open :hide-window nil)
(setq my-cmpn (tell-class doc-cmpn-class mid:get-first :along :structure))
;;; run along structure (p.7-53) component by component
(while (setq my-cmpn (tell my-cmpn mid:get-next :along :structure))
 (setq my-cmpn-props (tell my-cmpn mid:set-props :read-only t))
);); endwhile
)

;;; (doc-read-only "TPSB-design_A.boo/book_3.doc")

;;; FUNCTIONS FOR GETTING DATA FROM DESIGN BOOKS

(defun get-constraints (book)
"find all the constraint objects in book"
;;; first find the constraints in TPSB
(let (TPSB-book TPSB-doc constr-list my-head my-constr)
(preserving-context
(setq book "TPSB-design_A.boo")
(setq TPSB-book (dt-object book))
(tell TPSB-book mid:open); see p.7–6 for opening documents in a hidden manner

;;; run thru docs in book in fixed manner (assume 3 books in order)
(setq TPSB-doc (tell TPSB-book mid:get-child))
;;;(tell TPSB-doc mid:get-name)
(setq TPSB-doc (tell TPSB-book mid:get-child))
;;;(tell TPSB-doc mid:get-name)
Examplar product book

(setq TPSB-doc (tell TPSB-doc mid:get-next))
;;(tell TPSB-doc mid:get-name)
(setq TPSB-doc (tell TPSB-doc mid:get-next))
;;(tell TPSB-doc mid:get-name)
(tell TPSB-doc mid:open)

;; set up a list to hold all constr objs
;; and save current document in head
(setq constr-list (cons *document* ()))

;; now run through looking for constraints
;; get head of name pool in current document
(setq my-head (name-find-head doc-cmpn-class "constraint"))

(setq my-constr (tell my-head mid:get-child :along :name)) ;; get first value
(push my-constr constr-list)
;;(get-text my-constr)
;; now loop until got all of them
(while (setq my-constr (tell my-constr mid:get-next :along :name))
;; until my-constr == nil, loop and get child
(push my-constr constr-list)
)
constr-list))
;; return constraints list to caller

;;(get-constraints "TPSB-design_A.boo")
;;(length constr-list)

(defun get-rules (book)
"find all the rules in a document"
(let ( TPSB-rules Man-rules-doe rule-list my-head-rule my-rule)
(preserving-context
;; now get the rules in
(setq TPSB-rules (dt-object book))
(tell TPSB-rules mid:open :hide-window t);; see p.7-6 for opening documents in a hidden manner
;; assume only one document on book
(setq Man-rules-doc (tell TPSB-rules mid:get-child))
(tell Man-rules-doc mid:get-name)
(tell Man-rules-doc mid:open)

(setq rule-list (cons *document* ())) ;; set up a list to hold all rule objs
;; now run through looking for constraints
;; get head of name pool in current document
(setq my-head-rule (name-find-head doc-cmpn-class "rule"))
(tell my-head-rule mid:get-props)
;;(get-first-word my-rule)
(setq my-rule (tell my-head-rule mid:get-child :along :name)) ;; get first val
(push my-rule rule-list)
;;(tell (car rule-list) mid:get-props)
(get-first-word my-rule)
;; now loop until got all of them
(while (setq my-rule (tell my-rule mid:get-next :along :name))
  ;; until my-rule == nil, loop and get child
  (push my-rule rule-list)
)
rule-list))
);;; return rule-list to caller
;;(get-rules "Manufacturing.boo")

(defun get-BOM (doc)
"find all BOM in specified document"
(let {TPSB-doc BOM-list my-head-inst my-inst)
  (preserving-context
    ;; then find the BOM in appendix 1
    (setq TPSB-doc (dt-object doe))
    (tell TPSB-doc mid:open);;; see p.7–6 for opening documents in a hidden manner
    (setq BOM-list (cons *document* () )) ;;; set up a list to hold all rule objs)
    ;; now run through looking for constraints
    ;; get head of name pool in current document
    (setq my-head-inst (name-find-head doc-cmpn-class "Instance"))
    (tell my-head-inst mid:get-props)
    ;;(get-first-word my-inst)
    (setq my-inst(tell my-head-inst mid:get-child :along :name));;; get first val
    (push my-inst BOM-list)
    ;;(tell (car BOM-list) mid:get-props)
    (get-first-word my-inst)
    ;; now loop until got all of them
    (while (setq my-inst (tell my-inst mid:get-next :along :name))
      ;; until my-inst == nil, loop and get child
      (push my-inst BOM-list)
    )
  BOM-list))
);;; RETURN BOM-list to caller

(defun open-parts-lib ()
"call: (open-parts-lib) returns: Lib-parts-doc ie."
;; then find the parts in the parts-lib stored at the end of appendix1
(let (TPSB-lib Lib-parts-doe)
  (preserving-context
    (setq TPSB-lib (dt-object "Parts-library.boo"))
    ;; then find the library in library book
    ;; assume only one document in book
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(setq Lib-parts-doc (tell TPSB-lib mid:get-child))
(tell Lib-parts-doc mid:get-name);; template
(setq Lib-parts-doc (tell Lib-parts-doc mid:get-next))
(tell Lib-parts-doc mid:get-name);; misc-lib
(tell Lib-parts-doc mid:open)
Lib-parts-doc
;; unfinished, see above get-rules etc
))

(defun get-lib-part (doe part)
"returns the obj that has the matching 'part' name"
(let (my-lib-part)
(preserving-context
(tell doe mid:open) ;; now send message to part asking for its constraints
;; that match the front text of each constraint
(setq my-lib-part (name-find-head doc-cmpn-class "Part"))
(setq my-lib-part (tell my-lib-part mid:get-child :along :name)) ;; get PART master
(setq my-lib-part (tell my-lib-part mid:get-next :along :name)) ;; get first real PART
;; look at name of part, and return part that matches name eg. (setq part "fuse 1")
(until (or (string-contained part (get-text (tell (tell my-lib-part mid:get-child) mid:get-child)))
(string-contained (get-text (tell (tell my-lib-part mid:get-child) mid:get-child)) part ))
(get-text my-lib-part)
(setq my-lib-part (tell my-lib-part mid:get-next :along :name))
)
my-lib-part)
);; return first part to caller
;; (setq obj1 (get-lib-part Lib-parts-doc "relay 1"))
;; (setq obj1 (get-lib-part Lib-parts-doc "fuse 1"))

(defun return-part-prop (my-part name)
"runs through a PART structure and returns object whose name matches 'name'"
(let (obj my-part-doc my-part-doc my-part-name my-part-props my-part-props-child)
(setq obj nil)
;; select document it is contained in
(setq my-part-doc (tell my-part mid:get-document))
(tell my-part-doc mid:open)
;; part name value
(setq my-part-name (tell my-part mid:get-child ))
;;(tell my-part-name mid:get-name)
(get-first-word my-part-name)
;; part props
(setq my-part-props (tell my-part-name mid:get-next))
;;(tell my-part-props mid:get-name)
;; text para holding li-line components
(setq my-part-props-child (tell my-part-props mid:get-child))
;;;(tell my-part-props-child mid:get-name)
;;; run through part-props
;setq my-part-props-child (tell my-part-props-child mid:get-child)
;;;(tell my-part-props-child mid:get-name)
;;; para
;setq my-part-props-child (tell my-part-props-child mid:get-child)
;;;(tell my-part-props-child mid:get-name)
;;; Assemble
;setq my-part-props-child (tell my-part-props-child mid:get-child)

;;; & check each prop.
(if (or (string-contained (tell my-part-props-child mid:get-name) name)
    (string-contained name (tell my-part-props-child mid:get-name)) )
  (setq obj my-part-props-child)
)
;;;(print (tell my-part-props-child mid:get-name))
;;;(print name)

(while (setq my-part-props-child (tell my-part-props-child mid:get-next))
  (if (or (string-contained (tell my-part-props-child mid:get-name) name)
    (string-contained name (tell my-part-props-child mid:get-name)) )
    (setq obj my-part-props-child)
)
obj)
);;enddefine

;;;(return-part-prop my-part cl-constr-name)
;;;(setq item (return-part-prop my-part "Cost"))
;;;(tell item mid:get-name)

(defun get-constraint-name (ptr)
"constraints my be embedded in a variety of top level components"
"so to get key word from parent of constraint, have to get parent"
"return the parent text name"
(let (ptr-parent)
  (tell (tell ptr mid:get-document) mid:open)
  (setq ptr-parent (tell ptr mid:get-parent))
  (get-first-word ptr-parent)
)
)

(defun consistent-part-props (my-part constr-list)
"runs through a PART structure, checking each part-prop against the list of constraints"
"returns a list of objs within the part that fail, ie. they have correct constraint"
"but wrong value eg: Assemble: by-machine as constraints, but Assemble: by-hand in part"

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"Each list item is a pair, front is obj, back is constraint violated"

;;; select document it is contained in
(let (i obj my-part-doc my-part-doc my-part-name my-part-props
my-part-props-child)
(preserving-context
(let (my-part-doc (tell my-part mid:get-document))
(tell my-part-doc mid:open)
;;; set return list up
(setq return-list ())
;;; part name value
(setq my-part-name (tell my-part mid:get-child ))
;;;(tell my-part-name mid:get-name)
;;;(get-first-word my-part-name)
;;;(get-first-word (tell my-part-name mid:get-child))
;;; part props
(setq my-part-props (tell my-part-name mid:get-next))
;;;(tell my-part-props mid:get-name)
;;; text para holding in-line components
(setq my-part-props-child (tell my-part-props mid:get-child))
;;;(tell my-part-props-child mid:get-name)
;;; run through part-props
(setq my-part-props-child (tell my-part-props-child mid:get-child))
;;;(tell my-part-props-child mid:get-name)
;;; para
(setq my-part-props-child (tell my-part-props-child mid:get-child))
;;;(tell my-part-props-child mid:get-name)

;;; FIRST PART-PROP: Assemble
(let (my-first-prop (tell my-part-props-child mid:get-child))
;;; now get the right data from constr-list items
(let (my-first-prop mid:get-name)

;;; & check each part-prop in current-part against constr-1
;;; if match push t, if no match push nil, if match and constraint value does not match
;;; push mis-match onto returned list
(for ((setq i 0) (< i (length constr-list)) (inc i))
;;; for each constraint list item do
;;;(;;(setq i 1)
(setq my-current-prop my-first-prop);; reset to start of props list
(while my-current-prop
(if (string-contained (tell my-current-prop mid:get-name)
    (get-constraint-name (nth i constr-list)))

;;; if find match, check contents
(if (or (string-contained (get-text(tell my-current-prop mid:get-child))
    (get-text (nth i constr-list)))
 (string-contained (get-text (nth i constr-list)))

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(get-text(tell my-current-prop mid:get-child)))

();;; if match, do nothing, else
(push (cons my-current-prop (nth i constr-list)) return-list)
);;; endif
);;; endwhile
);;; endfor
return-list)))
;;(setq const-list (cdr (reverse constr-list)))
;;(setq it (consistent-part-props my-partl const-list))
;;(length return-list)

*********************************************************************
;; START
"'*********************************************************************

(defun run-consistency-check ()
(setq constraint-list (get-constraints "TPSB-design_A.boo"))
(setq rule-list (get-rules "Manufacturing.boo"))
(setq BOM-list (get-BOM "TPSB-design_A.boo/appendixl.doc"))
(setq Lib-parts-doe (open-parts-lib))

;; now run through BOM, for each component do:­
;; lookup part in library
;; run through part, matching constraint name with part-prop name
;; when find match, do:­
;; if contents match then return true, else nil
;;
;; now get the constraint names and match them against part properties
;; and then search through part looking for this key word name

;; for each BOM comp. do
(tell (car (reverse BOM-list)) mid:open)
;;(tell (car (reverse BOM-list)) mid:get-name) ;; select document assocated with list
(print-txt-to-file "The following components failed consistency checks:­"
"TPSB-design_A.boo/appendix2.doc")
(setq r-list ()
(for ((setq i 0) (< i (­ length BOM-list) 1)) (inc i))
;; (setq i 0)
(setq item (get-named-child (tell (nth i BOM-list) mid:get-child) "Part-ref"))

(setq item-text (get-text item))
;; get library part corresponding to current name in BOM
(setq my-partl (get-lib-part Lib-parts-doe item-text))
;;; and check it out against the list of constraints found above
(setq r-list (consistent-part-props my-part1 (cdr (reverse constraint-list))))
Examplar product book

(for ((setq j 0) (< j (length r-list)) (inc j))
    ;; (setq j 0)
    (constraint-mishap (nth j r-list) (nth i BOM-list)
"TPSB-design_A.boo/appendix2.doc")
)
)
)

;; RUN CONSISTENCY CHECKS on product books
(run-consistency-check)
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signed:

Philip F. Culverhouse
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